BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Direct Testimony and Exhibits of

**Dr. Roger H. Bezdek**

June 1, 2015

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## I. INTRODUCTION

Q. **Please state your name address and occupation.**

A. My name is Roger H. Bezdek, 2716 Colt Run Road, Oakton, Virginia, 22124. I am an economist.

Q. **By whom are you employed and in what position?**

**A.** I am the president of Management Information Services, Inc., (MISI), an economic research firm specializing in energy, environmental, and regulatory issues.

Q. **On whose behalf are you testifying in this proceeding?**

**A.** I am testifying on behalf of Peabody Energy Corporation.

Q. **Have you included a description of your qualifications, duties and responsibilities?**

**A.** Yes. A description of my qualifications is included as Bezdek Exhibit 1.

Q. **Please describe your educational background and professional experience.**

A. I received a Ph.D. in Economics from the University of Illinois (Urbana).

I have 40 years' experience in research, management, and consulting in the energy, utility, environmental, and regulatory areas, and have served in private industry, academia, and the U.S. Federal government. My experience includes Corporate Director, Corporate President and CEO, University Professor, Research Director in the Bureau of Economic Analysis of the U.S. Department of Commerce, Research and Program Director at the Energy Research and Development Administration and the U.S. Department of Energy, Special Advisor on Energy in the Office of the Secretary of the Treasury, and a U.S. energy delegate to the European Community and to the North Atlantic Treaty Organization. While with DOE, I was one of the founders of the Federal Government's Renewable Energy Program.

I have served as a consultant to the White House, the Office of former Vice President Al Gore, Federal and state government agencies, organizations that include the National Science Foundation, NASA, Greenpeace, and EPA, and numerous Fortune 500 businesses and corporations. I also have presented energy briefings to the staffs of multiple presidential candidates, including then-Senator Barack Obama and then-Senator Hillary Clinton in 2008. I am active with the National Research Council of the U.S. National Academies of Science (NAS), and have served on various NAS committees, including, most recently, the joint NAS/Chinese Academy of Sciences Committee on U.S.-Chinese Energy Cooperation and on the NAS Committee on Fuel Economy of Medium and Heavy Duty Vehicles.

I have testified before Federal, state, and city governments. I am the author of six books and over 300 articles in scientific and technical journals. I serve as an editorial board member and peer-reviewer for various professional publications, and I am the Washington editor of *World Oil* magazine.

## II. OVERVIEW OF OPINIONS

Q. **What are the purposes of your testimony in this proceeding?**

A. The major purpose of my testimony in this proceeding is to assess whether the Commission should adopt a new environmental cost value for $CO_2$ based on the benefits of $CO_2$ emissions and the problems with the federal social cost of carbon (SCC).

Q. **Can you summarize your principal conclusions as to the environmental benefits of $CO_2$ emissions?**

A. The environmental benefits of carbon dioxide emissions are enormous and have been well documented and estimated.

- $CO_2$ is not harmful and is actually good for the planet: More $CO_2$ will be beneficial, crop yields will increase substantially, and greening of the planet due to $CO_2$ is already occurring.
- The impact of $CO_2$ emissions on plant growth is highly beneficial: The more $CO_2$ there is in the air, the better plants grow, as has been demonstrated in literally thousands of laboratory and field experiments.

Q. **Can you summarize your principal conclusions as to the economic benefits of $CO_2$ emissions?**

A.
- The effect of $CO_2$ fertilization on agricultural productivity can be quantified, and a doubling of the air's $CO_2$ content above the current level will increase the productivity of most herbaceous plants by about one-third.
- The economic value of $CO_2$ fertilization is enormous: The total economic value of the $CO_2$ benefit for 45 crops cumulatively totaled $3.2 trillion, 1961-2012, and is forecast to total nearly $10 trillion, 2012 – 2050.
- The agricultural, social, and economic benefits of carbon dioxide emissions are increasing rapidly, and there is no limit for the foreseeable future to these benefits as $CO_2$ emissions increase.
- There is a strong, positive, direct causal relationship between carbon dioxide emissions and GDP.
- Future economic growth requires fossil fuels because these are the only fuels that can provide the abundant, reliable, affordable energy that the world will depend on in the coming decades.
- My findings are even more relevant for Minnesota than for the U.S. as a whole due to the state's northern location and relatively colder temperatures, which makes it exceedingly dependent on fossil fuels.

Q. **Can you summarize your principal conclusions as to the federal government's social cost of carbon?**

A.
- The empirical scientific evidence supports an environmental externality figure for carbon dioxide of approximately zero.
- The federal government's SCC estimates are not credible.
- The federal SCC estimates do not adequately consider the benefits of fossil fuels and $CO_2$ emissions.
- The integrated assessment models (IAMs) relied upon by the federal Interagency Working Group (IWG) in generating the current federal

SCC do not adequately consider the benefits from carbon dioxide emissions.

- The IAMs relied upon by the IWG have not been shown by a preponderance of the evidence to be reliable, accurate, reasonable, and the best available measures for the cost of carbon -- in fact, just the opposite is true.
- The benefits of $CO_2$ emissions with respect to economic growth exceed by orders of magnitude the federal SCC figures -- the benefits estimates are so large as to relegate the federal SCC estimates to statistical noise.
- Extensive relevant scientific knowledge on environmental externalities has become available over the 17 years since the Commission first established cost values, and this greatly strengthens my conclusions.
- The federal SCC is not a reasonable measure and the preponderance of evidence demonstrates that it is not the best available measure to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422.

Q. **Can you summarize your principal conclusions as to the impact of higher energy prices?**

A. The impact of higher energy prices on lower income ratepayers is devastating.

- Higher energy prices greatly harm lower income ratepayers in Minnesota and energy costs are consuming the incomes of Minnesota's low- and middle-income families at levels comparable to other necessities such as housing, food, and health care.
- The impact of higher energy prices on minorities is especially severe because minority families are more likely to be found among the lowest-income households.

- The impact of higher energy prices on minority and elderly ratepayers in Minnesota is disproportionately burdensome, since they are among those most vulnerable to energy price increases, and the benefits of maintaining fossil fuel energy are much greater for these ratepayers.

Q. **Can you summarize your principal recommendations?**

A.
- The benefits of carbon dioxide emissions should be considered in developing any environmental externality figure for $CO_2$ in Minnesota.
- The benefits of $CO_2$ greatly exceed the costs, and any regulatory or benefit-cost analysis should take this huge discrepancy into account.
- The federal SCC is not a reasonable measure and should not be used to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422.
- The federal SCC estimates should not be used in setting regulatory policies in Minnesota or elsewhere.
- If an environmental externality figure for carbon dioxide is to be used in any regulatory proceeding, it should be set at a value of approximately zero.
- The impact of higher energy prices on lower-income, minority, and elderly ratepayers in Minnesota is disproportionately burdensome, and this should be taken into account in any regulatory proceeding.
- The best available measure to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422 is a metric that considers both the benefits and the costs of $CO_2$, and the benefit-cost measure described here should be used.

Q. **Have you determined an environmental externality figure for carbon dioxide?**

A. I have not determined a precise externality figure for carbon dioxide. However, from my research (summarized in Bezdek Exhibit 2) and as discussed below, I believe the empirical scientific evidence supports an environmental externality figure for carbon dioxide of about zero.

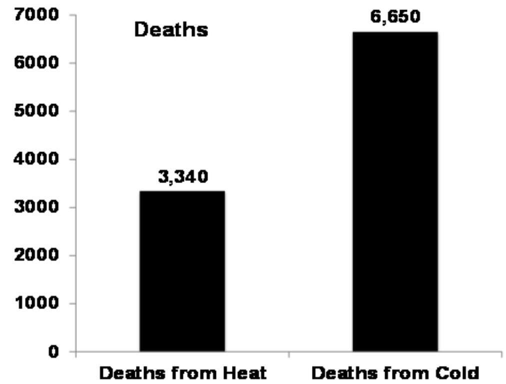
Q. **If you were examining only effects in Minnesota, do you expect that your conclusions would change?**

A. No, not materially. However, my conclusions are even more relevant for Minnesota than for the U.S. as a whole due to the state's northern location and relatively colder temperatures. It is thus exceedingly dependent on fossil fuels.

Minnesota agriculture is highly petrochemical intensive, and to maintain or expand harvests will require more oil, natural gas, and other energy resources – not less. Further, more energy is required to heat a structure than to cool it, and the state's relatively cold temperatures require large quantities of energy to ensure survivability and livability. Transportation – by vehicle, train, boat, or airplane – in a colder climate is more difficult and energy intensive than transportation in a warmer climate. One of the primary hazards during a cold winter is the loss of electrical power and access to energy.[1]

Of special importance, cold is a much greater health danger than heat. As shown in Figure 13-1, exposure to excessive natural cold causes twice as many deaths in the U.S. as heat, and excessive cold is responsible for 63% of the U.S. extreme weather deaths. Thus, for example: "Cold-related deaths are far more numerous than heat-related deaths in the United States, Europe, and almost all countries outside the tropics, and almost all of them are due to common illnesses that are increased by cold."[2] As shown in Part V of Bezdek Exhibit 3, humans would flourish in a warmer climate, and adaptation will increase the benefits even more.

**Figure 13-1: U.S. Extreme Weather Deaths From Heat and Cold, 2006-2010**




Source: *Los Angeles Times*, 2014.

## III. <u>FEDERAL GOVERNMENT'S SOCIAL COST OF CARBON ESTIMATE</u>

**Q. What is your opinion regarding the social cost of carbon values that have been calculated by the federal government?**

A. In my opinion, the federal government's SCC estimates are not credible and should not be used in setting regulatory policies in Minnesota or elsewhere.

As discussed in Bezdek Exhibit 2, the IWG SCC estimates are not reliable because they are based on highly speculative assumptions and forecasts, flawed IAM simulations, unjustified damage functions, improper discount rates, and other significant problems. The IWG relied critically on IAMs to develop its SCC estimates. However, these models have crucial flaws that make them "close to useless" as tools for policy analysis; for example:[3] i) Certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the models' SCC estimates; ii) the models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; iii) the models tell us nothing about the most important driver of the SCC; iv) IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading; the damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation -- and yet those damage functions are taken seriously when IAMs are used to analyze climate policy.

Researchers have thus concluded that IAMs are of little or no value for evaluating alternative climate change policies and estimating the SCC. On the contrary, an IAM-based analysis suggests a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily.[4] The National Academies of Science (NAS) found that the SCC assessment suffers from uncertainty, speculation, and lack of information about future emissions of greenhouse gases (GHGs), the effects of past and future emissions on the climate system, the impact of changes in climate on the physical and biological environment, and the translation of these environmental impacts into economic damages.[5] NAS thus concluded, "As a result, any effort to quantify and monetize the harms associated with climate change will raise serious questions of science, economics, and ethics and should be viewed as provisional."[6] As shown in Part VII of Bezdek Exhibit 3, economic analysis of climate change shows that damages are consistently overestimated and overvalued, and that those errors are driven by politics rather than analysis.

Because of its many flaws and overall unreliability, the federal SCC must be rejected.

Q. **Do you think that the federal social cost of carbon estimates adequately consider the benefits of fossil fuels and $CO_2$ emissions?**

A. No, the federal social cost of carbon estimates do not adequately consider the benefits of fossil fuels and $CO_2$ emissions.

Q. **Why not?**

A. The federal SCC estimates are highly biased: as demonstrated throughout both the 2010 and 2013 IWG reports, their stated purpose is to estimate the cost of $CO_2$ emissions, and they devote little attention to $CO_2$ benefits. For example, on at least a dozen occasions, the 2010 and 2013 IWG reports refer to damages caused by $CO_2$ and the benefits of reducing $CO_2$. The SCC estimates fail to adequately consider or incorporate the enormous direct $CO_2$ benefits – plant growth and agricultural productivity – and the indirect $CO_2$ benefits – those produced by the fossil fuels from which $CO_2$ derives. Instead, the few, minor benefits acknowledged by the IWG reports – for example, reduced space heating – are constrained.

## IV. ENVIRONMENTAL BENEFITS OF $CO_2$ EMISSIONS

Q. **What are the environmental benefits of carbon dioxide emissions?**

A. The environmental benefits of carbon dioxide emissions are enormous and well documented.

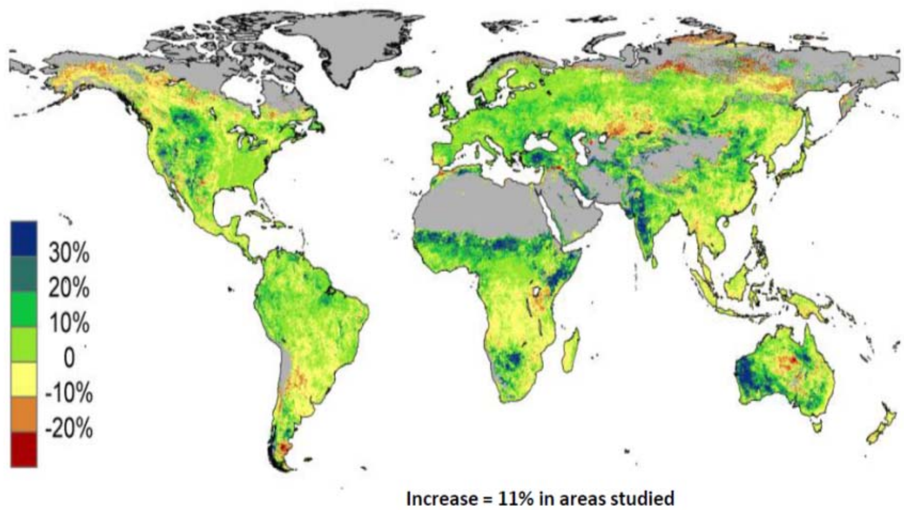
$CO_2$ is not a pollutant: It is not known to have any negative impacts on human health, it is essential for life, and is the basis of nearly all life on Earth -- without $CO_2$ life on this planet would not exist. It is the primary raw material or "food" utilized by the vast majority of plants to produce the organic matter out of which they construct their tissues, which subsequently become the ultimate source of food for nearly all animals and humans. Consequently, the more $CO_2$ there is in the air, the better plants grow, as has been demonstrated in thousands of studies.[7] And the better plants grow, the more food there is available. As shown in Part IV to Bezdek Exhibit 3, plants will flourish under higher $CO_2$ conditions, becoming healthier and more resistant to pests and disease.

Researchers have identified 55 benefits from increased atmospheric $CO_2$ concentrations. Plants grow faster; increase their photosynthetic rate by as much as 50%; increase their leaf area, plant branch, and fruit numbers; and decrease their water demands and suffer less air pollution stress. In particular, this decreases soil erosion by expanding plant cover. Biodiversity is also enhanced because it increases the niche security of many different forms of plants, and biomass gains a greater ability to remove that carbon from the atmosphere, creating a natural negative feedback on $CO_2$.[8]

The implication that $CO_2$ is a harmful "pollutant" is thus wrong. $CO_2$ concentrations in the atmosphere have been much higher in the past, even well before any human industrial activities were emitting $CO_2$.[9] The IWG largely ignored or discounted scientific data demonstrating the likely benefits from increased concentrations of $CO_2$ in the atmosphere.

Professor William Happer – the former head of basic research at DOE – finds that greening of the planet is already being observed (Figure 17-1), that any modest warming from more $CO_2$ will be beneficial, and that crop yields will increase substantially.[10]

**Figure 17-1: Global Greening From $CO_2$ Fertilization: 1982-2010**



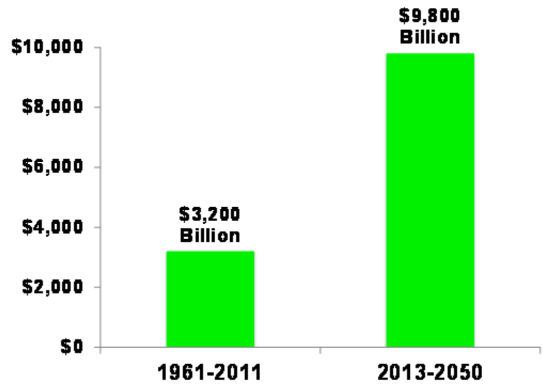

Source: Happer, 2014.

Q. **Has the economic value of these environmental benefits of $CO_2$ been estimated?**

A. Yes. The increased crop production due to $CO_2$ above 280 ppm (the level that existed at the beginning of the Industrial Revolution) can be calculated for each year between 1961 and 2011, which can then be used to estimate the annual economic benefit of atmospheric $CO_2$ enrichment (above the baseline of 280 ppm) on crop production since 1961. The economic benefit of Earth's rising atmospheric $CO_2$ concentration on global food production is enormous and totaled \$3.2 trillion from 1961 to 2011 (Figure 18-1).[11] I forecast that over the period 2012 - 2050, these

$CO_2$ benefits will total nearly $10 trillion – Figure 18-1. The IWG essentially ignored these benefits.

**Figure 18-1: Benefits of More $CO_2$ For Global Crop Production**



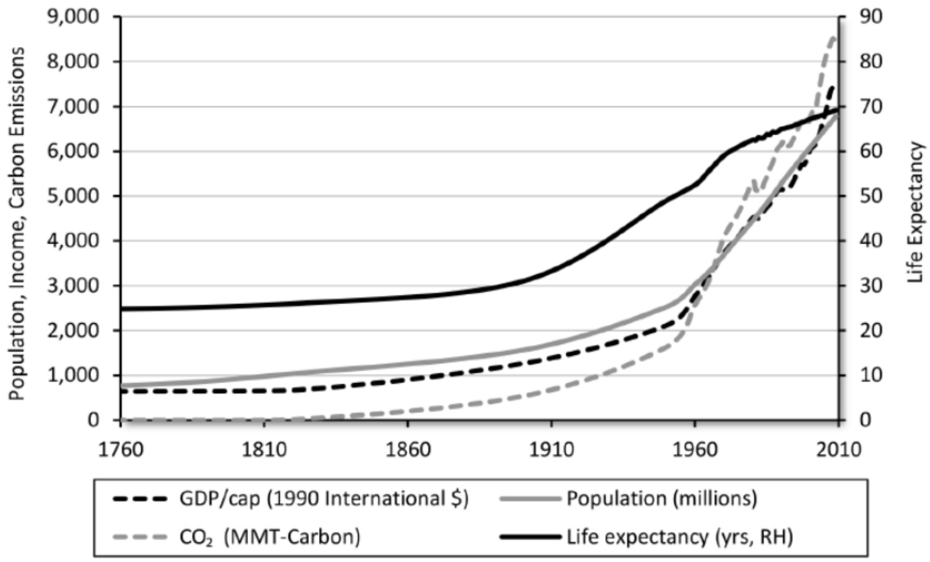

Source: Idso, 2013.

## V. ECONOMIC BENEFITS OF $CO_2$ EMISSIONS

**Q. What are the social and economic benefits of carbon dioxide emissions?**

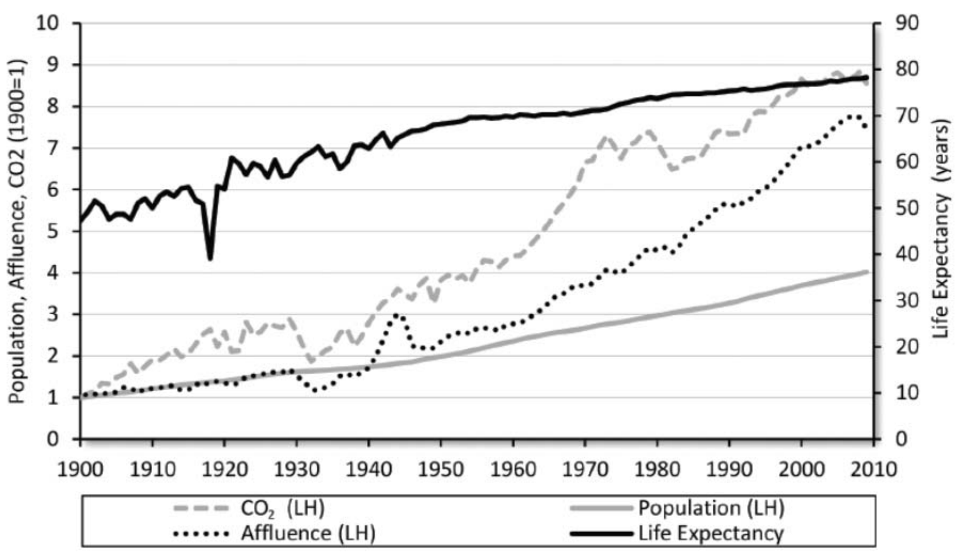
A. The successful utilization of fossil fuels facilitated successive industrial revolutions, created the modern world, created our advanced technological society, and enabled the high quality of life currently taken for granted. World economic and technological progress over the past two centuries would simply have been impossible without the massive use of vast quantities of fossil fuels. For example, from 1750 to 2009, global life expectancy more than doubled, global population increased 8-fold, and incomes increased 11-fold.[12] As shown on Figure 19-1, these increases in living standards correlate with increases in $CO_2$ emissions. Figure 19-2 shows a similar trend for increases in the United States.

**Figure 19-1: Global Progress, 1760–2009: Trends in World Population, GDP Per Capita, Life Expectancy, and $CO_2$ Emissions From Fossil Fuels**




Source: Goklany, 2012.

**Figure 19-2: U.S. Carbon Dioxide Emissions, Population, GDP per Capita, and Life Expectancy at Birth, 1900–2009**




Source: Goklany, 2012.

**Q. Is there a limit to these benefits as carbon dioxide emissions increase?**

A. No, not for the foreseeable future.

$CO_2$ is not harmful and is actually good for the planet. More $CO_2$ will be beneficial, crop yields will increase substantially, and "Greening of the planet is already being observed."[13] With respect to the "optimum" level of $CO_2$, at 150 ppm plants stop growing; the pre-industrial level was 280 ppm, and the present level is about 400 ppm. However, compared to the levels of $CO_2$ that prevailed since the Cambrian, we have been in a $CO_2$ famine in recent geological times. More $CO_2$ will be very beneficial to agriculture. $CO_2$ enrichment at 2, 3, and 4 times natural concentration will cause plants to grow faster and improve plant quality.[14] As Dr. Patrick Moore – a founder of Greenpeace -- notes,

> Plants grow best at a $CO_2$ concentration of around 1,500 ppm, which increases plant yield by 25-65%. The present $CO_2$ level in the global atmosphere is about 400 ppm. Thus, trees and other plants would benefit from a level of $CO_2$ about four times higher than it is today. There is solid evidence that trees are already showing increased growth rates due to rising $CO_2$ levels.[15]

As Sylvan Wittwer, the father of agricultural research on this topic, stated, the effects of increased $CO_2$ "know no boundaries and both developing and developed countries are, and will be, sharing equally," for "the rising level of atmospheric $CO_2$ is a universally free premium, gaining in magnitude with time, on which we all can reckon for the foreseeable future".[16]

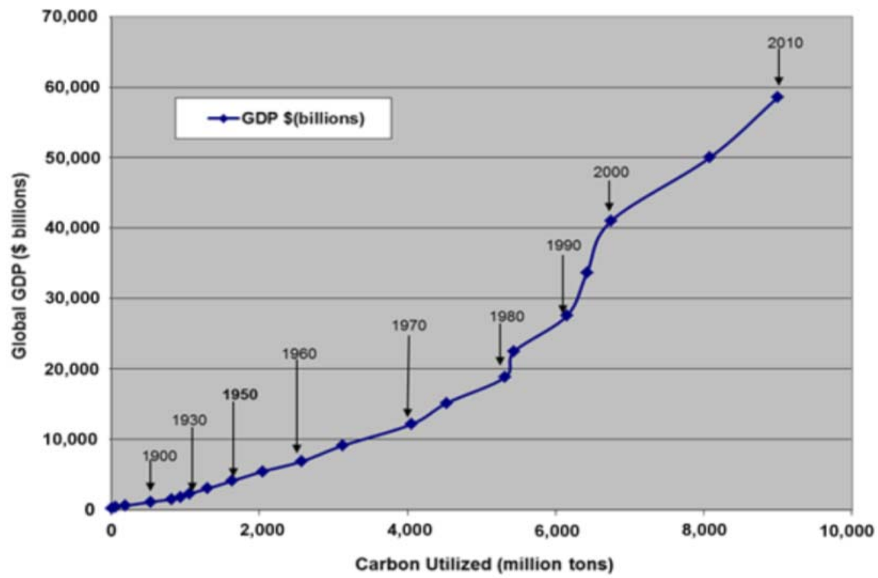
Q. **Please explain the relationship between carbon dioxide emissions and gross domestic product (GDP).**

A. There is a strong, direct causal relationship between carbon dioxide emissions and GDP. Robert Zubrin analyzed the relationship between global GDP per capita and carbon use from 1800 through 2010.[17] He found that the relationship is generally linear, with GDP per capita and carbon use both increasing by a factor of ten between 1910 and 2010. As shown in Figure 21-1, Zubrin also compared GDP to carbon utilization and found the relationship "is not merely linear, but is more nearly quadratic, with total economic output rising as roughly the square of carbon use."[18]

Taking the ratio of current global GDP to carbon use and dividing it out indicates that, at present, each ton of carbon used produces about $6,700 of global GDP.[19] Seven tons denied corresponds to a loss of $47,000, or a good American job.

**Figure 21-1: Global GDP vs. Carbon Utilization, 1800 - 2010**

(2010 Dollars)

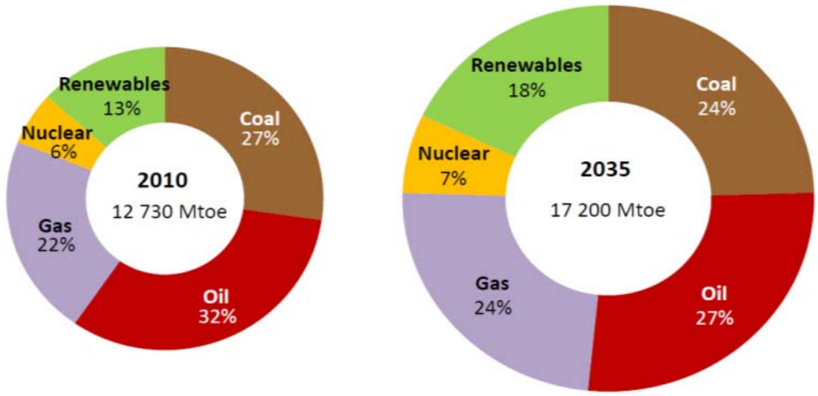



Source: Zubrin, 2013.

**Q. Why does future economic growth require fossil fuels?**

A. Future economic growth requires fossil fuels because these are the only fuels that can provide the abundant, reliable, affordable energy that the world will depend on in the coming decades. According to all major forecasts available, fossil fuels will remain the principal sources of energy worldwide for the foreseeable future and will continue to supply 75-80% of world energy. For example, Figure 22-1 illustrates the forecast of the International Energy Agency.[20]

**Figure 22-1: Energy Demand by Fuel, 2010 and 2035**



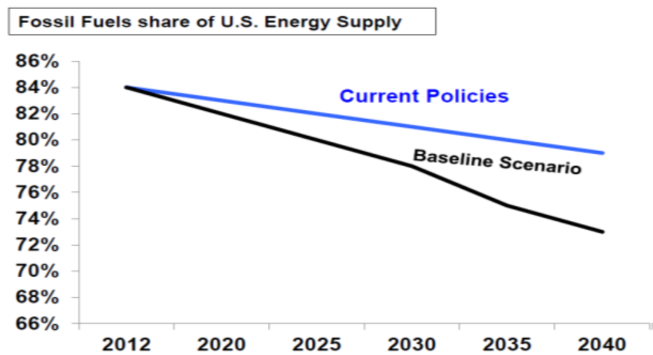

Source: International Energy Agency.

**Q. Why can't similar rates of growth be sustained by other fuel sources?**

A. Similar rates of growth cannot be sustained by other fuel sources, such as renewables, because they are unreliable, intermittent, expensive, and are not scalable. For example, wind and solar are intermittent energy sources because the power they produce can suddenly disappear when the wind stops blowing, a cloud appears, and/or at night. In just 30 minutes, 1,000 MW — the output of a nuclear reactor — can disappear and threaten stability of the grid. Hydro and geothermal are limited geographically and are not expected to increase their generation or capacity significantly. Liquid fuels such as ethanol and biodiesel have lower energy densities and are thus less energy efficient.[21] According to both IEA and EIA, renewables currently comprise less than 15% of world energy, and by 2040 they will account for only about 15%.

Fossil fuels, oil, coal, and natural gas, are the cheapest and most reliable sources of energy in the world. That is why they supply 85% of U.S energy and over 80% of global energy – and will continue to do so for many decades (Figure 23-1).

**Figure 23-1: U.S. Energy Demand: Fossil Fuels Will Continue to Dominate**




Source: International Energy Agency, *World Energy Outlook 2014*.

## VI. $CO_2$ FERTILIZATION

**Q. What is the impact of $CO_2$ emissions on plant growth?**

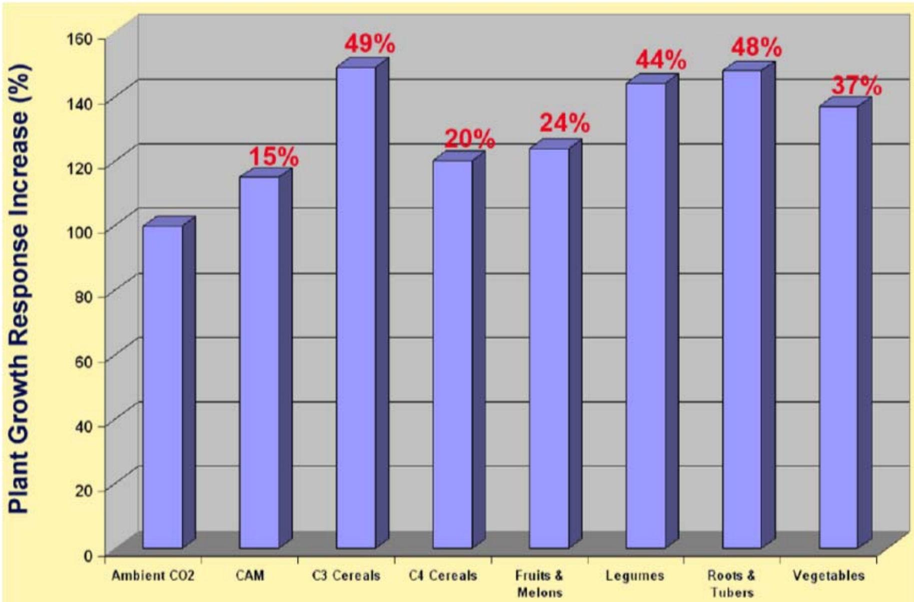
A. The more $CO_2$ there is in the air – natural plant food – the better plants grow, as has been demonstrated in thousands of studies.[22] More $CO_2$ also helps plants grow due to more efficient water use because the $CO_2$ helps plants open their pores wider.[23] Finally, $CO_2$ allows plants to better compensate for environmental stresses that affect plant growth and development, such as high soil salinity, high air temperature, low light intensity, high light intensity, UV-B radiation, water stress, and low levels of soil fertility.

**Q. Can you quantify the effect of $CO_2$ fertilization on agricultural productivity?**

A. Yes. Typically, a doubling of the air's $CO_2$ content above present-day concentrations raises the productivity of most herbaceous plants by about one-third; and this positive response occurs in plants that utilize all three of the major biochemical pathways (C3, C4, CAM) of photosynthesis. As shown in Figure 25-1, a 300-ppm increase in atmospheric $CO_2$ will result in significant yield increases for important food sources.[24] Thus, with more $CO_2$ in the air, the growth and productivity of nearly all crops will increase, providing more food to sustain the biosphere and a growing world population.

**Figure 25-1: Plant Growth Response to a 300 ppm**

**Increase in Atmospheric $CO_2$**




Source: Idso and Idso, 2000.

Q. **What is the economic value of $CO_2$ fertilization?**

A. The economic value of $CO_2$ fertilization is enormous. As previously discussed, the economic benefit of Earth's rising atmospheric $CO_2$ concentration on global food production is enormous and totaled $3.2 trillion, 1961-2012. I forecast that over the period 2012 - 2050, these $CO_2$ benefits will total nearly $10 trillion.

Q. **How does the $CO_2$ fertilization factor into your opinions concerning the social benefits of carbon?**

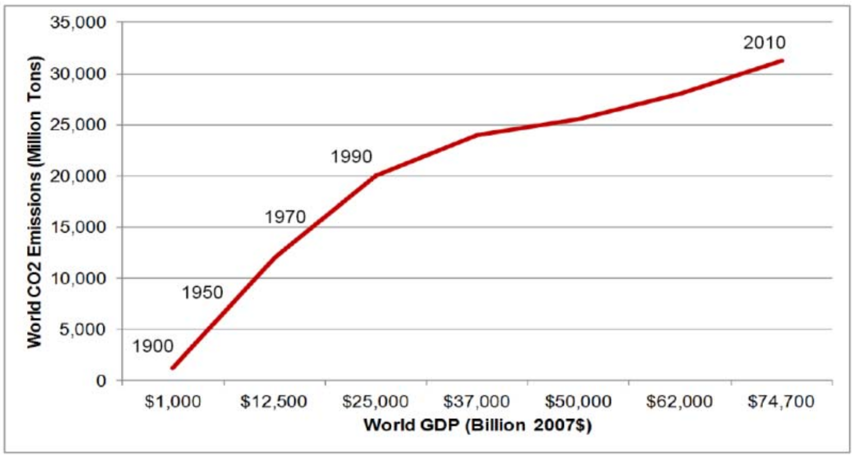
A. The $CO_2$ fertilization factor strengthens my opinions concerning the social benefits of carbon. As noted, the estimated $CO_2$ cumulative global fertilization benefits total approximately $10 trillion over the period 2013 – 2050. This is in addition to the cumulative global economic benefits from the use of fossil fuels over the period 2013 – 2040, which total about $2,800 trillion (2005 dollars), as discussed later in more detail. Thus, including the $CO_2$ fertilization factor into my benefit estimates would increase the estimated carbon benefits by another $10 trillion.

## VII. FUTURE BENEFITS OF $CO_2$ EMISSIONS

Q. **Please explain your methodology for determining future benefits derived from increasing $CO_2$ emissions.**

A. I first compared $CO_2$ emissions from fossil fuels with GDP over the past century. Figure 28-1 shows a strong relationship between world GDP and $CO_2$ emissions from fossil fuels.

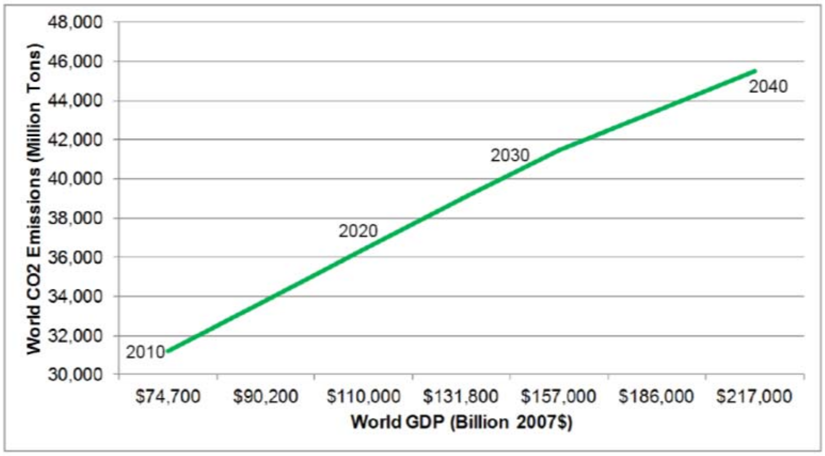
**Figure 28-1: Relationship Between World GDP and $CO_2$ Emissions**




Source: U.S. Energy Information Administration, International Energy Agency, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

Next, as illustrated by Figure 28-2, I prepared the forecast relationship between world GDP and $CO_2$ emissions in the EIA reference case through 2040, which is forecast to be roughly linear. Once again, future economic growth – as measured by world GDP – requires fossil fuels which, in turn, generate $CO_2$ emissions. Thus, according to EIA data and forecasts, fossil fuels, which generate $CO_2$ emissions, are essential for world economic growth, and significant $CO_2$ emissions reductions will be associated with significant reductions in economic growth.

**Figure 28-2: Forecast Relationship**
**Between World GDP and $CO_2$ Emissions**
(EIA Reference Case)




Source: U.S. Energy Information Administration, International Energy Agency, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

Q. **What assumptions have you made regarding the economic growth rates?**

A. I followed the assumptions regarding the economic growth rates utilized by IEA and EIA in their forecasts.

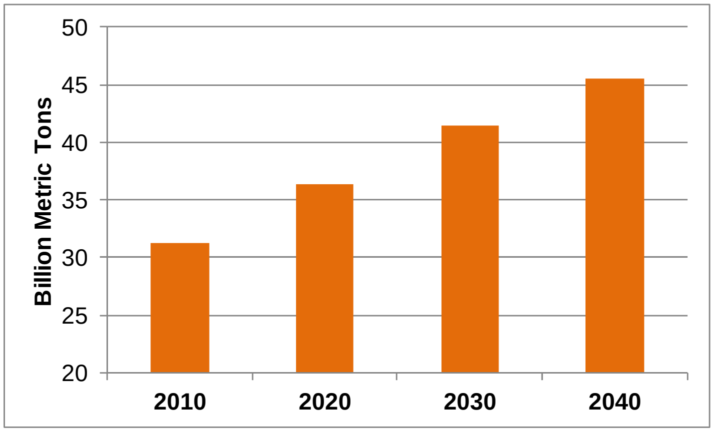
IEA notes that its forecasts are highly sensitive to the underlying assumptions about the rate of growth of GDP; that is, GDP growth requires energy and energy demand is driven by economic growth.[25] IEA assumes that world GDP, in purchasing power parity, will grow by an average of 3.5% annually over the period 2010-2035.[26] It finds that most forecasts of economic growth over the long term fall within a relatively narrow range, even if there may be significant divergence between countries.[27]

Q. **What assumptions have you made regarding the growth rates of carbon dioxide emissions?**

A. I followed the assumptions made by EIA in its forecasts regarding the growth rates of carbon dioxide emissions. EIA notes that energy-related carbon dioxide emissions -- produced through the combustion of liquid fuels, natural gas, and coal -- account for much of the world's anthropogenic GHGs.[28] In the EIA *IEO 2013* Reference case, which I adhered to and is shown in Figure 30-1, world energy-related $CO_2$ emissions increase by almost 50% between 2010 and 2040.

**Figure 30-1: Forecast World Energy-related $CO_2$ Emissions**

(EIA Reference case)




Source: U.S. Energy Information Administration.

Q. **What assumptions have you made regarding future environmental or social costs from increasing carbon dioxide emissions?**

A. I used the Federal government's assumptions regarding future environmental and social costs from increasing carbon dioxide emissions. While, as discussed, the IWG SCC estimates are not credible, I nevertheless used the 2013 IWG assumptions and forecast estimates of SCC costs to ensure objectivity.

## VIII. <u>IMPACT OF HIGHER ENERGY PRICES</u>

Q. **What is the impact of higher energy prices on lower income ratepayers?**

A. The impact of higher energy prices on lower income ratepayers is devastating. Table 32-1 shows that households with the lowest incomes spend the largest shares of their disposable income to meet energy needs. For example, for the nine million American households earning less than $10,000 per year, nearly ¾ of their average income was used to meet energy needs. Among the 56 million households making more than $50,000 per year, less than 9% of average income was spent on energy needs. The national average for energy costs as a percentage of household income is about 11%.[29]

Thus, the poorest pay, in percentage terms, nearly nine times as much for energy as the most affluent households – and more than 11 times as much for residential energy.[30]

**Table 32-1: U.S. Household Energy Expenditures by Income, 2013**

| Pre-tax Income | <$10K | $10K - $30K | $30K - $50K | >$50K | Average |
|---|---|---|---|---|---|
| **Percent of households** | 7.6% | 22.9% | 19.4 % | 50.1% | |
| **Residential energy** | $1,622 | $1,719 | $1,937 | $2,568 | $2,117 |
| **Transportation fuel** | $1,991 | $2,473 | $3,497 | $4,668 | $3,730 |
| **Total energy** | $3,613 | $4,192 | $5,434 | $7,256 | $5,907 |
| **Average after-tax income** | $4,726 | $18,261 | $33,297 | $84,828 | $53,092 |
| **Energy percent of after-tax income** | 76.5% | 23.0% | 16.3 % | 8.6% | 11.1% |
| **Residential energy percent of after-tax income** | 34.3% | 9.4% | 5.8 % | 3.0% | 4.1% |

Sources: U.S. Bureau of Labor Statistics, U.S. Department of Energy, U.S. Energy Information Administration, and U.S. Congressional Budget Office.

These data confirm the extremely regressive nature of energy costs, and Table 32-2 shows the average annual expenditures for U.S. households earning $50,000 or less. These households spend more on energy than on food, and twice as much on energy than on healthcare.

**Table 32-2: Average Annual Household Expenditures**

| Pre-tax annual income (average) | $50,000 or Less | % of Total Expenditures |
|---|---|---|
| After-tax income (average) | $36,218 | -- |
| Clothing | $1,340 | 3.7% |
| Energy – residential & transportation | $5,396 | 14.9% |
| Healthcare | $2,861 | 7.9% |
| Food | $5,287 | 14.6% |
| Housing (ex. utilities) | $10,395 | 28.7% |
| Transportation (ex. fuel) | $5,179 | 14.3% |
| Entertainment | $1,920 | 5.3% |
| Insurance and pensions | $1,956 | 5.4% |
| Education and reading | $507 | 1.4% |
| Tobacco and alcohol | $761 | 2.1% |
| All other | $616 | 1.7% |
| Total expenditures | $36,218 | 100% |

Source: U.S. Bureau of Labor Statistics, *Consumer Expenditure Survey 2009*, October 2010.

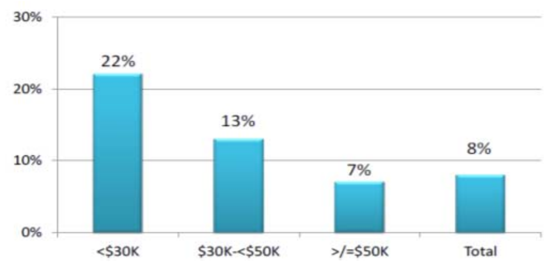
High and increasing energy prices have a detrimental effect on the lives of those with limited incomes.[31] An EPC survey found that 8% of low-income respondents annually experience utility shut-offs due to rising energy costs.[32] Sadly, according to the EPC survey, 70% of those living at or below 150% of poverty reported that they were buying less food in response to increases in home energy costs. About 31% of the poorest families indicated that they purchased less medicine due to high energy costs,[33] and approximately one out of five changed plans for education.[34] Thus, low income Americans are under the greatest strain: "Inability to pay utilities is second only to inability to pay rent as a reason for homelessness."[35]

Q. **What is the impact of higher energy prices on lower income ratepayers in Minnesota?**

A. High and increasing energy prices are straining the budgets of Minnesota's lower- and middle-income families, as shown in Figure 33-1. Minnesota households with pre-tax annual incomes below $50,000, 41% of Minnesota's population spend an average of 16% of their after-tax income on energy. Energy costs for the 24% of households earning less than $30,000 before taxes represent 22% of their family incomes, before accounting for any energy assistance programs.[36]

The 41% of Minnesota's families that have annual incomes of $50,000 or less have an average after-tax income of $23,697, less than $2,000 per month. Measured in constant 2005 prices, residential electricity prices in Minnesota are 20% above 2005 levels, and much of this increase is due to fuel cost changes and the cost of compliance with U.S. EPA Clean Air Regulations. Energy costs are consuming the after-tax household incomes of Minnesota's low- and middle-income families at levels comparable to other necessities such as housing, food, and health care.

**Figure 33-1: Minnesota Household Energy Costs as a Percent of Income**




**Gross pre-tax annual income**

Source: U.S. Energy Information Administration.

Q. **What is the impact of higher energy prices on minorities?**

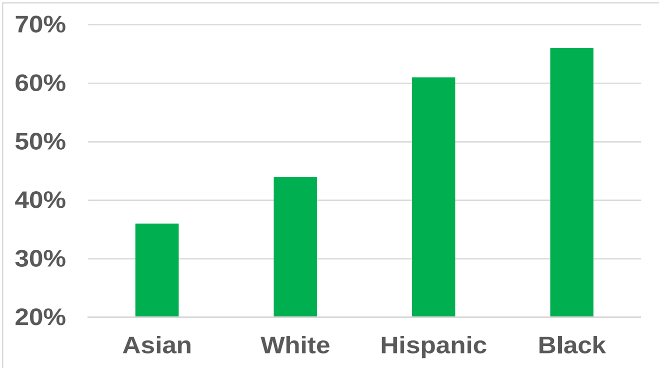
A. Table 34-1 summarizes 2012 household incomes for Asian, Black, Hispanic, and white families by income bracket. The average incomes of Hispanic and Black households were 25% and 33% lower, respectively, than the average income of U.S. households. Asian households, on the other hand, had average annual incomes 28% higher than the U.S. average income. Based on the data in Table 34-1 and Figures 34-1 and 34-2, disproportionate numbers of Black and Hispanic families are significantly more vulnerable to energy price increases than Asian or White families.

**Table 34-1: Distribution of U.S. Households by Pre-Tax Annual Income, 2012**

| Pre-tax annual income: Percentage of households | <$10K | $10-<$30K | $30-<$50K | <$50K | ≥$50K | Totals |
|---|---|---|---|---|---|---|
| Asian | 7% | 15% | 15% | 36% | 64% | 100% |
| Black | 15% | 30% | 20% | 66% | 34% | 100% |
| Hispanic | 10% | 28% | 22% | 61% | 39% | 100% |
| White | 5% | 21% | 18% | 44% | 56% | 100% |
| U.S. average | 7% | 23% | 19% | 49% | 51% | 100% |

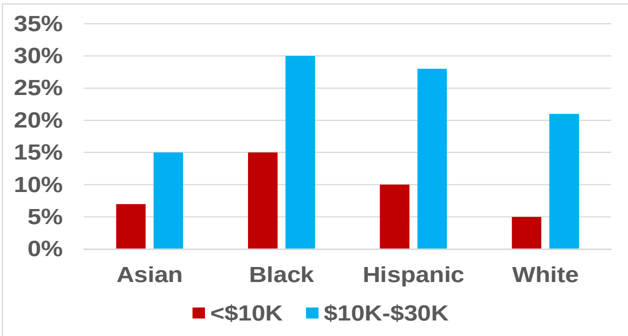
Source: U.S. Bureau of the Census, *Current Population Survey*, August 2013.

**Figure 34-1: Percent of U.S. Households with Incomes below $50,000, 2012**




Source: U.S. Bureau of the Census, *Current Population Survey*, August 2013.

**Figure 34-2: Percentage of U.S. Households with Low Incomes, 2012**




Source: U.S. Bureau of the Census, *Current Population Survey*, August 2013.

**Q. What is the impact of higher energy prices on minority and elderly ratepayers in Minnesota?**

A. The impact of higher energy prices on minority and elderly ratepayers in Minnesota is disproportionately burdensome.

The impacts of high energy costs fall disproportionately on Minnesota's minorities and elderly residents.[37] Social Security recipients comprise

28% of the state's households. Unlike young working families with the potential to increase incomes by taking on part-time work or increasing overtime, many fixed-income seniors are limited to cost-of-living increases that may not keep pace with energy costs. Table 35-1 summarizes Minnesota's 2013 pre-tax median incomes for elderly and minority households, and compares these with the U.S. median household income.

**Table 35-1: U.S. and Minnesota Median Pre-tax Household Incomes, 2013**

| | Median Household Income | MN Pct. Diff. Vs. U.S. Median | Pct. of Households |
|---|---|---|---|
| U.S. | $52,250 | | |
| Minnesota | $60,702 | 16% | |
| MN: Black | $31,021 | -41% | 4% |
| MN: Hispanic | $41,708 | -20% | 3% |
| MN: Age 65+ | $38,531 | -26% | 22% |

Source: U.S. Bureau of the Census, *American Community Survey 2013*, 2014.

Minnesota's minorities and senior citizens are among the most vulnerable to energy price increases due to their relatively low household incomes. As shown in Table 35-1, Minnesota's minorities and elderly households have median incomes substantially below the U.S. median. These relatively low median incomes indicate that Minnesota's minority and senior households are among those most vulnerable to energy price increases.

Q. **How does any impact on lower income ratepayers factor into your analysis of future social benefits of maintaining fossil fuel energy?**

A. The impact on lower income ratepayers did not factor directly into my analysis of future social benefits of maintaining fossil fuel energy. However, as has been shown, the impact of high energy costs is devastating to lower income ratepayers. Thus, the benefits of maintaining fossil fuel energy are much greater for these ratepayers.

## IX. BENEFITS OF $CO_2$ IN THE FEDERAL SOCIAL COST OF CARBON

Q. **Do the integrated assessment models relied upon by the IWG in generating the current federal social cost of carbon adequately consider the benefits from carbon dioxide emissions?**

A. No. As previously discussed, the models are focused on damages, not benefits.

Q. **Do you think that the integrated assessment models relied upon by the IWG have been shown by a preponderance of the evidence to be reliable, accurate, reasonable, and the best available measures for the cost of carbon?**

A. No. In fact, just the opposite is true. For example: 1) the IWG's SCC estimates are based on the arithmetic average of three IAMs-- DICE, FUND, and PAGE; 2) each IAM has its own damage function, based on estimated damages for each sector (agriculture, sea level rise, etc.); 3) the "damage functions" used in these models are simply a guess about the relationship between changes in temperature and GDP; 4) the average SCC estimates from the models differ by a factor of three to eight, depending on discount rate used; 5) dollar figures for "damage per sector" disagree among the models, reflecting the wide choice of assumptions made by model builders; 6) integrated damage figures differ even in sign (!) for increases in global temperature below $3^{o}$ C; and 7) the IWG did not reconcile these and other fatal inconsistencies.

As discussed, rigorous assessment of these IAMs by leading economists have concluded that the IAMs are "close to useless."

Q. **What is the difference between your approach and the integrated assessment models in determining the benefits of carbon dioxide?**

A. My approach is rigorously based on two centuries of historical data, whereas the IWG IAM approach is based on unverified, inaccurate hypothetical models, arbitrary damage functions, and malleable assumptions. As Robert Pindyck notes, the IAM models have crucial flaws that make them "close to useless" as tools for policy analysis.[38] An IAM-based analysis suggests a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily.[39]

In short, the SCC estimates developed and utilized by the IWG have little or no validity and are "close to useless."[40] I thus conclude that the federal SCCs: 1) Are artificial constructs designed by Obama Administration to penalize fossil fuels; 2) allow the Administration to achieve via regulation what it cannot via Congress – carbon tax, Waxman-Markey, UN commitment, etc.; 3) are a malleable concept dependent on questionable modeling assumptions; 4) lack transparency; 5) lack adequate consideration of $CO_2$ benefits; 6) rely heavily on computer models that imply levels of knowledge and precision that are illusory; 7) allow a modeler to obtain any desired result; 8) employ arbitrary assumptions that have huge effects on SCC estimates – even their sign.

On the other hand, my $CO_2$ benefit estimates are simple, straightforward, logical, transparent, understandable, and based on two centuries of historical fact. The $CO_2$ benefits are largely indirect: They derive from the fossil fuels which produce $CO_2$.

Q. **Should the benefits of carbon dioxide emissions be considered in developing any environmental externality figure for $CO_2$ in Minnesota?**

A. Yes. Federal agencies must "assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."[41] It is thus inexcusable that the IWG process hypothesizes almost every conceivable carbon "cost" – including costs to agriculture, forestry, water resources, forced migration, human health and disease, coastal cities, ecosystems, wetlands, etc. – but fails to analyze potential carbon benefits, either direct or indirect.[42]

Minnesota, and other jurisdictions, should consider the benefits of $CO_2$ emissions in developing any environmental externality figure for carbon dioxide. Minnesota should also realize that the economic and social benefits of $CO_2$ exceed by orders of magnitude even the invalid and inflated federal SCC estimates.

Q. **How do your calculations of the benefits of carbon dioxide emissions with respect to crop production worldwide compare to the federal social cost of carbon figures?**

A. The benefits of carbon dioxide emissions with respect to crop production worldwide are not explicitly included in the federal SCC figures. If they were, the federal SCC estimates would be significantly smaller.

Q. **How do your calculations of the benefits of carbon dioxide emissions with respect to economic growth compare to the federal SCC figures?**

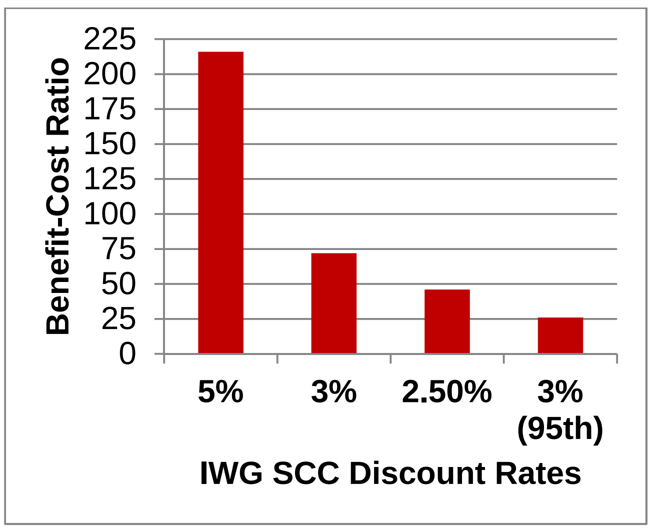
A. My calculations of the benefits of carbon dioxide emissions with respect to economic growth exceed by orders of magnitude the federal SCC figures.

While the federal SCC estimates are of questionable validity, I nevertheless compared the $CO_2$ costs and benefits (on a normalized per ton basis) using the federal SCC estimates and assumptions. I found that the current benefits clearly outweigh any hypothesized costs by, literally, orders of magnitude: The benefit-cost (B-C) ratios range up to more than 200-to-1 (Figure 42-1). I utilized forecast data to estimate B-C ratios through 2040 and found that future benefits also greatly exceed hypothesized costs by orders of magnitude: In the range of 50-to-1 to 250-to-1. To place these findings in perspective, normally, B-C ratios in the range of 2-to-1 or 3-to-1 are considered favorable. Thus, my main conclusion is that the benefits of $CO_2$ overwhelmingly outweigh estimated $CO_2$ costs no matter which SCC estimates are used. In fact, the SCC estimates are relatively so small as to be in the statistical noise of the estimated $CO_2$ benefits. These findings must inform energy, environmental, and regulatory policies in Minnesota and elsewhere.

I utilized EIA economic and energy forecasts with the forecast Federal SCC estimates to develop estimated future $CO_2$ B-C ratios, which are shown for the three 2013 IWG report discount rates in Figure 42-2. This figure indicates that the $CO_2$ B-C ratios remain extremely high through 2040 – up to 250-to-1 – using each of the three discount rates.

**Figure 42-1: 2010 $CO_2$ Benefit-Cost Ratios**

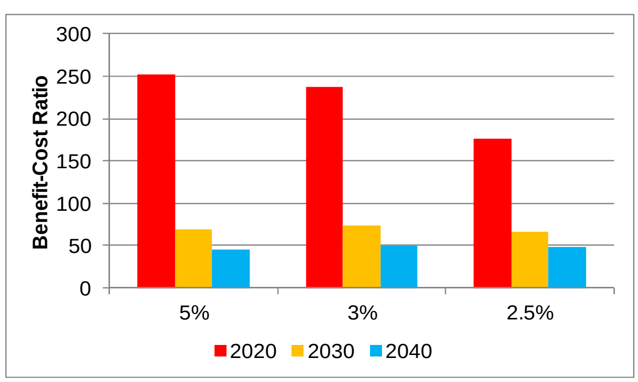
(Based on 2013 IWG Report)




Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

**Figure 42-2: Forecast Reference Case $CO_2$ Benefit-Cost Ratios**

(Based on 2013 IWG Report)



Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

## X. BENEFITS VERSUS COSTS IMPLICATIONS

Q. **What are the implications of your calculations of the benefits and costs of carbon dioxide emissions?**

A. The benefits greatly exceed the costs – by orders of magnitude – and any meaningful regulatory or benefit-cost analysis must take this huge discrepancy into account.

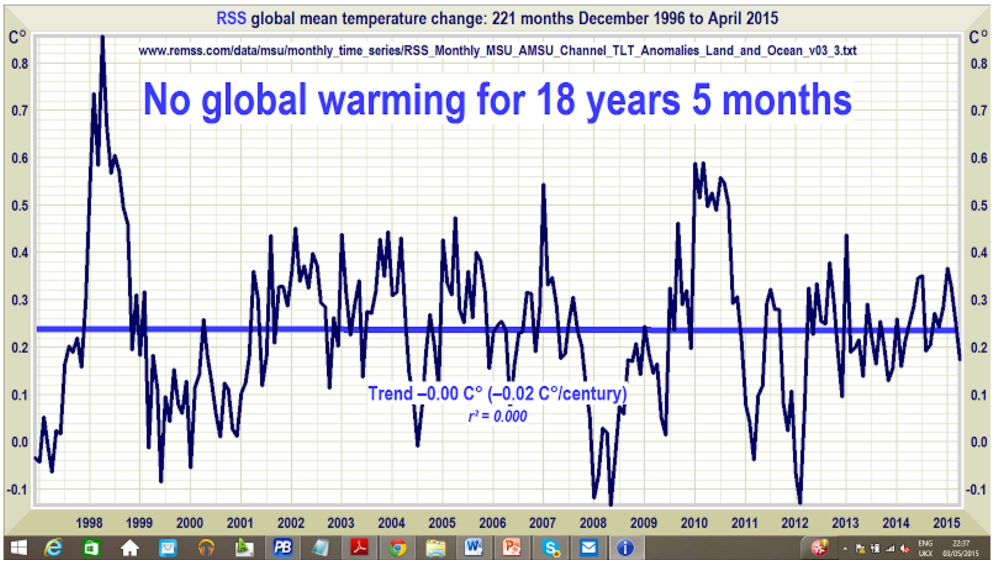
Q. **The Minnesota Department of Commerce, Division of Energy Resources stated that relevant scientific knowledge on environmental externalities has changed over the 17 years since the Commission first established cost values. Does this affect your conclusions?**

A. The Minnesota Department of Commerce is correct: Extensive relevant scientific knowledge on environmental externalities has become available in the last 17 years. The plethora of scientific knowledge and irrefutable empirical data that have become available over the past two decades greatly strengthens my conclusions.

For example, the average global temperature has not increased since the Commission first established cost values. It is frequently contended that increased $CO_2$ levels are causing global warming and increasing "extreme weather" events, and that this justifies large SCC values. However, there are at least three major problems with this hypothesis. First, the contention is that higher concentrations of $CO_2$ create a "greenhouse effect" and lead to higher temperatures. But there is no empirical scientific evidence for significant climate effects of rising $CO_2$ levels, and there is no convincing evidence that anthropogenic global warming (AGW) will produce catastrophic climate changes. Average temperatures in the U.S. and globally have not been increasing in recent decades, and even show a slight cooling trend. As shown in Figure 44-1, according to the Remote

Sensing System satellite record there has been no global temperature increase for 18 years 5 months (October 1996 to April 2015) – despite significant recorded increases in $CO_2$ emissions over this period.

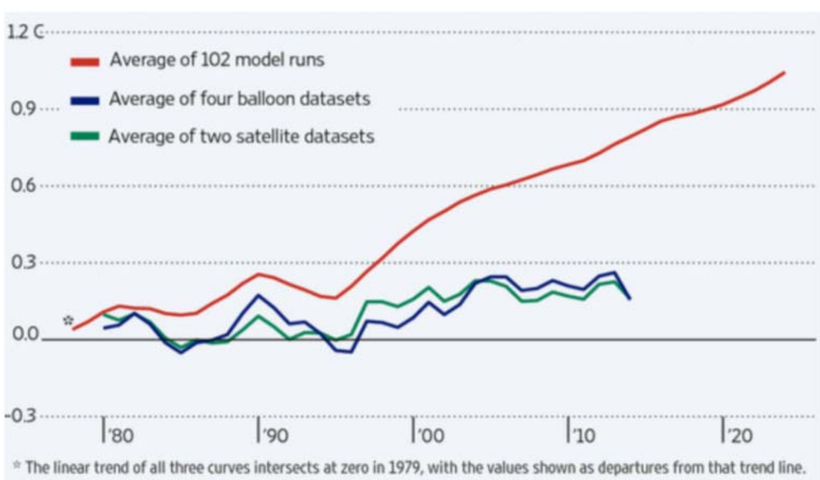
**Figure 44-1: RSS Global Mean Temperature Change, Oct. 1996 – April 2015**




Source: Remote Sensing System

Due to the absence of warming for almost two decades, Figure 44-2 shows that models predicting increased temperatures on the basis of $CO_2$ concentrations are increasingly inaccurate.

**Figure 44-2: Global Mid-Troposperic Temperature, 5-year Means (Cº)**




Source: Roy Spencer and American Meteorological Society.



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As shown in Bezdek Exhibit 3, climate trends demonstrate that: (i) natural swings in temperature are common and there has been a "hiatus" in warming (Part I-A); and (ii) extreme weather is not increasing, and warming would moderate it further in any event (Part I-B). Climate models are not sufficiently reliable to form a basis for policymaking (Part II). Solar influences on climate have been substantially underestimated (Part I-D). Historical cycles of warming (such as the Medieval Warm Period) have been more significant than predictions today, and historical warming had positive impacts for humanity and culture. (Part I-C).

Although $CO_2$ emissions have increased, there is no indication of increased hurricanes (Figure 44-3), tornadoes (Figure 44-4), wildfires (Figure 44-5), drought (Figure 44-6), or other extreme weather events. In fact, such events have actually decreased globally over the past century.

Numerous researchers have found that there has been no increase in extreme weather events over the past century (Figure 44-7). For example, Dr. Judith Curry found that "In the U.S., most types of weather extremes were worse in the 1930's and even in the 1950's than in the current climate, while the weather was overall more benign in the 1970's. This sense that extreme weather events are now more frequent and intense is symptomatic of 'weather amnesia' prior to 1970. The extremes of the 1930's and 1950's are not attributable to greenhouse warming and are associated with natural climate variability."[43] As Dr. Richard Tol noted, "There is a history of exaggeration in the study of climate change impacts."[44] As shown in Part VI of Bezdek Exhibit 3, the evidence does not support asserted ecosystem impacts, including ocean acidification, supposed harms to oceanic and terrestrial life, claimed sea level rise, and alleged melting sea ice and glaciers.

**Figure 44-3: Comparison of $CO_2$ Emissions and U.S. Hurricanes, 1900-2013**



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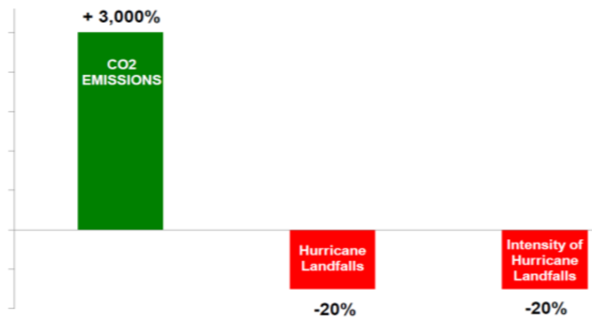
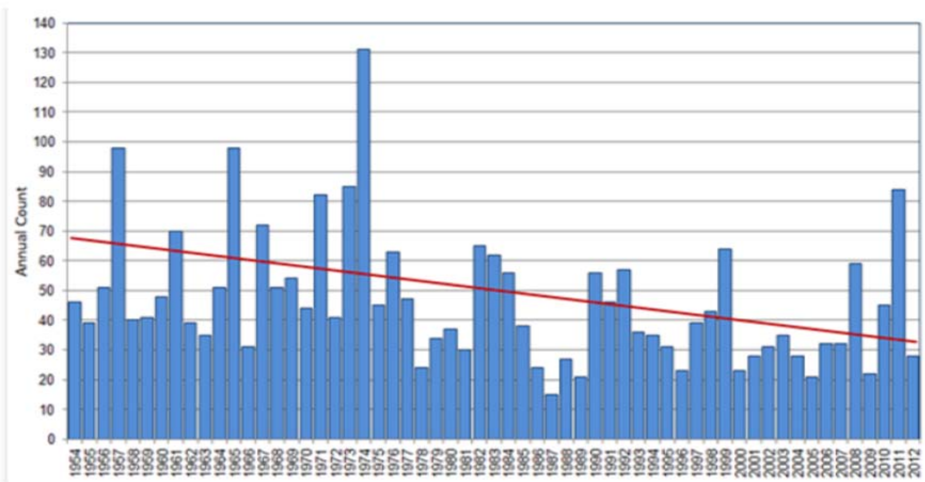


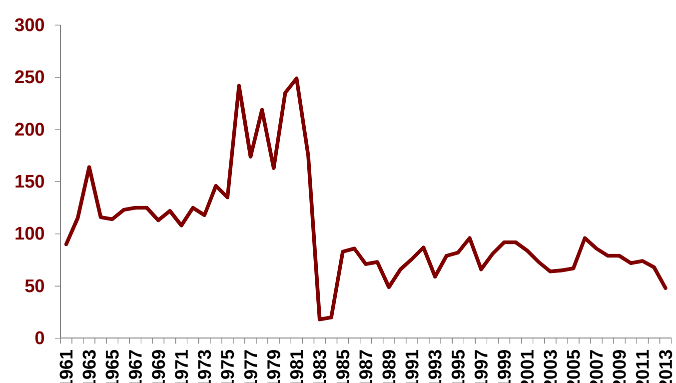

Source: IEA; USA; Earth Policy Institute; *USA Today*.

**Figure 44-4: U.S. Annual Count of Strong to Violent Tornados (F3+)**



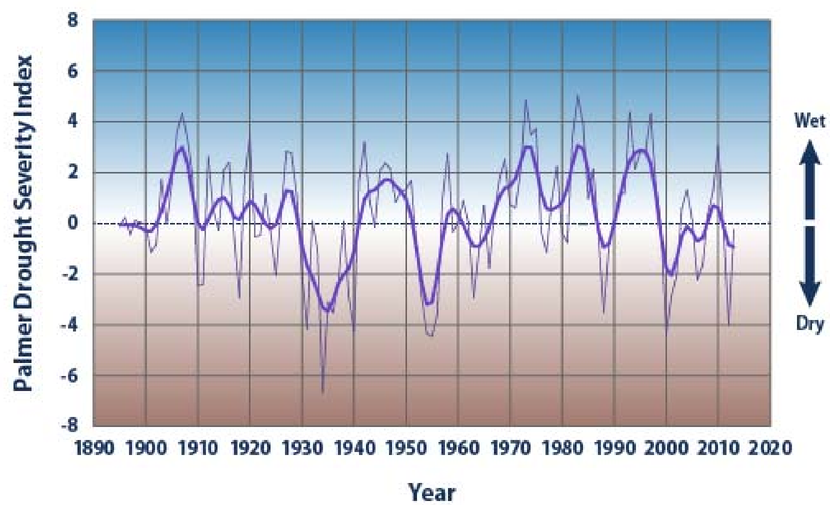

Sources: NOAA; NWS Storm Prediction Center.

**Figure 44-5: Number of Wildfires in the U.S.**



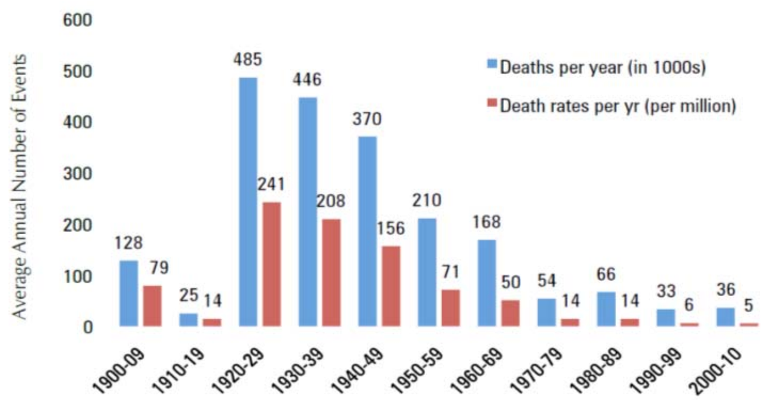
Source: National Interagency Fire Center.

**Figure 44-6: Average Drought Conditions in the U.S. 48 States, 1880-2011**




Sources: NOAA, National Climatic Data Center, and EPA.

**Figure 44-7: Global Deaths Due to Extreme Weather Events**




Source: Goklany and Morris.

Q. **Do you accept the alleged scientific consensus that the Earth's climate is unequivocally warming, and that humans are causing most of it through activities that increase concentrations of GHGs, such as burning fossil fuels?**

A. No. In reality, the "scientific consensus" is a manufactured myth, as shown by Part III of Bezdek Exhibit 3.

John Cook, who claims to have reviewed over 11,000 climate science articles,[45] contended that 97.1% of the reviewed abstracts conclude that humans are causing global warming. However, in 2013, Legates, et. al.

published a recount of Cook's data that determined that only 64 – 0.5% – of the 11,944 papers published since 1991 endorse the "consensus" that most warming since 1950 is anthropogenic.[46] Among other problems with Cook's work, Duarte noted that Cook included numerous psychology studies, marketing papers, and surveys of the general public as "scientific" endorsement of AGW – which invalidates Cook's research.[47] IPCC author Richard Tol assessed the Cook paper and concluded that is an incompetent piece of research and "a treasure trove of how-not-to lessons for a graduate class on survey design and analysis."[48]

Another widely cited source for "consensus" is an article by Zimmerman and Doran that reported the results of a two-question online survey of selected scientists.[49] In addition to issues such as question wording, only 79 respondents listed climate science as an area of expertise and said they published more than half of their recent peer-reviewed papers on climate change. Seventy-nine scientists – of the 3,146 who responded – does not constitute a "consensus."

The lack of consensus is evident from other surveys and statistics:

- Since 1998, 31,000 American scientists, including more than 9,000 with PhDs, have signed a petition which states that there is no convincing scientific evidence that human release of GHGs is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate.[50]
- Half of the responses to a 2008 international survey of climate scientists were on the "skeptic" side, with no consensus to support any alarm.[51]
- A survey of meteorologists found that 63% of 571 who responded believe global warming is mostly caused by natural, not human, causes.[52]
- A survey by the American Meteorological Society (AMS) found that only 25% of respondents agreed with UN IPCC claims that humans are primarily responsible for recent warming.[53]

- A survey of 51,000 Canadian scientists found that although 99% of 1,077 replies believed climate is changing, 68% disagreed that "The debate on the scientific causes of recent climate change is settled." Only 26% attributed global warming to "human activity like burning fossil fuels."[54]

These survey results demonstrate that the often-asserted global warming consensus does not exist. While there is thus no consensus, it is important to note that even if there was some sort of legitimate consensus, it would be irrelevant. Science is not based on consensus; it is based on experiments, verifiable data, empirical observations, and facts. There are many examples where "consensus science" has been overturned by experiments and new data, including famous examples of Galileo and Einstein, and science is never completely irrefutable.

Q. **Is the Federal Social Cost of Carbon reasonable and the best available measure to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422?**

A. No, the Federal Social Cost of Carbon is not a reasonable measure and the preponderance of evidence demonstrates that it is not the best available measure to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422, for the reasons discussed above.

Q. **Since you found that the Federal Social Cost of Carbon not the best available measure to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422, what measure is better supported by the evidence?**

A. The best available measure supported by the evidence to determine the environmental cost of $CO_2$ under Minn. Stat. § 216B.2422 is a metric that considers both the benefits and the costs of $CO_2$, for the reasons discussed above. This is critical, because effective implementation of state policies related to electricity generation and planning depend upon the accuracy of the cost values required by the statute.

One such measure is the benefit-cost data described here and in Bezdek Exhibit 2. This measure is reasonable, empirically verifiable, and based on scientific and historical fact and thus has irrefutable scientific evidentiary support – unlike the federal SCC. As discussed, regulatory agencies are required to assess both the costs and the benefits of an intended regulation, and legitimate benefit-cost analysis must assess both the costs and the benefits of a proposed initiative, program, or regulation to determine if the benefits exceed the costs. It is thus a self-evident truism that a valid B-C analysis must include both costs and benefits, and the measure I propose does this. It is a reasonable and practicable measure that will result in more accurate energy resource plan evaluation.

**Endnotes**

[1]See the discussion in Robert L. Hirsch, Roger H. Bezdek and Robert M. Wendling, *The Impending World Energy Mess*, Toronto, Canada: Apogee Prime Press, 2010,

[2]W.R. Keatinge and G.C. Donaldson *Southern Medical Journal*, 2004.

[3]Robert S. Pindyck, "Climate Change Policy: What Do The Models Tell Us?" National Bureau of Economic Research, Working Paper 19244, July 2013.

[4]Ibid.

[5]National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Washington, D.C.: National Academies Press, 2009.

[6]Ibid.

[7]C.D. Idso and Singer, S.F., *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. The Heartland Institute, Chicago, Illinois, USA, 2009; C.D. Idso and Idso, S.B., *The Many Benefits of Atmospheric* $CO_2$ *Enrichment*. Vales Lake Publishing, LLC, Pueblo West, Colorado, USA, 2011.

[8]*Farming, Fishing, Forestry, and Hunting in an Era of Changing Climate: Hearing Before the Subcommittee. on Green Jobs and the New Economy of the Senate Committee on Environment and Public Works,* 113th Cong. 5 (2014) (responses to questions for the record of Dr. David R. Legates).

[9]United States Senate Environment and Public Works Committee, *Critical Thinking on Climate Change Empirical Evidence to Consider Before Taking Regulatory Action and Implementing Economic Policies*, Minority Report, September 4, 2014.

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[10]William Happer, "The Myth of Carbon Pollution," presented at the George Marshall Institute, Washington, D.C., October 15, 2014.

[11]The largest of these benefits is noted for rice, wheat and grapes, which saw increases of $579 billion, $274 billion and $270 billion, respectively.

[12]Indur M. Goklany, *The Improving State of the World: Why We're Living Longer, Healthier, More Comfortable Lives on a Cleaner Planet*, Washington, D.C.: Cato Institute, 2007.

[13]Happer, op. cit.

[14]Ibid.

[15]Patrick Moore, *Confessions of a Greenpeace Dropout*, Beatty St. Publishing, Inc. 2013, p. 364.

[16]S.H. Wittwer, "*Food, Climate, and Carbon Dioxide: The Global Environment and World Food Production*." Lewis Publishers, Boca Raton, FL, 1995.

[17]Robert Zubrin, "The Cost of Carbon Denial," *National Review*, July 31, 2013.

[18]ibid.

[19]Specifically, Zubrin used the ratio of a recent estimate of global GDP ($60 trillion) to carbon use (9 billion tons) to derive the estimate of about $6,700. Ibid.

[20]International Energy Agency, *World Energy Outlook*, Paris, 2013, and Maria van der Hoeven, "Oil and Gas in the Global Energy Mix," presented at the International Oil Summit, Paris, April 4, 2013.

[21]For example, while diesel fuel has an energy density of about 46 megajoules per kilogram, biodiesel has about 38 Mj/kg, and ethanol has about 25 MJ/kg.

[22]Idso, C.D., and S.F. Singer, 2009: *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. The Heartland Institute, Chicago, IL; Center for the Study of Carbon Dioxide and Global Change, 2011 -- Plant Growth Database available at http://www.co2science.org/data/plant_growth/plantgrowth.php.

[23]*Global Climate Change Impacts in the United States*, Center For the Study of Science, Cato Institute, 2012.

[24]Ibid.; C.D. Idso and K.E. Idso, "Forecasting World Food Supplies: The Impact of Rising Atmospheric CO2 Concentrations," *Technology* 7 (suppl), 33-56.

[25]International Energy Agency, *World Energy Outlook*, 2012, op. cit.

[26]Ibid.

[27]IEA bases its medium-term GDP growth assumptions primarily on IMF forecasts, and its longer term GDP assumptions are based on forecasts made by various economic forecasting organizations, as well as IEA's assessment of prospects for the growth in labor supply and improvements in productivity.

[28]Ibid.

[29]Estimates derived from U.S. Bureau of Labor Statistics, *Consumer Expenditure Survey*; U.S. Bureau of the Census, *Current Population Survey*; U.S. Department of Energy, *Residential Energy Consumption Survey*; U.S. Energy Information Administration, *Annual Energy Review*, *Short Term Energy Outlook*, and *Household Vehicle Energy Use: Latest and Trends*; U.S. Congressional Budget Office, *Effective Federal Tax Rates Under Current Law, 2001-2014* and *Effective Federal Tax Rates, 1979-2006*. See the discussion in "Energy Cost Impacts on American Families, 2001-2012," American Coalition for Clean Coal Electricity, February 2012, www.americaspower.org.

[30]Many lower-income families qualify for federal or state energy assistance. However, these programs have been unable to keep up with the increase in household energy costs.

[31]Joy Moses, *Generating Heat Around the Goal of Making Home Energy Affordable to Low Income Americans: Current Challenges and Proposed Solutions*, Center for American Progress, Washington, D.C., December 2008.

[32]Energy Programs Consortium and National Energy Assistance Directors' Association, "2008 Energy Costs Survey," June 2008.

[33]Ibid.
[34]Ibid.
[35]Tennessee Interfaith Power and Light, "Impacts of Fuel Bills upon Lower Income," Knoxville, Tennessee, 2014.
[36]"Energy Cost Impacts on Minnesota Families," www.americaspower.org, March 2015.
[37]Ibid.
[38]Robert S. Pindyck, "Climate Change Policy: What Do The Models Tell Us?" op. cit.
[39]Ibid.

[41]"Regulatory Planning and Review, Executive Order 12866 of September 30, 1993," *Federal Register*, Vol. 58, No. 190, Monday, October 4, 1993.
[42]This should, theoretically, invalidate the IWG methodology and disqualify the use of the SCC estimates in any Federal rulemaking or cost-benefit analysis. However, as was the case with the recent microwave regulation, this is not the case.

[45]J. Cook, D. Nuccitelli, S.A. Green, M. Richardson, B. Winkler, R. Painting, et al., "Quantifying the Consensus On Anthropogenic Global Warming In The Scientific Literature," *Environmental Research Letters, 8*, 2013.
[46]David R. Legates, Willie Soon, William M. Briggs, and Christopher Monckton, "Climate Consensus and 'Misinformation': A Rejoinder to *Agnotology, Scientific Consensus, and the Teaching and Learning of Climate Change,"* Science & Education, August 2013.
[47]Jose Duarte, "Cooking Stove Use, Housing Associations, White Males, and the 97%," 8- 28-14, www.joseduarte.com/blog/cooking-stove-use-housing-associations-white-males-and-the-97.
[48]Richard Tol, "Mr. Obama, 97 Percent of Experts is a Bogus Number," May 28, 2015, http://www.foxnews.com/opinion/2015/05/28/climate-change-and-truth-mr-obama-97-percent-experts-do-not-agree-with.html.
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[50]"Global Warming Petition Project," Oregon Institute of Science and Medicine, www.petitionproject.org. It was organized and circulated by Arthur Robinson, president of the Oregon Institute of Science and Medicine in 1998, and again in 2007. Past National Academy of Sciences president Frederick Seitz wrote a cover letter endorsing it. Dennis Avery, "31,000 Scientists Sign Oregon GW Skeptic Petition," *Canada Free Press*, May 24, 2008; Devin Henry, "Climate Change Petition Pits Scientists Against Each Other," *Minnesota Daily*, May 28, 2008; "What Warming Consensus?" *The Washington Times*, November 16, 1998.
[51]Hans von Storch, "A Survey of Climate Scientists Concerning Climate Science and Climate Change,"2010, www.academia.edu/2365610/A_Survey_of_Climate_Scientists_Concerning_Climate_Science_and_Climate Change.
[52]Those polled included members of the American Meteorological Society and the National Weather Association. Edward Maibach, *a National Survey of Television Meteorologists About Climate Change: Preliminary Findings*, Center for Climate Change Communication, George Mason University, March 29, 2010.
[53]E. Maibach, N. Stenhouse, S. Cobb, R. Ban, A. Bleistein, et al., "American Meteorological Society Member Survey on Global Warming: Preliminary Findings," Fairfax, VA: Center for Climate Change Communication. 2012.
Survey on Global Warming: Preliminary Findings. Fairfax, VA: Center for Climate Change Communication. 2012.
[54]"Causes of Climate Change Varied: Poll," *Edmonton Journal*, March 6, 2008.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
STATE OF MINNESOTA

In the Matter of the Further Investigation in to
Environmental and Socioeconomic Costs
Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 1

to

Direct Testimony of

**Dr. Roger H. Bezdek**

June 1, 2015

## EXHIBIT 1: BEZDEK STATEMENT OF QUALIFICATIONS

**Dr. Roger H. Bezdek, President**
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**Dr. Bezdek** has over 30 years experience in the energy, utility, environmental, and regulatory areas, serving in private industry, academia, and the Federal government, and is the founder and president of MISI – a Washington, D.C.-based economic, energy, and environmental research firm. His background includes energy R&D, technology, and markets; oil, coal, natural gas, renewable, and nuclear energy analyses; assessment of DOE energy programs; estimation of the costs and benefits of energy systems; economic analyses of environmental and energy technologies; energy forecasting; environmental impact assessments; and creation, funding, and management of Federal government and private industry energy programs.

**Dr. Bezdek** has served as Corporate Director, Corporate President and CEO, University Professor, Research Director in ERDA/DOE, Research Director in the U.S. Treasury Department, Senior Advisor in the Office of the Secretary of the Treasury, U.S. energy and environmental delegate to the European Community and to NATO, and as a participant in the U.S. State Department AMPART program. He has served as a consultant to the White House, the Office of then-vice President Al Gore, Federal and state government agencies, and various corporations and research organizations, including NSF, NASA, DOE, DOD (Air Force & Marine Corps), EPA, NHSTA, Lockheed Martin, IBM, Goldman Sachs, Raytheon, Peabody Energy, RAND Corporation, J.P. Morgan Chase, Greenpeace, Ontario Power Generation, British Aerospace, American Solar Energy Society, the Rockefeller Foundations, UN Environmental Program, Pew Charitable Trusts, National Energy Technology Laboratory, Electric Power Research Institute, Eastman Kodak, Japan Atomic Energy Research Institute, Edison Electric Institute, Georgetown Climate Center, and Nuclear Energy Institute. During 2003/04, he served on the select Federal Task Force (White House, DOD, Treasury Department, Federal Reserve) charged with rebuilding the economy of Iraq. He is active with the U.S. National Academies of Science (NAS), and has served on numerous NAS committees, including, most recently, the joint NAS/Chinese Academy of Sciences Committee on U.S.-Chinese Energy Cooperation and on the NAS Committee on Fuel Economy of Medium and Heavy Duty Vehicles. During 2008, he presented energy briefings to the staffs of Senators Barack Obama, John McCain, and Hillary Clinton.

**Dr. Bezdek** received his Ph.D. in Economics from the University of Illinois (Urbana), is an internationally recognized expert in environmental and energy analysis and forecasting, and testifies frequently before the Federal, state, and city governments. He is the author of six books and over 300 articles in scientific and technical journals and serves as an editorial board member and peer-reviewer for professional publications. He is the recipient of numerous honors and awards (including awards from the White House; the U.S. Department of Energy; the U.S. Treasury Department -- Secretary's Honor Award; the National Science Foundation; ASPO -- M. King Hubbert Award; the *Wall Street Journal*; the Association for Computing Machinery; and the USSR Academy of Sciences) and is listed in *Marquis Who's Who*. He has served as U.S. representative to international organizations on energy and environmental issues, and lectures frequently on economic and energy issues, economic forecasting, and environmental topics. He is the Washington editor of *World Oil* magazine. His most recent book is *The Impending World Energy Mess*.

BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS
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STATE OF MINNESOTA

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Exhibit 2

to

Direct Testimony of

**Dr. Roger H. Bezdek**

June 1, 2015

**BEZDEK EXHIBIT 2**

# CARBON DIOXIDE: SOCIAL COST OR SOCIAL BENEFIT?

Prepared for Shook, Hardy & Bacon

By

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May 2015

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## EXECUTIVE SUMMARY

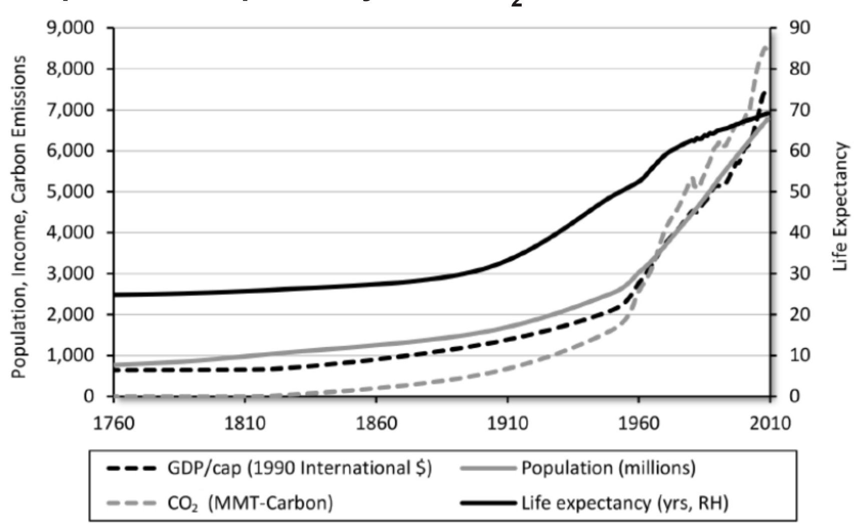
### IWG SCC Estimates

Federal agencies are required to assess the benefits and the costs of proposed regulations. In February 2010, a Federal Interagency Working Group (IWG) developed estimates of the social cost of carbon (SCC) of about $22/ton, and in May 2013 the IWG revised upward its SCC estimates to about $36/ton. The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year, and is meant to be a comprehensive estimate of climate change damages. SCCs are being used by federal agencies to incorporate the social benefits of reducing $CO_2$ emissions into benefit-cost analyses of regulatory actions. However, in benefit-cost (B-C) analyses both the benefits and the costs of $CO_2$ must be considered, and, here we analyze and compare the benefits and the costs of $CO_2$.

### The Indirect Benefits of Carbon: Fossil Fuels

The successful development and utilization of fossil fuels facilitated successive industrial revolutions, created the modern world, created the world's advanced technological society, and enabled the high quality of life currently taken for granted. Over the past 250 years, global life expectancy more than doubled, population increased 8-fold, and incomes increased 11-fold. Concurrently, as shown in Figure EX-1, $CO_2$ emissions increased 2,800-fold, increasing from about 3 million tons to 8.4 billion tons.

**Figure EX-1: Global Progress — as Indicated by Trends in World Population, GDP Per Capita, Life Expectancy, and $CO_2$ Emissions From Fossil Fuels**




Source: Goklany, 2012.

## The Key Role of Electrification

Electrification is the world's most significant engineering achievement of the past century, and has been ranked as the world's second most significant innovation of the past 6,000 years, after the printing press. Electricity has created, shaped, and defined the modern world, economic growth and electricity usage are closely correlated, and electricity has facilitated virtually every technological achievement of the past 150 years. Electricity enables people to live longer and better and the UN links electricity consumption to quality of life.

Further, electrification will be increasingly important in 21st century, and world electricity consumption is forecast to double within four decades as electricity supplies an increasing share of the world's total energy demand. However, an adequate, reliable, and affordable electricity supply is essential.

## Energy, Poverty, and Health

Increased energy costs are highly regressive, since they hurt the poor, low income families, and seniors living on fixed incomes much more than the affluent. Expenditures for essentials such as energy consume larger shares of the budgets of low-income families than they do for those of more affluent families. For example, households earning $50,000 or less spend more on energy than on food, spend twice as much on energy than on healthcare, and spend more than twice as much on energy as on clothing. Further, being unable to afford energy bills can be harmful to one's health.

## Energy, the Economy, and Jobs

There is a strong relationship between the economy and jobs, on the one hand, and the price of energy and electricity on the other. Increases in energy and electricity prices harm the economy and decreases in energy and electricity prices benefit the economy. Programs and policies that increase electricity prices – in a city, state, region, or nation -- over what they would be otherwise will have adverse effects on the economy and jobs, and vice versa. We determined that a reasonable electricity elasticity estimate is -0.1, which implies that a 10 percent increase in electricity prices will result in a one percent decrease in GDP.

## Direct $CO_2$ Benefits

$CO_2$ is the basis of life on Earth, it facilitates plant growth, and enhances agricultural productivity. It is the primary raw material utilized by plants to produce the organic matter out of which they construct their tissues, which subsequently become the ultimate source of food for animals and humans. Thus, the more $CO_2$ there is in the air, the better plants grow, as has been demonstrated in thousands of studies.

We assessed the annual total monetary value of the direct $CO_2$ benefit for 45 crops over the period 1961-2011 and estimated that it cumulatively totaled $3.2 trillion. We forecast that over the period 2012 - 2050, these $CO_2$ benefits will total $9.8 trillion.

**The Federal Interagency Working Group Social Cost of Carbon**

The Federal IWG is comprised of 12 federal agencies. It published its first set of estimates of the Social Cost of Carbon in February 2010 and an updated, significantly increased set in May 2013. Integrated assessment models (IAMs) form the basis for the IWG SCC estimates, and the IWG ran simulations of three different IAMs with a range of parameter values, discount rates, and assumptions regarding GHG emissions to derive its SCC estimates. However, the IAMs are deeply flawed and useless as tools for policy analysis.

The IWG's shortcomings include lack of transparency to explain and justify the assumptions behind the estimates; questionable treatment of uncertainty and discounting of the future; assumption of perfect substitutability between manufactured capital and "natural" capital in the production of goods and services; and the way IAMs estimate monetary costs of non-market effects – which lead to skepticism about policies based on the results of the models. To paraphrase Robert Pindyck, the IWG SCC estimates contain fatal flaws and the IWG estimates are thus "close to useless" as tools for policy analysis.

**Indirect Benefits of $CO_2$ and Fossil Fuels**

Seminal research has concluded:

- "Ours is a high energy civilization based largely on combustion of fossil fuels."
- "The theoretical and empirical evidence indicates that energy use and output are tightly coupled, with energy availability playing a key role in enabling growth."

There is a strong relationship between world GDP and the $CO_2$ emissions from fossil fuels. It is clear that, at present, fossil fuels – from which $CO_2$ is an essential byproduct – are creating, annually, $60 - $70 trillion in world GDP.

The benefits $CO_2$ emissions clearly outweigh any hypothesized costs by, literally, orders of magnitude: From 50-to-1 to 500-to-1, depending on assumed the discount rate. Normally, benefit-cost (B-C) ratios in the range of 2-to-1 or 3-to-1 are considered very favorable. In other words, the benefits of $CO_2$ overwhelmingly outweigh the estimated $CO_2$ costs no matter which government report or discount rates is used.

## Implications

The IWG SSC estimates are questionable because they are based on highly speculative assumptions, forecasts, IAM simulations, damage functions, discount rates, etc. Independent assessments concluded that these estimates suffer from uncertainty, speculation, and lack of information about critical variables, that they "raise serious questions of science, economics, and ethics," and that they are "close to useless" as tools for policy analysis."

The benefit estimates developed here are simple, straightforward, logical, transparent and understandable, and based on two centuries of historical fact. The $CO_2$ benefits that we compare to the SCC herein are almost entirely indirect: They derive from the use of fossil fuels which produce $CO_2$. There is extensive literature verifying the critical role of fossil fuels in creating current technology, wealth, and high standards of living. This relationship will remain well into the foreseeable future.

The benefit estimates derived here are extremely large compared even to the questionable IWG SCC estimates, and thus the B-C ratios are very high. The benefit estimates can be modified: They can be scaled, adjusted, forecast, expressed as average or marginal values, be converted to different base year dollars, estimated for past, current, or future years, etc. Nevertheless, they will remain orders of magnitude larger than any reasonable SCC estimates.

# I. INTRODUCTION

Under Executive Order 12866, Federal agencies are required "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."[1] In February 2010, a Federal Interagency Working Group (IWG) consisting of 12 agencies developed estimates of the social cost of carbon of about $22/ton, and in May 2013 the IWG revised upward its SCC estimates to about $36/ton.[2] The social cost of carbon (SCC) is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year, and is meant to be a comprehensive estimate of climate change damages.[3]

The purpose of the SCC estimates is to allow agencies to incorporate the social benefits of reducing $CO_2$ emissions into benefit-cost analyses of regulatory actions,[4] and EPA and other federal agencies use the SCC to estimate the climate benefits of rulemakings. The new, higher SCC estimates were used for the first time in a June 2013 rule on efficiency standards for microwave ovens.[5] These SCC estimates, prepared with little publicity, debate, or public input, have potentially ominous implications for fossil fuels in general and for the coal industry in particular. EPA states that "The U.S. government has committed to updating the current estimates as the science and economic understanding of climate change and its impacts on society improves over time."[6] Given recent history, it is likely that in forthcoming updates the SCC values will increase, and there are literally trillions of dollars at stake.

There are at least two major deficiencies in the use of SCC in benefit-cost analysis and proposed rulemaking. First, the methodology used by the IWG in developing the SCC estimates is not rigorous and is flexible enough to produce almost any estimates desired by the IWG. There is a limited amount of research linking climate impacts to economic damages, and much of this is speculative, at best. As objective analysts have concluded, the SCC estimates developed and utilized by the IWG have little or no validity and are "close to useless."[7]

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[1]"Regulatory Planning and Review, Executive Order 12866 of September 30, 1993," *Federal Register*, Vol. 58, No. 190, Monday, October 4, 1993.
[2]Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013; Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010.
[3]Ibid.
[4]Ibid.
[5]U.S. Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens," 10 CFR Parts 429 and 430.
[6]U.S. Environmental Protection Agency, "The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions," www.epa.gov/climatechange.
[7]Robert S. Pindyck, "Climate Change Policy: What Do The Models Tell Us?" National Bureau of Economic Research, Working Paper 19244, July 2013.

Second, no attempt is made to estimate, or even acknowledge the existence of carbon benefits or positive externalities of carbon. Since the development of rigorous benefit-cost (B-C) analysis by the U.S. Army Corps of Engineers and the Bureau of Reclamation in the 1950s, such analysis has sought to assess both the costs and the benefits of a proposed initiative, program, or regulation to determine if the benefits exceed the costs.[8] Thus a valid B-C analysis must include both costs and benefits. This is recognized by the federal government in Executive Order 12866, which requires agencies "to assess both the costs and the benefits of the intended regulation."[9] It is thus inexcusable that the IWG process hypothesizes almost every conceivable carbon "cost" – including costs to agriculture, forestry, water resources, forced migration, human health and disease, coastal cities, ecosystems, wetlands, etc. – but fails to analyze potential carbon benefits, either direct or indirect.[10] This is especially true because OMB has recently emphasized that careful consideration of both costs ***and*** benefits is important in determining whether a regulation will improve social welfare and to assess whether it is worth implementing at all.[11]

There are two types of carbon benefits that must be identified, analyzed, and, to the degree possible, quantified: Direct benefits and indirect benefits. The major direct carbon benefit is to increase agricultural productivity. As discussed in Chapter III, in addition to increasing the quantity of food available for human consumption, the rising atmospheric $CO_2$ concentration is also increasing the quality of the foods.

Much more important, as discussed in Chapters II and IV, the indirect benefits of carbon include the immense benefits to the economy and society of affordable, reliable energy produced by carbon-based fuels. These fuels have driven the creation of modern technological society worldwide, raised the standard of living of everyone on the planet, increased life spans by decades, and over the past 20 years alone have elevated over a billion persons out of poverty. Fossil fuels are invaluable and irreplaceable, and will remain so for the foreseeable future.

This report is organized as follows:

- Chapter II discusses the indirect social benefits of carbon: The energy produced by fossil fuels.
- Chapter III analyzes direct carbon benefits resulting from increased agricultural productivity and plant growth.

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[8]See, for example, John S. Dryzek, *The Politics of the Earth: Environmental Discourses*, UK: Oxford University Press, 2013, pp. 84-88.
[9]"Regulatory Planning and Review, Executive Order 12866 of September 30, 1993," op. cit.
[10]This should, theoretically, invalidate the IWG methodology and disqualify the use of the SCC estimates in any Federal rulemaking or cost-benefit analysis. However, as was the case with the recent microwave regulation, this is not the case.
[11]U.S. Office of Management and Budget, "2013 Draft Report to Congress on the Benefits and Costs of Federal Regulations and Agency Compliance With the Unfunded Mandates Reform Act," www.whitehouse.gov/sites/default/files/omb/inforeg/2013_cb/ draft_2013_cost_benefit_report.pdf.

- Chapter IV assesses carbon benefits compared to carbon costs and finds that the benefits exceed the costs by orders of magnitude.
- Chapter V reviews and critiques the IWG reports used to develop the SCC estimates.
- Chapter VI discusses caveats and implications.

# II. THE INDIRECT SOCIAL BENEFITS OF CARBON: FOSSIL FUELS

## II.A. Three Industrial Revolutions

The development and utilization of fossil fuels facilitated successive industrial revolutions, created the modern world, created our advanced technological society, and enabled the high quality of life currently taken for granted. While this may appear to be a self-obvious truism, the centrality of fossil fuels to everything in society can be appreciated from the recent work of Robert Gordon.[12] He raises basic questions about the process of economic growth and questions the assumption that economic growth is a continuous process that will persist indefinitely. Gordon notes that there was virtually no growth before 1750, and thus there is no guarantee that growth will continue indefinitely. Rather, his research suggests that the rapid progress made over the past 250 years could well turn out to be a unique episode in human history.

Gordon's analysis of past economic growth is anchored by the three industrial revolutions:

- The first (IR #1) centered in 1750-1830 resulted from the inventions of the steam engine and cotton gin through the early railroads and steamships, although much of the impact of railroads on the American economy came later between 1850 and 1900.
- The second industrial revolution (IR #2), 1870-1900, created the inventions that made the biggest difference in the standard of living -- electric light, the internal combustion engine, municipal waterworks and subsidiary and complementary inventions, including elevators, electric machinery and consumer appliances; motor vehicles and airplanes; to highways, suburbs, and supermarkets; sewers, television, air conditioning, and the interstate highway system.
- The third revolution (IR #3) is associated with the invention of the web and Internet around 1995.[13]

Gordon's analysis links periods of slow and rapid growth to the timing of the three IR's that is, IR #1 (steam, railroads) from 1750 to 1830; IR #2 (electricity, internal combustion engine, running water, indoor toilets, communications, entertainment, chemicals, petroleum) from 1870 to 1900; and IR #3 (computers, the web, mobile phones) from 1960 to present. As noted, he finds that IR #2 was more important than the others and was largely responsible for 80 years of relatively rapid productivity growth between 1890 and 1972. Once the spin-off inventions from IR #2 (airplanes, air conditioning, interstate highways) had matured, productivity growth during 1972-96 was

[12] Robert J. Gordon, "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds," NBER Working Paper No. 18315, August 2012; © 2012 by Robert J. Gordon.

[13] However, he notes that electronic mainframe computers began to replace routine and repetitive clerical work as early as 1960. His treatment of IR #3 includes examples of the many electronic labor-saving inventions and convenience services that already were widely available before 1995.

much slower than before.  In contrast, IR #3 created only a short-lived growth revival between 1996 and 2004.  Many of the original and spin-off inventions of IR #2 could happen only once – urbanization, transportation speed, the freedom of females from the drudgery of carrying tons of water per year, and the role of central heating and air conditioning in achieving a year-round constant temperature.[14]

A useful organizing principle to understand the pace of growth since 1750 is the sequence of three industrial revolutions.[15]  The first (IR #1) with its main inventions between 1750 and 1830 created steam engines, cotton spinning, and railroads.  The second (IR #2) was the most important, with its three central inventions of electricity, the internal combustion engine, and running water with indoor plumbing, in the relatively short interval of 1870 to 1900.  The first two revolutions required about 100 years for their full effects to percolate through the economy.  During the two decades 1950-70 the benefits of the IR #2 were still transforming the economy, including air conditioning, home appliances, and the interstate highway system.  After 1970 productivity growth slowed markedly, most plausibly because the main ideas of IR #2 had by and large been implemented by then.

Importantly, the computer and Internet revolution (IR #3) began around 1960 and reached its climax in the “dot.com” era of the late 1990s, but its main impact on productivity has withered away over the past decade.  Many of the inventions that replaced tedious and repetitive clerical labor by computers happened a long time ago, in the 1970s and 1980s.[16]

Gordon developed a graph that links together decades of research by economic historians to provide data on real output per capita through the ages.[17]  Figure II-1 displays the record back to the year 1300 and traces the “frontier” of per-capita real GDP for the leading industrial nation – the U.K. or the U.S.  The blue line represents the U.K. through 1906 (approximately the year when the U.S. caught up) and the red line the U.S. from then through 2007.  British economic historians estimate that the U. K. grew at about 0.2 percent per year for the four centuries through 1700.  The graph shows striking the lack of progress; there was almost no economic growth for four centuries and probably for the previous millennium.

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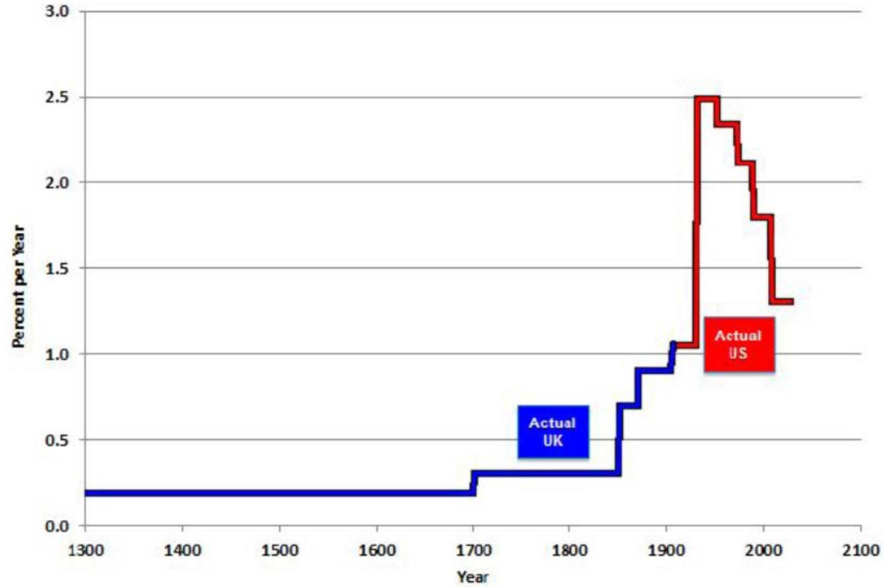
[14]Gordon, op. cit.
[15]Ibid.
[16]As Gordon notes, “Invention since 2000 has centered on entertainment and communication devices that are smaller, smarter, and more capable, but do not fundamentally change labor productivity or the standard of living in the way that electric light, motor cars, or indoor plumbing changed it.”
[17]Gordon, op. cit.

**Figure II-1**
**Growth in Real Per Capita GDP, 1300 - 2100**




Source: Robert J. Gordon, National Bureau of Economic Research, 2012.

Gordon's research, as summarized in this figure, is of potentially profound importance for several reasons. First, it forcefully and poignantly illustrates the critical importance of the industrial revolutions that began in the late 1700s in dramatically improving economic growth rates, productivity, and persons' standards of living and well-being. Second, it indicates that the trends of the period of 1800 to about 1975 may have been one-time anomalies and that prospects for continued productivity and economic growth may be much less favorable than most analysts anticipate.

## II.B. The Unique, Essential Historical Role of Fossil Fuels

The third implication of Gordon's work, which he does not seem to fully appreciate, is the absolutely essential role in all of the IRs played by fossil fuels.[18] Simply stated, without the availability of adequate supplies of accessible, reliable, abundant, and affordable fossil fuels none of the industrial and economic progress of the past two centuries would have been possible. This is an indisputable, critical fact that seems to have been insufficiently appreciated in the debate over the social cost of carbon – see the discussion in section II.C.

For example, coal was the essential driving force behind most of the revolutionary technologies Gordon identifies: Steam engines, cotton spinning, railroads, electric light, municipal waterworks and subsidiary and complementary inventions,

[18] See, for example, Robert U. Ayres and Benjamin Warr, *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Northampton, MA: Edward Elgar. 2009.

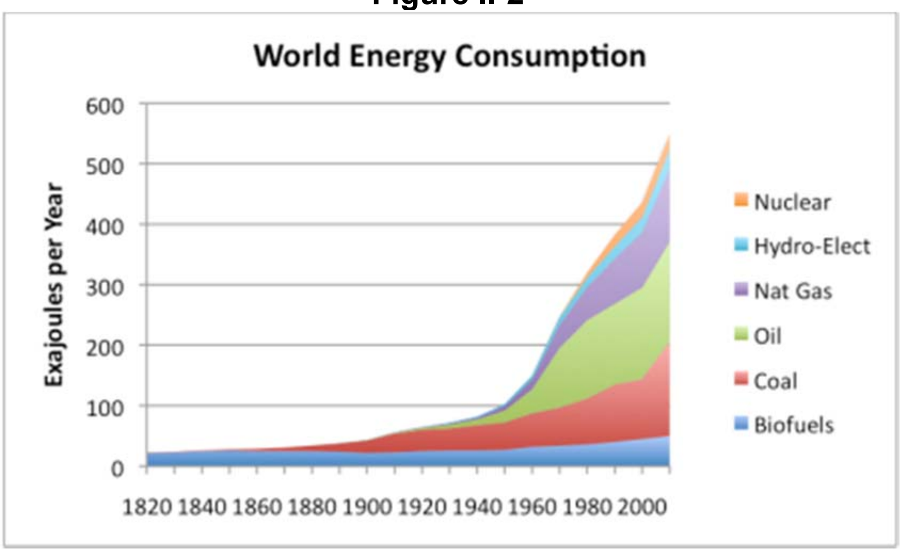
including elevators, electric machinery and consumer appliances; suburbs and supermarkets; sewers, television, air conditioning, indoor plumbing, etc.

It is constructive to compare the growth in per capita GDP shown in Figure II-1 with the increased use of fossil fuels over roughly the same period. Figure II-2 shows the enormous increase in world energy consumption that has taken place over the last 200 years. This rise in energy consumption is almost entirely from increased fossil fuel use.[19]

Figure II-3 shows the rapid increase in world per capita annual primary energy consumption by fuel over the past two centuries. Once again, it is seen that almost all of the entire increase (90 percent) in per capita primary energy consumption resulted from increased fossil fuel utilization – the increased use of hydro-power offset the decreased use of wood.[20] Figure II-4 shows the growth of world population, per capita energy consumption, and total energy use over the past two centuries, compared to 2010 levels. Figures II-3 and II-4 illustrate that, over the period 1850-2010:

- World population increased 5.5-fold.
- Total world energy consumption increased nearly 50-fold.
- World per capita energy consumption increased nearly 9-fold.
- Nearly all of the world's increase in energy consumption was comprised of fossil fuels.

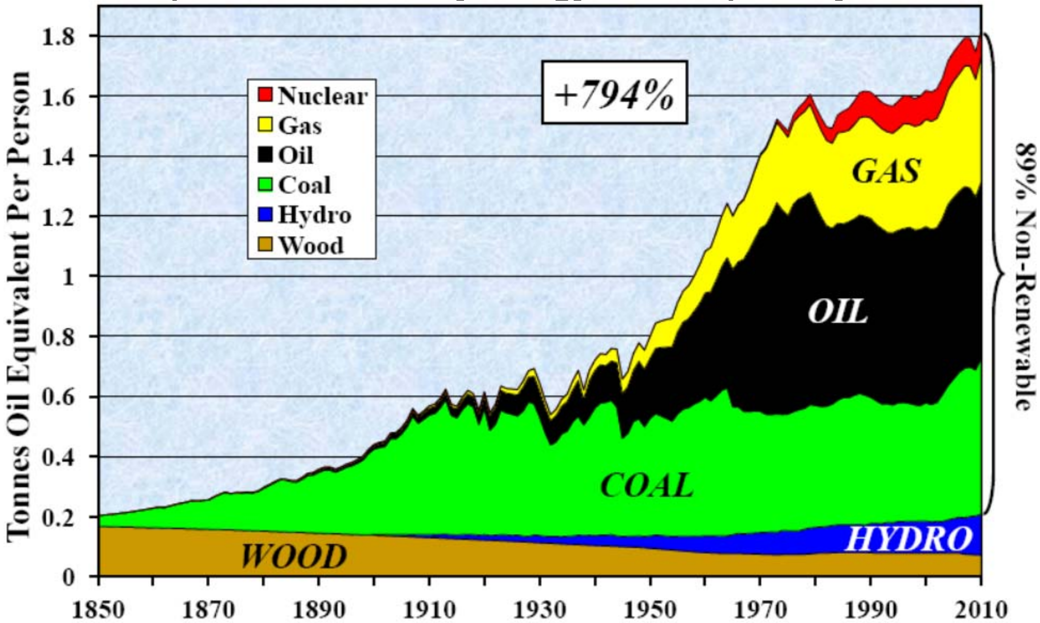
**Figure II-2**




Source: Gail Tverberg," World Energy Consumption Since 1820"

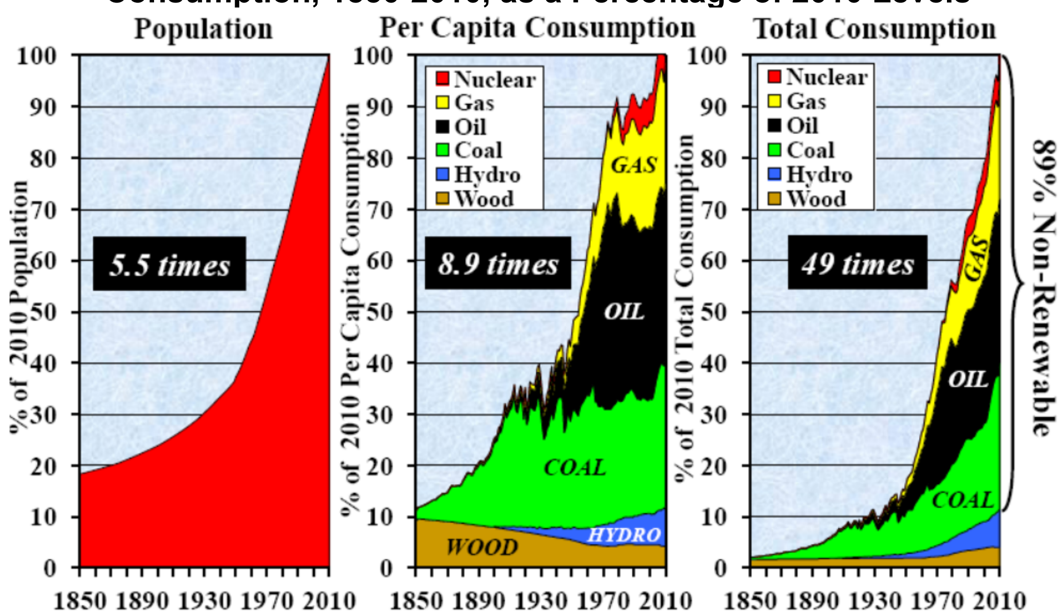
[19]Gail Tverberg," World Energy Consumption Since 1820," www.ourfiniteworld.com, March 12, 2012.
[20]J. David Hughes, "The Energy Sustainability Dilemma: Powering the Future in a Finite World," presented at Cornell University, Ithaca, New York, May 2, 2012.

**Figure II-3**
**World Per Capita Annual Primary Energy Consumption by Fuel 1850-2010**




Source: Hughes, "The Energy Sustainability Dilemma: Powering the Future in a Finite World,"

**Figure II-4**
**World Population, Per Capita and Total Energy Consumption, 1850-2010, as a Percentage of 2010 Levels**




Source: Hughes, "The Energy Sustainability Dilemma: Powering the Future in a Finite World," Comparison of Figure II-1 with Figures II-2 through II-4 forcefully illustrates a central fact: World economic and technological progress over the past two centuries would simply have been impossible without the massive, successful use of vast quantities of fossil fuels.

Thus, "For most of its existence, mankind's well-being was dictated by disease, the elements and other natural factors, and the occasional conflict. Virtually everything required — food, fuel, clothing, medicine, transport, mechanical power — was the direct or indirect product of living nature."[21] Subsequently, mankind developed technologies to augment or displace these resources, food supplies and nutrition improved, and population, living standards, and human well-being advanced.[22] The IRs discussed above accelerated these trends: Growth became the norm, population increased rapidly, and productivity and living standards improved dramatically. Technologies dependent on cheap, abundant, reliable fossil fuels enabled these improving trends. Nothing can be made, transported, or used without energy, and fossil fuels provide 80 percent of mankind's energy and 60 percent of its food and clothing.[23]

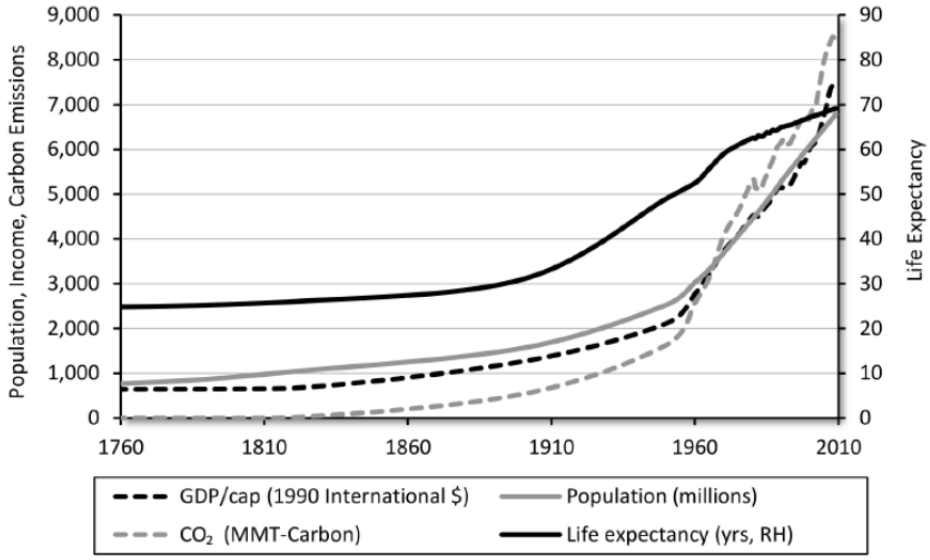
Key to these developments was that these technologies accelerated the generation of ideas that facilitated even better technologies through, among other things, greater accumulation of human capital (via greater populations, time-expanding illumination, and time-saving machinery) and more rapid exchange of ideas and knowledge (via greater and faster trade and communications). From 1750 to 2009, global life expectancy more than doubled, from 26 years to 69 years; global population increased 8-fold, from 760 million to 6.8 billion; and incomes increased 11-fold, from $640 to $7,300.[24] Living standards advanced rapidly over the past two centuries and, concurrently, as shown in Figure II-5, carbon dioxide emissions increased 2,800-fold, from about 3 million metric tons to 8.4 billion metric tons.

Figure II-6 illustrates that in the U.S. from 1900 to 2009 population quadrupled, U.S. life expectancy increased from 47 years to 78 years, and incomes (denoted "affluence") grew 7.5-fold while carbon dioxide emissions increased 8.5-fold. Thanks largely to the extensive utilization of fossil fuels, "Americans currently have more creature comforts, they work fewer hours in their lifetimes, their work is physically less demanding, they devote more time to acquiring a better education, they have more options to select a livelihood and live a more fulfilling life, they have greater economic and social freedom, and they have more leisure time and greater ability to enjoy it."[25]

[21]Indur M. Goklany, "Humanity Unbound How Fossil Fuels Saved Humanity from Nature and Nature from Humanity," *Policy Analysis*, No. 715, December 20, 2012, pp. 1-33.
[22]Ibid.
[23]Thus, "Absent fossil fuels, global cropland would have to increase by 150 percent to meet current food demand, but conversion of habitat to cropland is already the greatest threat to biodiversity. By lowering humanity's reliance on living nature, fossil fuels not only saved humanity from nature's whims, but nature from humanity's demands." See Ibid.
[24]Ibid.
[25]Ibid.

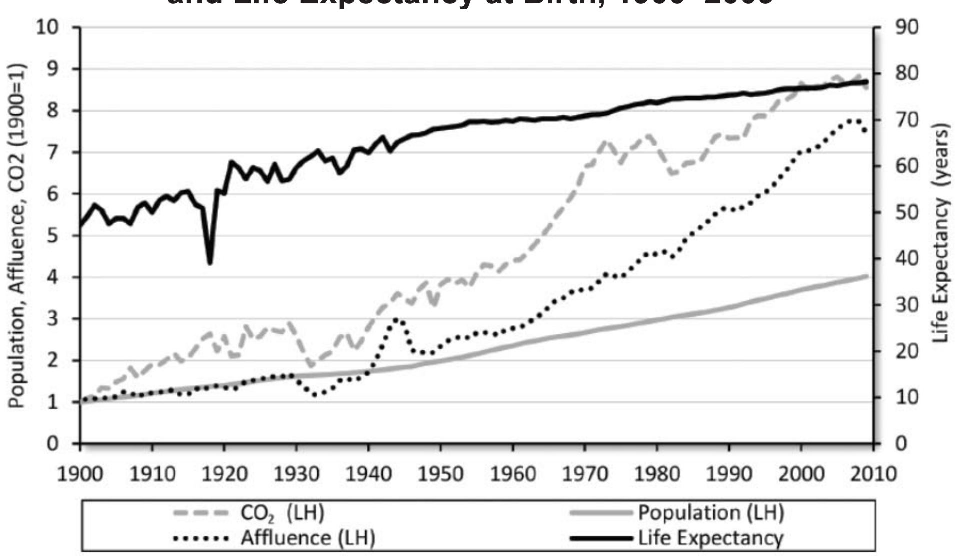
And these trends are evident not just in the United States but, for the most part, elsewhere as well.[26]

**Figure II-5**
**Global Progress, 1760–2009 — as Indicated by Trends in World Population, GDP Per Capita, Life Expectancy, and $CO_2$ Emissions From Fossil Fuels**




Source: Goklany, 2012.

**Figure II-6**
**U.S. Carbon Dioxide Emissions, Population, GDP per Capita, and Life Expectancy at Birth, 1900–2009**




Source: Goklany, 2012.

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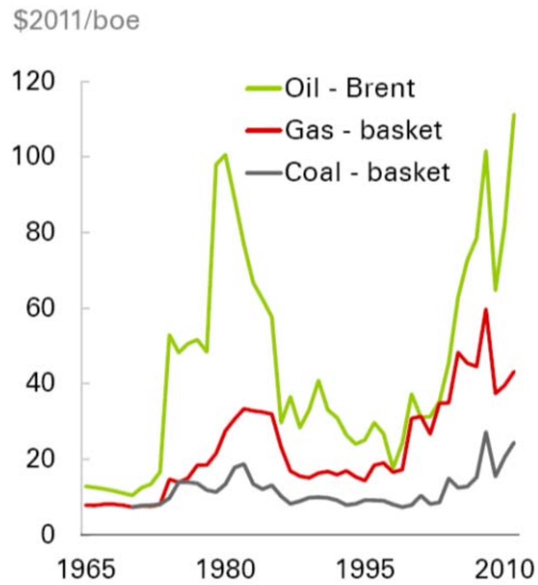
[26] Indur M. Goklany, *The Improving State of the World: Why We're Living Longer, Healthier, More Comfortable Lives on a Cleaner Planet*, Washington, D.C.: Cato Institute, 2007; © 2007 the Cato Institute.

Figure II-7 shows fossil fuel prices over the past five decades. It illustrates that oil has been, by far, the most expensive and price-volatile, followed by natural gas. Coal has been the least expensive and least price-volatile.

**Figure II-7**
**Historical Fossil Fuel Prices**



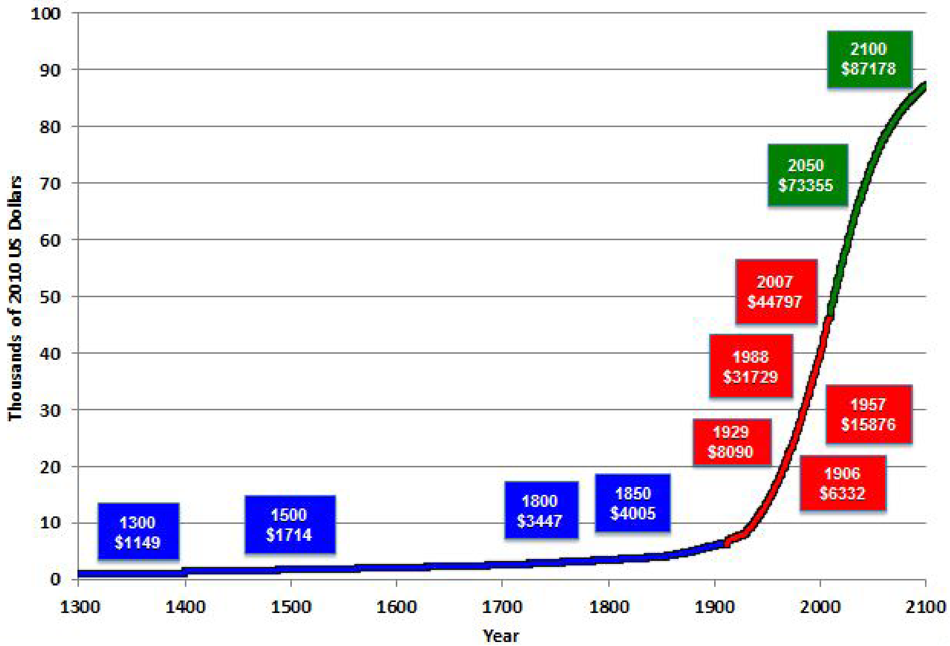

Source: *BP Energy Outlook 2030*

### II.C. The Unique, Essential Future Role of Fossil Fuels

Robert Gordon combined the historical U.K./U.S. growth record with a hypothetical, rather pessimistic forecast and overlaid on the historical record a smoothly curved line showing growth steadily increasing to the mid-20th century and then declining back to where it started, 0.2 percent per year by the end of the 21st century. He then translated these growth rates into the corresponding levels of per-capita income in 2005 dollars, which for the U.S. in 2007 was $44,800 – Figure II-8. The implied level for the U.K. in 1300 was about $1,150 in current prices, and it took five centuries for that level to triple to $3,450 in 1800 and more than a century almost to double to $6,350 in 1906, the transition year from the U. K. to the U.S. data. Even with the steady slowdown in the growth rate after 1988, the forecast level implied by the green line in Figure II-8 for the year 2100 is $87,000, almost double the actual level achieved in 2007.[27]

[27] Gordon, op. cit.

**Figure II-8**
**Actual and Hypothetical Levels of GDP Per Capita, 1300 - 2100**




Source: Robert J. Gordon, National Bureau of Economic Research, 2012.

Notably, even with Gordon's pessimistic assumption that the economic growth rate will decrease to 0.2 percent annually by 2100, the green forecast line in Figure II-8 rises rapidly. Further, under any reasonable assumptions, even modest forecast economic growth will require a very significant increase in energy supplies over the coming century. World economic growth over the past two centuries was powered almost exclusively with fossil fuels. What energy sources are forecast to power future world economic growth? That is, the question is: *What energy sources are required to enable the world to continue to (even modestly) increase income, wealth, productivity, and standards of living?*

According to all major forecasts available, fossil fuels will remain the principal sources of energy worldwide for the foreseeable future and will continue to supply 75 - 80 percent of world energy. Demand for oil, natural gas, and coal will increase substantially in both absolute and percentage terms over the next several decades. Assuring continued world economic growth, increased per capita income, and rising living standards requires this greatly increased use of fossil fuels.

The International Energy Agency (IEA) finds that fossil fuels will continue to meet the vast majority of the world's energy needs over the next two decades. These fuels, which represented 81 percent of the primary fuel mix in 2010, remain the dominant source of energy through 2035 in all of the IEA scenarios.[28]

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[28]International Energy Agency, *World Energy Outlook*, Paris, November 2012; © OECD/IEA 2012.

## II.D. The Key Role of Electrification

### II.D.1. The Engineering Achievement

Electrification is perhaps the world's most significant engineering achievement of the past century. For example:

- Electricity created modern cities: Climate control, lighting, elevators, subways, etc.
- Air conditioning led to technological changes and huge geographic population shifts – see the discussion below.
- Electricity made the assembly line and mass production possible.
- Refrigeration and sanitation technologies made the modern food industries possible, and vastly enhanced human health and safety.
- Electricity revolutionized transportation: Vehicles, airlines, mass transit, telecommuting, etc.
- Electricity revolutionized medicine, greatly improved human health, and increased life spans.
- Electricity revolutionized agriculture and facilitated reduction of the required agricultural labor force by 95 percent.
- Electricity created the "global village:" Telephone, radio, TV, FAX, cell phones, computers, Internet, IT, satellites, email, social media, etc.

Electricity has created, shaped and defined the modern world and, "For the U.S., access to electricity brought about a sea change to the quality of life, ranging from surviving childhood to drinking cleaner water to learning to read.[29] Economic growth and electricity usage are closely correlated, and electricity has facilitated virtually every technological achievement of the past 100 years, transforming industry, commerce, agriculture, transportation, medicine, communications, etc. The U.S. National Academy of Engineering assessed how engineering shaped the 20$^{st}$ century and changed the world, analyzed the 20$^{th}$ century's greatest engineering achievements, and ranked the top 20.[30] As shown in Table II-1, NAE ranked electrification as the "most significant engineering achievement of the 20th Century."

Similarly, in November 2013 the *Atlantic* magazine assembled a panel of scientists, engineers, entrepreneurs, and technologists to assess the 50 innovations

[29] Jude Clemente, "The Statistical Connection Between Electricity and Human Development," *Power* Magazine, September 1, 2010.
[30] U.S. National Academy of Engineering, "Greatest Engineering Achievements of the 20th Century," 2000; © 2014 National Academy of Engineering.

"that have done the most to shape the nature of modern life since the widespread use of the wheel."[31] Electricity was ranked the second most significant, after the printing press.

**Table II-1**
**Greatest Engineering Achievements of the 20th Century**

| | |
|---|---|
| 1. Electrification | 11. Highways |
| 2. Automobile | 12. Spacecraft |
| 3. Airplane | 13. Internet |
| 4. Water Supply and Distribution | 14. Imaging |
| 5. Electronics | 15. Household Appliances |
| 6. Radio and Television | 16. Health Technologies |
| 7. Agricultural Mechanization | 17. Petroleum and Petrochemical Technologies |
| 8. Computers | 18. Laser and Fiber Optics |
| 9. Telephone | 19. Nuclear Technologies |
| 10. Air Conditioning and Refrigeration | 20. High-performance Materials |

Source: National Academy of Engineering.

To take just one example of these electricity-dependent technologies, it is little appreciated how air conditioning – climate control – has profoundly affected and improved modern life.[32] For example, in the U.S.:

- Many of the central changes in society since World War II would not have been possible were air conditioning not available for homes and workplaces.
- Florida, Southern California, Texas, Arizona, Georgia, and New Mexico all experienced above-average growth during the latter half of the 20th century – which would have been impossible without air conditioning, and AC was crucial for the explosive postwar growth of Sunbelt cities like Houston, Phoenix, Las Vegas, and Miami.
- The advent of AC helped launch the massive Southern and Western population growth that has transformed the U.S. electoral map in the last half century: The Sunbelt's share of the nation's population increased from 28 percent in 1950 to 40 percent in 2000.
- Computers generate a lot of heat, and the development of the entire IT industry could not have occurred without cooling technologies first pioneered by air conditioning.

[31]James Fallows, "The 50 Greatest Breakthroughs Since the Wheel," *Atlantic*, November 2013, pp. 56-68; © 2014 The Atlantic Monthly Group.

[32]One reason for choosing this example is that there is currently a "war against air conditioning" being waged because it is alleged that AC contributes to global warming and other assorted evils; see, for example, Stan Cox, *Losing Our Cool: Uncomfortable Truths About Our Air-Conditioned World*, The New Press, 2012; and Doug Mataconis, "The War Against Air Conditioning," July 6, 2010, www.outsidethebeltway.com/the-war-against-air-conditioning.

- As discussed in section III.F.1, climate control improves health and saves lives. For example, more than 700 people died in the 1995 Chicago heat wave, and an estimated 30,000 Europeans succumbed to heat-related illnesses during the heat wave that struck the continent in 2003.
- AC launched new forms of architecture and altered the ways Americans live, work, and play: From suburban tract houses to glass skyscrapers, indoor entertainment centers, high-tech manufacturers' clean rooms, and pressurized modules for space exploration, many of modern structures and products would not exist without the invention of climate control.
- AC changed peoples' relationship with nature itself by creating indoor artificial climates, shifting seasonal patterns of work and play, and making U.S. geographical differences environmentally insignificant.
- As the technology of climate control developed, so also did the invention of more sophisticated products that required increasingly precise temperature, humidity, and filtration controls — consumer products such as computer chips and CDs must be manufactured in "clean rooms," which provide dust-free environments.
- Willis Carrier originally developed climate control to facilitate ink drying in the printing industry in New York City in the early 1900s and, ironically, by facilitating developments in computers and IT air conditioning helped create the 21$^{st}$ century Age of Information.
- Historian Raymond Arsenault found that air conditioning made factory work tolerable in the South, reduced infant mortality, eliminated malaria, and allowed developers to build skyscrapers and apartment blocks. Air conditioning industrialized and urbanized the South, lifting it out of its post-Civil War depression.[33]
- Gail Cooper found that "Air conditioning became an instrument of American modernity — it was a tool marking an American middle class identity as well as a symbol representing a particular and highly specified standard of living.[34]
- Political economist Richard Nathan stated that "The civil rights revolution and air conditioning are the two biggest factors that have changed U.S. demography and a lot of our politics in the last 30 years."[35]

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[33]Raymond Arsenault, "The End of the Long Hot Summer: The Air Conditioner and Southern Culture," *The Journal of Southern History*, Vol. 50, No. 4. (Nov., 1984), pp. 597-628.
[34]Gail Cooper, *Air-Conditioning America: Engineers and the Controlled Environment 1900-1960,* Baltimore: Johns Hopkins University Press, 1998. Cooper notes that AC for cars became a status symbol, so much so that some people without it supposedly drove around with their windows up in 100 degree heat to give an impression otherwise.
[35]Dr. Richard Nathan is the Distinguished Professor of Political Science and Public Policy at the State University of New York at Albany and the former Director of the Rockefeller Institute of Government; he was quoted in the *New York Times*, August 29, 1998.

Further, electrification will be increasingly important in 21st century, and examples of electricity's potential this century include addressing:

- Energy challenges, energy efficiency, and energy conservation,
- Environmental, sustainability, and climate issues,
- Economic development,
- Transportation issues,
- Improving people's standard of living,
- Health, medicine, and bio-tech,
- Continuing developments in communications, IT, etc.,
- The productivity challenge, electricity use, and productivity growth, and
- Others: Emerging electro-technologies, new industries, nanotechnology, robotics, superconductivity, 3-D printing, space exploration, etc.

### II.D.2. Electrification and Human Development

Energy alone is not sufficient for creating the conditions for economic growth, but it is absolutely necessary. It is impossible to operate a factory, run a store, grow crops, or deliver goods to consumers without using some form of energy. Access to electricity is particularly crucial to human development as electricity is, in practice, indispensable for certain basic activities, such as lighting, refrigeration, and the running of household appliances, and cannot easily be replaced by other forms of energy. Individuals' access to electricity is one of the most clear and un-distorted indications of a country's energy poverty status.[36] Thus, electricity access is increasingly at the forefront of governments' preoccupations, especially in the poorest countries.

As a representative of modern energy, the level of electricity consumption can be regarded as indicative of a country's development level, and studies have confirmed the causality between electricity consumption and human development. For example, it was found that long-run causality exists between electricity consumption and five basic human development indicators: Per-capita GDP, consumption expenditure, urbanization rate, life expectancy at birth, and the adult literacy rate. In addition, it was found that the higher the income of a country, the greater is its electricity consumption and the higher is its level of human development and, further, that as income increases, the contribution of electricity consumption to GDP and consumption expenditure increases.[37] In addition, researchers have found that:

[36]International Energy Agency, *World Energy Outlook 2011*, Paris, 2012.

[37]See, for example, Shuwen Niu, Yanqin Jia, Wendie Wang, Renfei He, Lili Hu, and Yan Liu, "Electricity Consumption and Human Development Level: A Comparative Analysis Based on Panel Data For 50 Countries," *International Journal of Electrical Power & Energy Systems*, Volume 53, December 2013, pp. 338–347. These authors recommended that, to improve human development, electricity should be incorporated into the basic public services construction to enhance the availability of electricity for low-income residents.

- Electricity consumption is significantly correlated with GDP as well as the UN Human Development Index (HDI) for 120 countries, and the countries with high consumption levels of per capita electricity rank high with respect to the HDI.[38]
- Per-capita energy and electricity consumption are highly correlated with economic development and other indicators of modern lifestyle, inferring that the more energy that is consumed, especially in the form of electricity, the better life is.[39]
- Electricity consumption is essential for people to improve their well-being in less-developed countries, especially in populous nations such as China and India.[40]

These benefits are so extensive that it is unequivocal the world requires more electricity, not less.[41]

Since 1993, the United Nations Development Program has used a summary composite index, the HDI, to measure, on a scale of 0 to 1, a nation's average achievements in three basic dimensions of human development, health, knowledge, and standard of living: (1) Health is measured by life expectancy at birth; (2) Knowledge is measured by a combination of the adult literacy rate and the combined primary, secondary, and tertiary gross enrollment ratio; and (3) Standard of Living is measured by GDP per capita.[42] UN member states are listed and ranked each year according to these measures.

The IEA reports more than 1.5 billion people in the world have no electric power, and another 2 billion have extremely limited access. In essence, 3.5 billion people — almost 12 times the population of the U.S. — have either no electricity or only a constrained supply. Indeed, the disparity in access to electricity around the world is staggering. The average consumer in Germany, for example, uses 6,670 kWh of power each year; the average Indian uses just 444 kWh. In Europe, virtually no household lacks access to electricity. By contrast, in India, over 400 million people have no electricity, 600 million cook with wood or dung, and over 900 million have no refrigeration.[43]

The consequences of these differences in electricity access are stark. In Germany, a newborn can expect to live until age 79, in India, only until age 64. In

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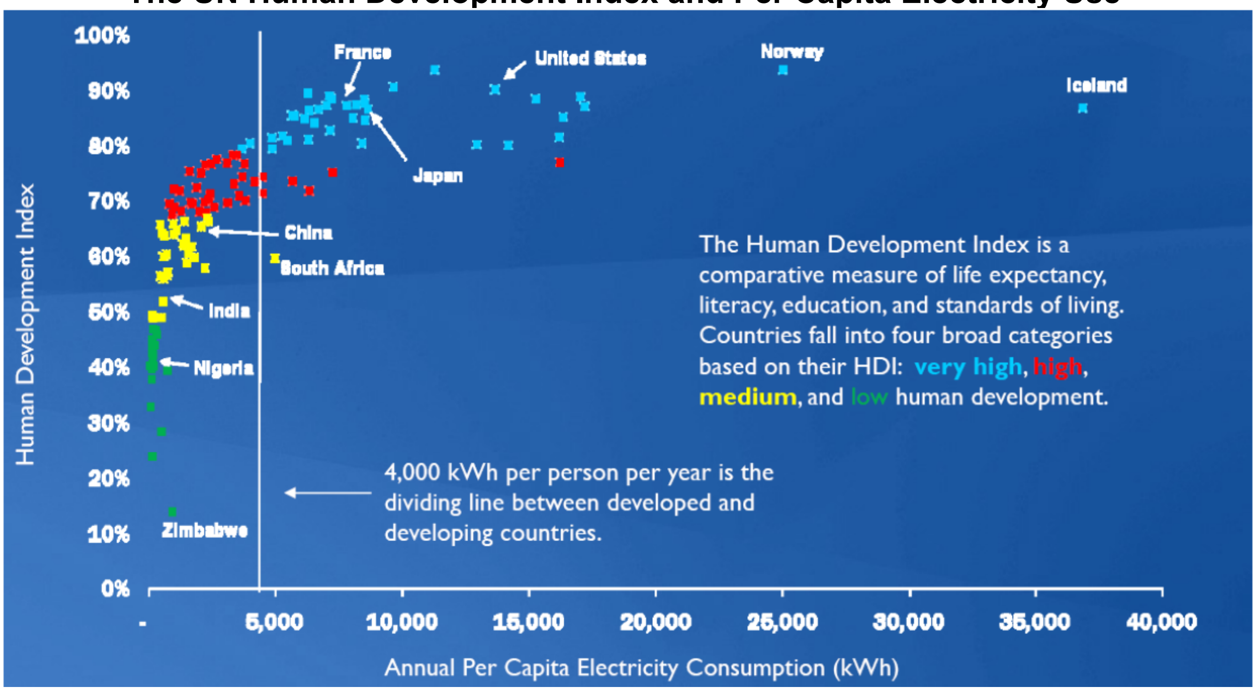
[38]M. Kanagawa and T Nakata, "Assessment of Access to Electricity and the Socioeconomic Impacts in Rural Areas of Developing Countries," *Energy Policy*, Vol. 36, No. 6 (2008), pp. 2,016-2,029.
[39]K.H. Ghali and M.I.T El-Sakka, "Energy Use and Output Growth in Canada: A Multivariate Cointegration Analysis," *Energy Economics*, Vol. 26 (2004) pp. 225-238.
[40]A. Mazur, "Does Increasing Energy or Electricity Consumption Improve Quality of Life in Industrial Nations?" *Energy Policy*, Vol. 39, No. 5 (2011), pp. 2,568-2,572.
[41]Clemente, op. cit.
[42]See United Nations Development Program, "International Human Development Indicators," http://hdr.undp.org/en/statistics.
[43]International Energy Agency, op. cit.

Germany, primary completion and literacy rates are about 100 percent, in India, they hover around 70 percent. In Germany, the GDP per capita is $34,401, in India it is $2,753. Consequently, Germany's HDI is 0.947 and India's is 0.612.

Statistical analyses find that there is sufficient evidence to conclude that those countries that use at least 2,000 kWh per capita a year (High Electricity Consumers) have a significantly higher HDI than those countries that do not (Low Electricity Consumers).[44] Electricity is essential, and access to electric power is central to human development. There is simply no better indicator of a country's level of development than its per capita use of electricity. Electricity enables people to live longer and better and, as shown in Figure II-9, the UN links electricity consumption to quality of life.

**Figure II-9**
**The UN Human Development Index and Per Capita Electricity Use**

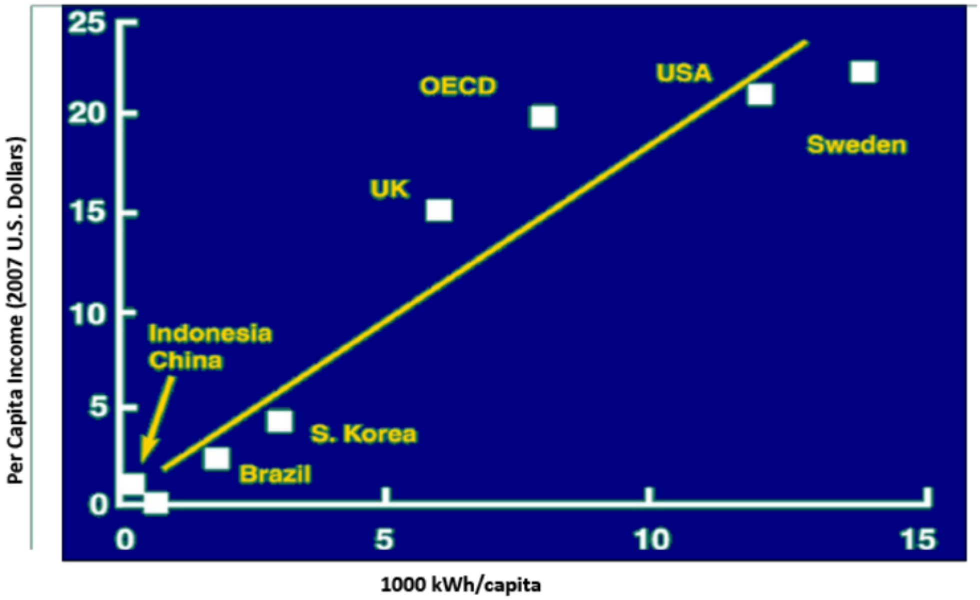



Source: United Nations Development Program, *Human Development Report, 2012*.

Electricity fuels and sustains prosperity and, as shown in Figure II-10, wealth expands with greater electricity use.

[44]Clemente, op. cit.

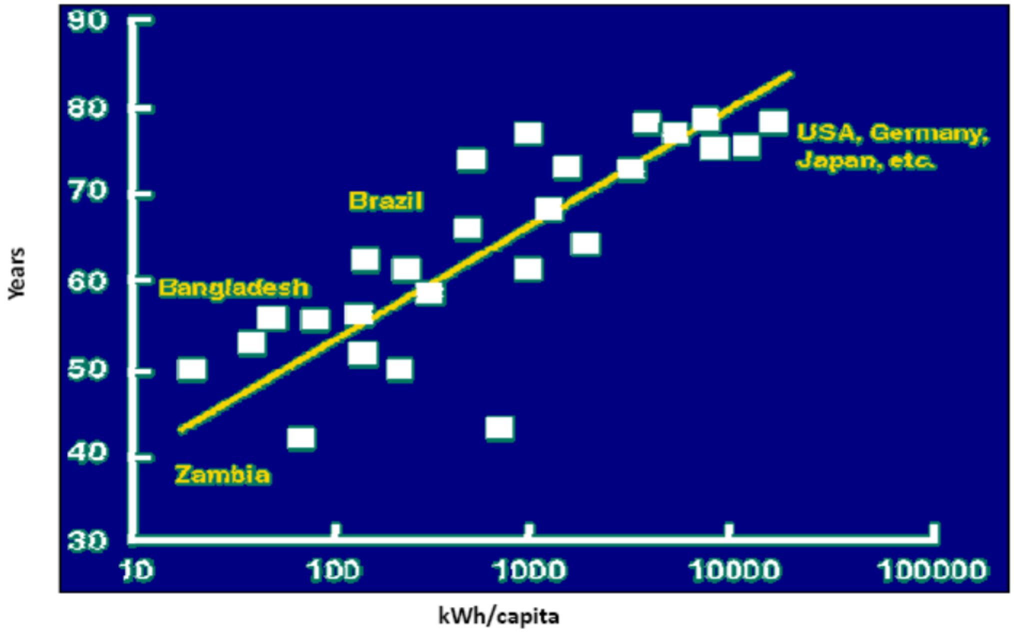
**Figure II-10**
**Per Capita Income and Per Capita Electricity Consumption**




Source: World Resources Institute, *IEEE Spectrum*.

Electricity facilitates increased health and well-being and, as shown in Figure II-11, longevity expands with greater electricity use.

**Figure II-11**
**Average Life Spans and Per Capita Electricity Consumption**




Source: World Resources Institute, *IEEE Spectrum*.

The current drive in some parts of the world (including parts of the U.S.) to increase the price of electricity in order to decrease consumption stands at great odds with experience and poses grave risks. Price increases and higher rates take electricity out of the reach of large segments of society and have adverse consequences and undesirable socioeconomic impacts. Indeed, the UN's eight Millennium Development Goals center not only on electricity availability, but on affordably priced power.[45] For the foreseeable future, mainstream generation technologies, typically based on fossil fuels, will continue to be the least expensive and most reliable sources of electricity in virtually every country in the world.

## II.E. The Regressive Burden of Energy Costs

### II.E.1. The Energy Burden Defined

The "energy burden" is defined as the percentage of gross annual household income that is used to pay annual residential energy bills, and it includes electricity, gasoline, heating, and cooking fuel.[46] It is a widely used and accepted term and is officially defined in the *Code of Federal Regulations* and in numerous federal and state

[45]United Nations, "Millennium Development Goals Beyond 2015," www.un.org/millenniumgoals.

[46]The individual household energy burden is calculated for each household and then averaged within income/origin categories. See the discussion in Applied Public Policy Research Institute for Study and Evaluation, *LIHEAP Energy Burden Evaluation Study*, report prepared for the Office of Community Services, U.S. Department of Health and Human Services, July 2005.

documents.[47] Energy burden is an important statistic widely used by policy-makers in assessing the need for energy assistance and can be defined broadly as the burden placed on household incomes by the cost of energy, or more simply, the ratio of energy expenditures to household income.[48]

The energy burden concept is used to compare energy expenditures among households and groups of households, and it is often used in the Low Income Home Energy Assistance Program (LIHEAP) and similar programs to estimate required payments. For example, consider the case where one household has an energy bill of $1,000 and an income of $10,000 and a second household has an energy bill of $1,200 and an income of $24,000. While the first household has a lower energy bill ($1,000 for the first household compared to $1,200 for the second), the first household has a much higher energy burden (10 percent of income for the first household compared to five percent of income for the second).

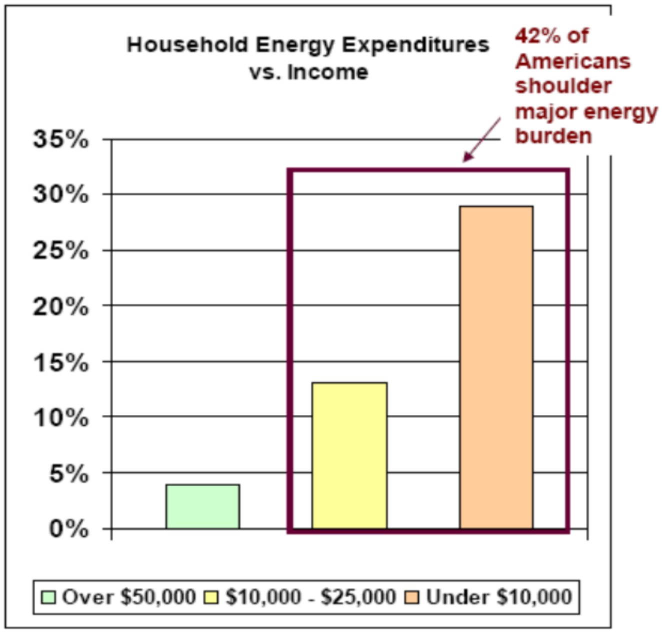
The energy burdens of low-income households are much higher than those of higher-income families, and energy burden is a function of income and energy expenditures. Since residential energy expenditures increase more slowly than income, lower income households have higher energy burdens. High burden households are those with the lowest incomes and highest energy expenditures.

As shown in Figure II-12:

- Families earning more than $50,000 per year spent only four percent of their income to pay energy-related expenses.
- Families earning between $10,000 and $25,000 per year (29 percent of the U.S. population) spent 13 percent of income on energy.
- Those earning less than $10,000 per year (13 percent of population) spent 29 percent of income on energy costs.

**Figure II-12**

[47]The CFR defines the residential energy burden as residential expenditures divided by the annual income of that household. See 10 CFR 440.3 - Definitions. - *Code of Federal Regulations* - Title 10: Energy - PART 440.
[48]U.S. Department of Energy, *Buildings Data Energy Book*, 2.9.2., “Energy Burden Definitions,” March 2011.



Source: American Association of Blacks in Energy.

Thus, for 42 percent of households – mostly senior citizens, single parents, and minorities – increased energy costs force hard decisions about what bills to pay: Housing, food, education, health care, and other necessities. Cost increases for any basic necessity are regressive in nature, since expenditures for essentials such as energy consume larger shares of the budgets of low-income families than they do for those of higher-income families. Whereas higher-income families may be able to trade off luxury goods in order to afford the higher cost of consuming a necessity such as energy, low-income families will always be forced to trade off other necessities to afford the higher-cost good.

When families with income constraints are faced with rising costs of essential energy, they are increasingly forced to choose between paying for that energy use and other necessities (also often energy-sensitive) such as food, housing, or health care. Because all of these expenditures are necessities, families who must make such choices face sharply diminished standards of living. For example, of the 8.7 million American households earning less $10,000 per year in 2008, 60 percent of the average after-tax income was used to meet those households' energy needs. Among the highest earners, the 56 million households making more than $50,000 per year, only 10 percent of the average after-tax income was spent on those households' energy needs. The national average for energy costs as a percentage of household income is about 12 percent.

### II.E.2. The Regressive Nature of Energy Costs

Table II-2 shows that households in the lowest-income classes spend the largest shares of their disposable income to meet their energy needs. For example, for the 8.7

million American households earning less $10,000 per year in 2010, nearly 70 percent of their average after-tax income was used to meet those households' energy needs. Among the highest earners, the 56 million households making more than $50,000 per year, only eight percent of the average after-tax income was spent on energy needs. The national average for energy costs as a percentage of household income is about 10.4 percent.[49]

**Table II-2**
**Estimated U.S. Household Energy Expenditures as a Percentage of Income, 2010**

| Pre-tax income | <$10K | $10K-$30K | $30K-$50K | >$50K | Average |
|---|---|---|---|---|---|
| **Percent of Households** | 7.1% | 23.1% | 19.4% | 50.3% | |
| **Residential Energy** | $1,559 | $1,729 | $1,997 | $2,501 | $2,157 |
| **Transportation Fuel** | $1,837 | $2,280 | $3,221 | $4,316 | $3,456 |
| **Total Energy** | $3,395 | $4,009 | $5,218 | $6,817 | $5,613 |
| **Average After-Tax Income** | $4,903 | $18,138 | $33,436 | $84,337 | $53,904 |
| **Energy Percent% of After-Tax Income** | 69.3% | 22.1% | 15.6% | 8.1% | 10.4% |

Sources: U.S. Bureau of the Census, *Current Population Survey*; U.S. DOE, *Residential Energy Consumption Survey*; U.S. DOE/EIA, *Annual Energy Review* and *Short-Term Energy Outlook*; U.S. DOE/EIA, *Household Vehicle Energy Use: Latest and Trends*; U.S. Congressional Budget Office, *Effective Federal Tax Rates Under Current Law, 2001-2014* and *Effective Federal Tax Rates, 1979-2006*.

The portion of U.S. household incomes expended on energy costs has increased significantly over the past decade, especially for lower-income groups — as illustrated in Figure II-13. Energy costs as a percentage of after-tax income increased nearly 75 percent between 2001 and 2010, from a national average of 6.0 percent to 10.4 percent. However, this figure indicates that the increases for different income groups varied widely:

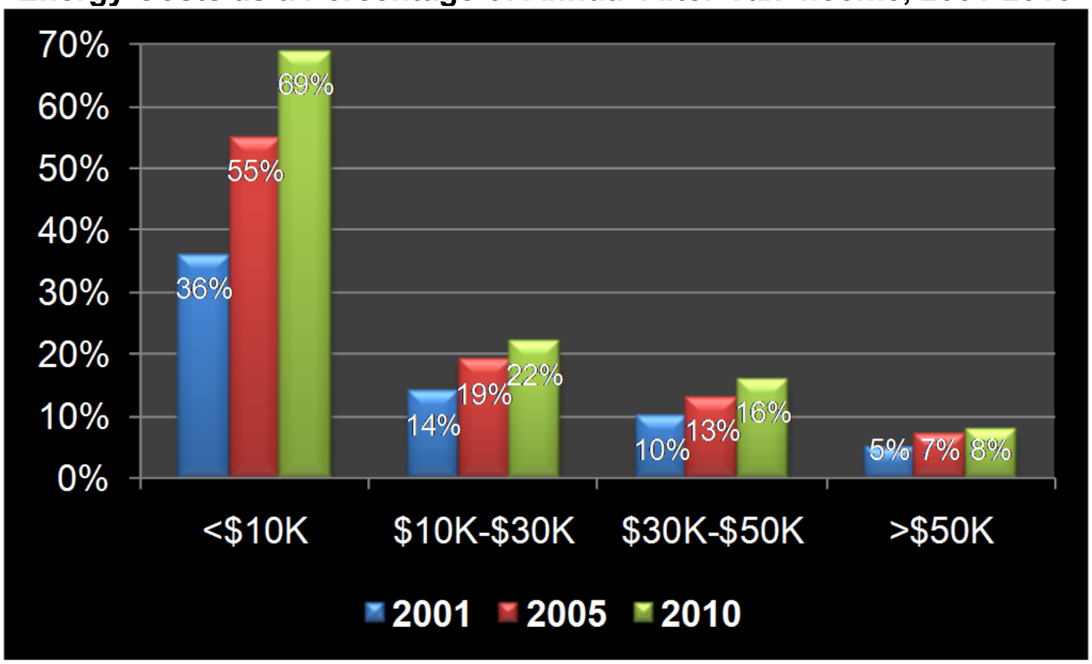
- For households earning less than $10,000 per year, the percent of after-tax income consumed by energy costs increased from 36 percent to 69 percent.
- For households earning between $10,000 and $30,000 per year, the percent of after-tax income consumed by energy costs increased from 14 percent to 22 percent.
- For households earning between $30,000 and $50,000 per year, the percent of after-tax income consumed by energy costs increased from 10 percent to 16 percent.

[49]Estimates derived from U.S. Bureau of Labor Statistics, *Consumer Expenditure Survey*; U.S. Bureau of the Census, *Current Population Survey*; U.S. Department of Energy, *Residential Energy Consumption Survey*; U.S. Energy Information Administration, *Annual Energy Review*, *Short Term Energy Outlook*, and *Household Vehicle Energy Use: Latest and Trends*; U.S. Congressional Budget Office, *Effective Federal Tax Rates Under Current Law, 2001-2014* and *Effective Federal Tax Rates, 1979-2006*. See the discussion in "Energy Cost Impacts on American Families, 2001-2012," American Coalition for Clean Coal Electricity, February 2012, www.americaspower.org.

- For households earning more than $50,000 per year, the percent of after-tax income consumed by energy costs increased from five percent to eight percent.

Thus, in 2010 the poorest households were paying, in percentage terms, nearly nine times as much for energy as the most affluent households. Even households earning between $10,000 and $30,000 per year were paying in percentage terms, nearly three times as much for energy as the most affluent households.

**Figure II-13**
**Energy Costs as a Percentage of Annual After-Tax Income, 2001-2010**




Source: 2010 BLS Consumer Expenditure Survey.

Thus, energy costs as a percentage of annual after-tax income have increased significantly for household incomes under $50,000:

- Nearly 50 percent of U.S. households earn less than $50,000 per year, and they spend 16 percent or more of their income on energy.
- Nearly 40 million U.S. households earning less than $30,000 per year spend 20 percent or more of their income on energy.

Table II-3 shows the average annual household expenditures for U.S. households earning $50,000 or less. Note that these households:

- Spend more on energy than on food,
- Spend twice as much on energy than on healthcare,
- Spend more than twice as much on energy as on clothing,

- Spend more on energy than on anything else, except housing,
- Spend more than 1/4 of their income on housing – nearly 40% on housing if utilities are included, and
- Have little discretionary income, and thus increased energy costs will displace spending on health, food, clothing, housing, and other necessities.

**Table II-3**
**Average Annual Household Expenditures, 2009**

| Pre-tax annual income (average) | $50,000 or Less | % of Total Expenditures |
|---|---|---|
| **After-tax income (average)** | $36,218 | -- |
| **Clothing** | $1,340 | 3.7% |
| **Energy – residential & transportation** | $5,396 | 14.9% |
| **Healthcare** | $2,861 | 7.9% |
| **Food** | $5,287 | 14.6% |
| **Housing (ex. utilities)** | $10,395 | 28.7% |
| **Transportation (ex. fuel)** | $5,179 | 14.3% |
| **Entertainment** | $1,920 | 5.3% |
| **Insurance and pensions** | $1,956 | 5.4% |
| **Education and reading** | $507 | 1.4% |
| **Tobacco and alcohol** | $761 | 2.1% |
| **All other** | $616 | 1.7% |
| **Total expenditures** | $36,218 | 100% |

Source: U.S. Bureau of Labor Statistics, *Consumer Expenditure Survey 2009*, October 2010.

### II.E.3. Impacts and Effects

High and Increasing energy prices have a detrimental effect on the lives of those with limited incomes, and they suffer from home energy arrearages and shut-offs, cutbacks on necessities and other items, risks to health and safety, and housing instability.[50] For example, in recent years, 15 – 20 million U.S households have been in arrears on their home energy bills, and more than 15 percent of all households were at least 30 days delinquent.[51] Unpaid utility bills harm both energy suppliers and low-income families. For example, in 2008, suppliers were experiencing a loss of nearly $5 billion in unpaid household bills, costs that they pass on to other consumers.[52] Families unable to pay their bills face utility shut-offs that deprive them of the basics of living such as heating, cooling, lights, refrigeration, and the ability to cook food. As discussed below, a survey conducted by the Energy Programs Consortium (EPC) found that eight percent of low-income respondents (defined as those living at 150 percent of the federal

[50]Joy Moses, *Generating Heat Around the Goal of Making Home Energy Affordable to Low Income Americans: Current Challenges and Proposed Solutions*, Center for American Progress, Washington, D.C., December 2008.
[51]National Energy Assistance Directors' Association, "NEADA Press Release: Consumers Continue to Fall Behind on Utility Bills, Arrearages Approach $5 billion, Up 14.8% From Last Year," May 2008.
[52]Ibid.

poverty level) experienced a utility shut-off during the past year due to rising home energy and gasoline costs.[53]

In addition to experiencing threats of disruption to their energy services, low-income families are often forced to limit the amount of money they spend on necessities and other important items in order to help manage their energy costs. Of particular concern are reduced purchases of food. According to the EPC survey, 70 percent of those living at or below 150 percent of poverty reported that they were buying less food in response to increases in home energy and gasoline costs. Further, families that are slightly above this poverty marker (151 percent to 250 percent of poverty) and families across all other income levels also reported spending less on food — although they were affected to a lesser degree than the lowest-income families. Thirty-one percent of the poorest families indicated that they purchased less medicine due to high energy costs.[54] They changed plans for education (19 percent), fell behind on credit card bills (18 percent), and reduced their contributions to savings (58 percent) — Table II-4.[55] Thus, Americans of all income levels suffer financially from high energy costs, but those at the bottom of the economic spectrum are under the greatest strain – and those families at or below 150 percent of poverty are the most affected by increased energy prices.[56]

**Table II-4**
**Actions Taken by U.S. Households as a Result of High Energy Prices**

[53]Energy Programs Consortium and National Energy Assistance Directors' Association, "2008 Energy Costs Survey," June 2008.
[54]Ibid.
[55]Ibid. For a more detailed discussion of the actions taken and their implications, see Appendix I.
[56]The energy burdens in the third world are much higher and the implications of high energy prices more severe; see, for example, Gautam N. Yadama, *Fires, Fuel and the Fate of 3 Billion: The State of the Energy Impoverished*, Oxford University Press, 2013.

| Actions taken | All respondents | ≤150% of poverty | 151%-250% of poverty |
|---|---|---|---|
| **Reduced purchases of food** | 43% | 70% | 51% |
| **Reduced purchases of medicine** | 18% | 31% | 23% |
| **Changed plans for education or children's education** | 11% | 19% | 18% |
| **Behind on credit card bills** | 11% | 18% | 15% |
| **Reduced amount of money put into savings** | 55% | 58% | 58% |

Source: 2008 Energy Costs Survey (NEADA).

## II.F. The Health and Safety Benefits of Affordable, Reliable Energy

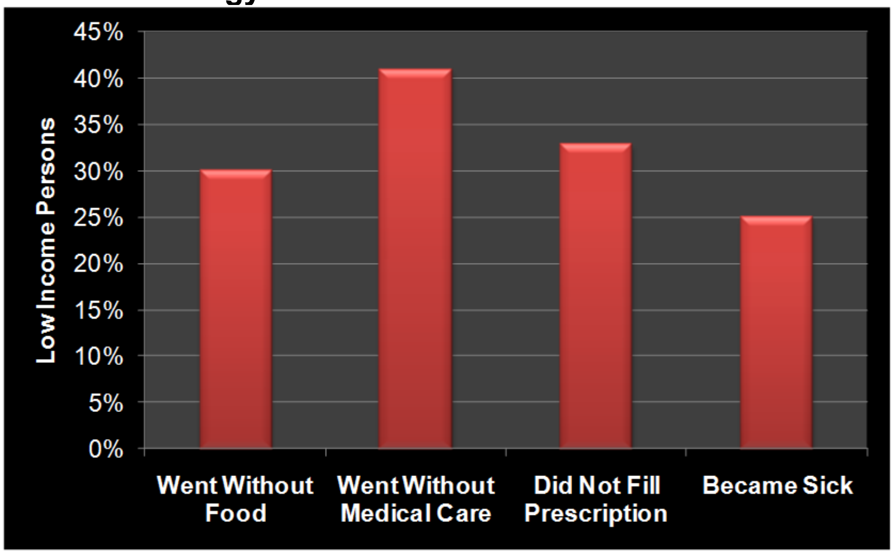
### II.F.1. Health Risks

A major impact of carbon restrictions will be to significantly increase U.S. electricity costs and rates. This will make electricity more expensive and less affordable, especially to those with limited incomes, and being unable to afford energy bills can be harmful to one's health – as illustrated in Figure II-14. Many people are forced to purchase less medicine when their utility bills increase. Other health hazards can occur if inside temperatures are too low or too high as a result of shut-offs or efforts to lower bills by reducing the use of heating and cooling equipment. Surveys have found that nearly one-third of households with incomes at or below 150 percent of poverty kept their homes at a temperature that was unsafe or unhealthy at some point during the year. Similarly, so also did 24 percent of those between 151 percent and 250 percent of poverty.[57]

Temperature extremes can be damaging to vulnerable populations, including the elderly, the disabled, and small children. These groups are particularly susceptible to hypothermia (cold stress or low body temperatures) and hyperthermia (heat stress or high body temperatures), conditions that can cause illness or death.[58] Young children are particularly at risk from extreme temperatures because their small size makes it difficult for them to maintain body heat.[59] Small children in households that are struggling to afford energy costs are more likely to be in poor health, have a history of hospitalizations, be at risk for developmental problems, and be food insecure. Compared with families receiving energy assistance, families who are eligible for such benefits but not receiving them are more likely to have underweight babies and 32 percent more likely to have their children admitted to the hospital.[60]

[57]Energy Programs Consortium and National Energy Assistance Directors' Association, "2008 Energy Costs Survey," June 2008.
[58]U.S. Department of Health and Human Services, "Tips for Health and Safety," available at www.acf.hhs.gov/programs/ocs/liheap/consumer_info/health.html.
[59]Children's Sentinel Nutrition Assessment Program and Citizens Energy Corporation, "Fuel for Our Future: Impacts of Energy Insecurity on Children's Health, Nutrition, and Learning," September 2007.
[60]Ibid.

**Figure II-14**
**Potential Health Impacts of Increased Energy Costs on Low Income Persons**




Source: National Energy Assistance Directors' Association.

High energy burdens among older, low-and moderate-income households, expose them to the risks of going without adequate heating or cooling, frequently resulting in adverse health and safety outcomes, including premature death – Figure II-14. Unaffordable home energy undermines state and national priorities for seniors to age in place and avoid institutional care.[61] Households at the lowest income level are often on a fixed income from Social Security, disability, or retirement. When energy prices escalate, their incomes do not keep pace, and they have little flexibility in their budgets to address increases in energy costs.[62]

Further, the job losses and price increases resulting from the increased energy costs will reduce incomes as firms, households, and governments spend more of their budgets on electricity and less on other items, such as home goods and services. The loss of disposable income also reduces the amount families can spend on critical health care, especially among the poorest and least healthy.[63]

[61] "Home Energy Costs: The New Threat to Independent Living for the Nation's Low-Income Elderly," *Journal of Poverty Law and Policy*, January-February 2008.
[62] Ibid.
[63] Randall Lutter and John F. Morrall. "Health-Health Analysis: A New Way to Evaluate Health and Safety Regulation", *Journal of Risk and Uncertainty*, 8(1), 43-66 (1994); Ralph L. Keeney, "Mortality Risks Induced by Economic Expenditures", *Risk Analysis* 10(1), 147-159 (1990); Krister Hjalte et al. (2003). "Health Analysis – an Alternative Method For Economic Appraisal of Health Policy and Safety Regulation: Some Empirical Swedish Estimates," *Accident Analysis & Prevention* 35 (1), 37-46; W. Kip Viscusi "Risk-Risk Analysis," *Journal of Risk and Uncertainty* 8 (1), 5-17 (1994); see also Viscusi and Richard J. Zeckhauser, "The Fatality and Injury Costs of Expenditures", *Journal of Risk and Uncertainty* 8(1), 19-41 (1994).

More generally, a substantial body of literature has developed examining the potential impacts of energy and environmental regulations on GDP, energy prices, income, and employment. It has been estimated, for example, that initiatives requiring expanded use of high cost energy alternatives would increase the cost of electricity to the point that per-capita income and employment rates would decrease in a quantitatively predictable manner.[64] If these estimates are approximately correct, and given the epidemiological findings on socioeconomic status and health, it follows that policies such as carbon restrictions that increase the costs of energy and electricity could result in a net increase in population mortality.[65]

EPA has acknowledged that "People's wealth and health status, as measured by mortality, morbidity, and other metrics, are positively correlated. Hence, those who bear a regulation's compliance costs may also suffer a decline in their health status, and if the costs are large enough, these increased risks might be greater than the direct risk-reduction benefits of the regulation."[66] The Office of Management and Budget, the Food and Drug Administration, and the Occupational Safety and Health Administration use similar methodology to assess the degree to which their regulations induce premature death amongst those who bear the costs of federal mandates.[67]

### II.F.2. Safety Risks

High energy prices also compromise the safety of low-income households. For example, the inability to pay utility bills often leads to the use of risky alternatives. In a survey of energy assistance recipients, 21 percent of respondents indicated that at some point in the previous year they were unable to use a main heating source because they could not pay their utility bill.[68] Twelve percent indicated that a utility company had shut off their main heating sources of natural gas or electricity during the previous year due to nonpayment.[69]

When households are cut off from their main heating source such as natural gas or fuel oil, or are trying to save money by reducing use of a main heating source, they most commonly turn to heating alternatives such as electric space heaters, which can be risky. According to the National Fire Protection Agency, these devices are associated with a significant risk of fire, injury, and death. In 2005, space heaters accounted for 32 percent of home heating fires, totaling 19,904 fires and 73 percent of

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[64]Harvey Brenner, "Health Benefits of Low-Cost Energy: An Econometric Study," *Environmental Management*, November 2005, pp 28 – 33; © 2005 Air and Water Management Association.
[65]Ibid. Brenner's research found that changes in the economic status of individuals produce subsequent changes in the health and life spans of those individuals and that decreased real income per capita and increased unemployment have consequences that lead to increased mortality in U.S. and European populations.
[66]U.S.EPA, "On the Relevance of Risk-Risk Analysis to Policy Evaluation," August 16, 1995.
[67]Ibid.
[68]National Energy Assistance Directors' Association, "2009 National Energy Assistance Survey," April 2009.
[69]Ibid.

home heating fire deaths, which killed 489 people.[70] Researchers at the Johns Hopkins School of Medicine also noted this problem in a 2005 study in which they found that power terminations were associated with a significant subset of fires involving children – – 15 percent of fires that brought patients to their hospital were rooted in utility shut-offs.[71]

### II.F.3. Housing Instability

Families and individuals who cannot afford their energy bills are at risk of housing instability. They may have to move to locations with lower utility costs, or shut-offs can make homes uninhabitable, forcing household members into homelessness or alternative forms of shelter. Unaffordable housing often compounds this problem as families experiencing difficulty paying mortgages or rent fall further behind due to energy bills that represent a higher-than-normal percentage of their income. This factor was particularly relevant during the recent subprime mortgage crisis, which resulted in excessively high mortgage payments for some families.

The connections between unmanageable home energy costs and homelessness are well-documented. For example, a Colorado study found that 16 percent of homeless people in the state cited their inability to pay utility bills as one of the causes of their homelessness.[72] A nationwide survey of individuals receiving energy assistance produced further evidence of this phenomenon. Twenty-five percent reported that within the previous five years, they had failed to make a full rent or mortgage payment due to their energy bills.[73] Difficulties with paying utilities resulted in other negative outcomes such as evictions (two percent of respondents), moving in with friends or family members (four percent of respondents), and moving into a shelter or homelessness (two percent).[74]
Further, "Inability to pay utilities is second only to inability to pay rent as a reason for homelessness."[75]

Housing instability disrupts lives, especially if individuals are forced to move between several different locations before regaining permanent housing. Household members may find themselves at a greater distance from work and/or school and face increased transportation costs and challenges. They can also be disconnected from familiar communities, neighbors, family members, and friends. For children, the outcomes can be devastating, with homelessness being associated with increased risk

[70]National Fire Protection Association, "U.S. Home Heating Equipment Fires Fact Sheet," 2007.
[71]Johns Hopkins School of Medicine, "Burn Injuries and Deaths of Children Associated with Power Shut-offs," April 2005.
[72]The Colorado Statewide Homeless Count, "Colorado Statewide Homeless Count, Summer 2006: Final Report," February 2007.
[73]National Energy Assistance Directors' Association, "2005 National Energy Assistance Survey," September 2005.
[74]Ibid.
[75]Tennessee Interfaith Power and Light, "Impacts of Fuel Bills upon Lower Income," Knoxville, Tennessee, 2014.

of physical illness, hunger, emotional and behavioral problems, developmental delays, negative educational outcomes, and exposure to violence.[76]

### II.F.4. Energy Cost-Related Health Risks to the Elderly

Between 2010 and 2050, the U.S. will experience rapid growth in its older population, and in 2050 the number of Americans aged 65 and older is forecast to be 88.5 million — more than double its population of 40.2 million in 2010.[77] The baby boomers are largely responsible for this increase in the older population, as they began crossing into this category in 2011.[78] The aging of the population will have wide-ranging implications for the country,[79] and senior citizens are particularly vulnerable to energy price increases due to their relatively low incomes. The average basic Social Security retirement benefit is currently about $15,200.[80] The median gross income of senior households over 65 years is currently about $31,400, and seniors have the highest per capita residential energy consumption among all age categories.[81] For many senior households, as with other households earning less than $50,000 annually, energy price increases can force difficult choices among energy, food, and other basic necessities of life, choices that would be made more difficult by higher energy costs resulting from restrictions on fossil fuels.

Older consumers with the lowest incomes will experience the greatest cost burdens: 35 percent of older households have total household incomes of less than $20,000, and they will experience the greatest energy burden. Although consumption data show that low-income older consumers tend to use less heating fuel than higher-income groups, higher winter heating costs are likely to be a greater burden on this group than on higher-income older consumers who have greater financial resources available to meet the increased costs. As shown in Figure II-15, large percentages of the elderly have high energy burdens, and nearly 34 percent of the elderly and more than 36 percent of the frail elderly have high energy burdens.

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[76]The National Center on Family Homelessness, "The Characteristics and Needs of Families Experiencing Homelessness," 2011.

[77]See U.S. Census Bureau, *The Next Four Decades: The Older Population in the United States: 2010 to 2050*, May 2010. Here, the "older population" refers to those aged 65 and older.

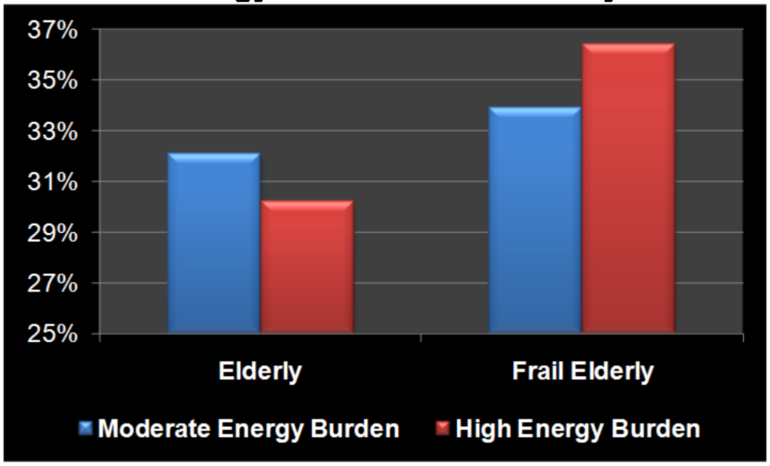
[78]The baby boomer generation consists of people born between 1946 and 1964.

[79]Projecting the size and structure, in terms of age, sex, race, and Hispanic origin, of the older population is important to public and private interests, both socially and economically. The projected growth of the older population in the United States will present challenges to policy makers and programs, such as Social Security and Medicare, and it will also affect families, businesses, and health care providers.

[80]U.S. Social Security Administration, "Monthly Statistical Snapshot," August 2013, September 2013.

[81]U.S. Census Bureau, "American Community Survey – 2010 American Community Survey 1-Year Estimates," 2012.

**Figure II-15**
**Energy Burdens of the Elderly**




Source: Division of Energy Assistance, U.S. Department of Health and Human Services.

Low income senior citizens dependent primarily on retirement income have especially high energy burdens: About 45 percent of such individuals have high energy burdens, as compared to about 36 percent of all low income persons.[82] Thus, the greatest burdens of increased energy costs will fall on households of elderly Social Security recipients – 20 percent of all households — who depend mainly on fixed incomes, with limited opportunity to increase earnings from employment. These households have an average Social Security income of about $15,000.

Elderly individuals with low average annual incomes are more vulnerable to increasing energy costs even if their energy consumption levels are below those for households with similar annual incomes. Unlike young working families with the potential to increase incomes by taking on part-time work or increasing overtime, fixed income seniors are largely limited to cost-of-living increases that often do not keep pace with rising energy prices. Maintaining affordable energy costs is critical to the well-being of millions of the nation's elderly citizens.

Elderly Americans' limited budgets are stretched even further by higher health care expenditures. Medical spending for those between the ages of 55 and 64 is almost twice the amount spent by those between the ages of 35 and 44, and the health care expenditures of those 65 and older are even larger. Health care costs have contributed to the rise in bankruptcy filings among the elderly. More serious, being unable to afford home energy can be harmful to the health of household members, and many persons are forced to purchase less medicine and health care when their utility bills are too high. A 2009 survey of low-income seniors[83] found that due to energy costs:

[82] APPRISE, "LIHEAP Energy Burden Evaluation Study Final Report," Prepared for Division of Energy Assistance, Office of Community Services, Administration for Children and Families, U.S. Department of Health and Human Services, PSC Order No. 03Y00471301D, July 2005.
[83] Jackie Berger, 2009 National Energy Assistance Survey, prepared for NEADA by APPRISE, June 15, 2010.

- 41 percent were forced to defer or forgo medical or dental care.
- 33 percent were unable to afford their prescriptions.
- 22 percent were unable to pay their energy bills due to medical expenses.
- Nearly 30 percent became ill because their home was too cold or too hot.
- 33 percent went without food for at least one day.

Thus, increased utility costs have serious implications for the health of many senior citizens.

### II.F.5. 2009 Energy Cost Survey

In 2009, the National Energy Assistance Directors Association, representing state LIHEAP directors, conducted a survey to update the information about LIHEAP-recipient households that was collected in the 2003, 2005, and 2008 surveys – more detail on these surveys is contained in Appendix I. LIHEAP is administered by the U.S. Department of Health and Human Services (HHS). Its purpose is "to assist low-income households, particularly those with the lowest incomes, that pay a high proportion of household income for home energy, primarily in meeting their immediate home energy needs."[84] The statutory intent of LIHEAP is to reduce home heating and cooling costs for low-income households.[85] During the period of study, low-income households across the country faced an increasingly difficult economic climate and continued to deal with high energy costs. The study confirmed that LIHEAP recipient households are likely to be vulnerable to temperature extremes:

- 39 percent had a senior in the household aged 60 or older.
- 44 percent had a disabled household member.
- 45 percent had a child 18 or younger.
- 92 percent had at least one vulnerable household member.

The study also provided information on challenges that these households faced:

- 36 percent were unemployed at some point during the previous year.
- 82 percent had a serious medical condition.
- 25 percent used medical equipment that requires electricity.

LIHEAP recipients reported that they face high energy costs:

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[84]See "Low Income Home Energy Assistance Program. Report to Congress for Fiscal Year 2001." U.S. Department of Health and Human Services, Administration for Children and Families, Office of Community Services, Division of Energy Assistance.
[85]Ibid.

- 37 percent reported that their energy bills were more than $2,000 in the past year.
- Pre-LIHEAP energy burden averaged 16 percent and post-LIHEAP energy burden averaged 11 percent for these households, compared to seven percent for all households in the U.S. and four percent for non low-income households in the U.S.
- 35 percent said that their energy bills were higher than they had been in the previous year and 40 percent said that they were more difficult to pay than in the previous year.
- 60 percent of those who said that it was more difficult to pay their energy bills reported that the main reason was their financial situation.

Households reported that they took several actions to make ends meet:

- 36 percent closed off part of their home.
- 26 percent kept their home at a temperature that was unsafe or unhealthy.
- 20 percent left their home for part of the day.
- 33 percent used their kitchen stove or oven to provide heat.

Many LIHEAP recipients were unable to pay their energy bills:

- 49 percent skipped paying or paid less than their entire home energy bill.
- 35 percent received a notice or threat to disconnect or discontinue their electricity or home heating fuel.
- 12 percent had their electric or natural gas service shut off in the past year due to nonpayment.
- 27 percent were unable to use their main source of heat in the past year because their fuel was shut off, they could not pay for fuel delivery, or their heating system was broken and they could not afford to fix it.
- 17 percent were unable to use their air conditioner in the past year because their electricity was shut off or their air conditioner was broken and they could not afford to fix it.

Many LIHEAP recipients had problems paying for housing over the past five years, due at least partly to their energy bills:

- 31 percent did not make their full mortgage or rent payment.
- Five percent were evicted from their home or apartment.
- Four percent had a foreclosure on their mortgage.
- 12 percent moved in with friends or family.

- Three percent moved into a shelter or were homeless.

Many of the LIHEAP recipients faced significant medical and health problems in the past five years, partly as a result of high energy costs. All of these problems increased significantly since the 2003 survey:

- 30 percent went without food for at least one day.
- 41 percent went without medical or dental care.
- 33 percent did not fill a prescription or took less than the full dose of a prescribed medication.
- 25 percent had someone in the home become sick because the home was too cold.

## II.G. Energy Costs and the Economy

Virtually all economists agree that there is a negative relationship between energy price changes and economic activity, but there are significant differences of opinion on the economic mechanisms through which price impacts are felt – see the discussion in Appendix II. Beginning with the oil supply shocks of the 1970's, analyses that have addressed the impact of energy price shocks on economic activity have produced, and continue to produce, a steady stream of reports and studies on the topic.

A number of studies have analyzed the long run impacts of changes in energy and electricity prices on the economy and jobs. For example:[86]

- In 2012 and 2013, Bildirici and Kayikci in several studies found causal relationships between electricity consumption and economic growth in the Commonwealth of Independent States countries and in transition countries in Europe.[87]
- In 2010, Lee and Lee analyzed the demand for energy and electricity in OECD countries and found a statistically valid relationship between electricity consumption and economic growth.[88]
- In 2010, Baumeister, Peersman, and Van Robays examined the economic consequences of oil shocks across a set of industrialized

[86]See also the discussion in Section II.H.2 and Appendices II and III.

[87]Melike Bildirici, Frazil Kayikci, "Economic Growth and Electricity Consumption in Former Soviet Republics" IDEAS, Federal Reserve Bank of St. Louis, 2012; Melike Bildirici, Frazil Kayikci, "Economic Growth and Electricity Consumption in Former Soviet Republics," *Energy Economics*, Volume 34, Issue 3 (May 2012), pp. 747–753; "Economic Growth And Electricity Consumption In Emerging Countries Of Europa: An ARDL Analysis," *Economic Research - Ekonomska Istrazivanja*, Vol. 25, No. 3 (2013), pp 538-559.

[88]Chien-Chaing Lee and Jun-De Lee, "A Panel Data Analysis of the Demand for Total Energy and Electricity in OECD Countries," *The Energy Journal*, Vol. 31, No 1 (2010), pp. 1-23.

countries over time and found that energy costs and GDP are negatively correlated.[89]

- In 2010, Brown and Hunnington employ a welfare-analytic approach to quantify the security externalities associated with increased oil use, which derive from the expected economic losses associated with potential disruptions in world oil supply.[90]
- In 2009, Blumel, Espinoza, and Domper used Chilean data to estimate the long run impact of increased electricity and energy prices on the nation's economy.[91]
- In 2008, in a study of the potential economic effects of peak oil, Kerschner and Hubacek reported significant correlations between energy and GDP – although they noted that sectoral impacts are more significant.[92]
- In 2008, Sparrow analyzed the impacts of coal utilization in Indiana, and estimated that electricity costs significantly affect economic growth in the state.[93]

In this section we:

- Review a comprehensive study that provides guidance on methodology and data
- Summarize a large number of studies that quantified the elasticity of economic variables with respect to changes in energy and electricity prices

### II.G.1. Estimating the Impact of Energy Prices on the Economy and Jobs

A Penn State study forecast the likely impacts of coal utilization for electricity generation on the economies of the 48 contiguous states in 2015.[94] The authors first estimated the overall economic benefits associated with the availability of coal as a relatively low-cost fuel resource, including the increased economic output, earnings, and employment associated with projected coal utilization for electricity generation in 2015.

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[89] Christiane Baumeister, Gert Peersman and Ine Van Robays, "The Economic Consequences of Oil Shocks: Differences Across Countries and Time," Ghent University, Belgium, 2010.

[90] Stephen P.A. Brown and Hillard G. Huntington, "Estimating U.S. Oil Security Premiums," Resources for the Future, Washington, D.C., June 2010.

[91] Gonzalo Blumel, Ricardo A. Espinoza, and G. M. de la Luz Domper, "Does Energy Cost Affect Long Run Economic Growth? Time Series Evidence Using Chilean Data," Instituto Libertad y Desarrollo Facultad de Ingenier´ıa, Universidad de los Andes, March 22, 2009.

[92] Christian Kerschnera and Klaus Hubacek, "Assessing the Suitability of Input-Output Analysis For Enhancing Our Understanding of Potential Economic Effects of Peak-Oil," Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK, 2008.

[93] F.T. Sparrow, Measuring the Contribution of Coal to Indiana's Economy," CCTR Briefing: Coal, Steel and the Industrial Economy, Hammond, Indiana, December 12, 2008.

[94] Adam Rose and Dan Wei, *The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015,* report prepared for the Center for Energy and Economic Development, Inc., Alexandria, Virginia, the Pennsylvania State University, July 2006.

They also estimated the net economic impacts of displacing 33 percent and 66 percent of projected coal generation by alternative energy resources, taking into account the positive economic effects associated with alternative investments in oil, natural gas, nuclear, and renewable energy supplies.

The authors noted that, with a broad base and high level of technological advancement, the U.S. economy exhibits a great deal of interdependence. Each business enterprise relies on many others for inputs into its production process and provides inputs to them in return. This means that the coal and coal-based electric utility industries' contributions to the nation's economy extend beyond their own production to include demand arising from a succession of "upstream" inputs from their suppliers and "downstream" deliveries to their customers. The economic value of these many rounds of derived demands and commodity allocations is some multiple of the value of direct production itself.

Thus, the coal and coal-based electric utility industries generate "multiplier" effects throughout the U.S. economy. The first round of demand impacts is obvious -- the direct inputs to electricity generation, including coal and primary factors (labor and capital). Subsequent rounds, or indirect demands for goods and services used by the providers of these inputs, however, thread their way through the economy in subtle ways, eventually stimulating every other sector in some way. Similarly, they generate income that is transformed into consumer spending on still more products. All of this economic activity also generates local, state, and federal tax revenues, which, when spent by all three levels of government, creates still more multiplier effects.

A method of capturing the locational attractiveness of a good or service is not to claim the entirety of output of its direct and indirect users, but only an amount relating to the price advantage of the input over its competitors. In this study, the authors calculated a "price differential" between coal and alternative fuels in electricity production, and then estimated how much economic activity is attributable to this cost saving. For this purpose, they used an economy-wide elasticity of output with respect to energy prices that measures the percentage change in economic activity with respect to a 1.0 percent change in price. They analyzed a variety of sources of information to arrive at a value of 0.10, meaning that the availability of coal-fueled electricity at a price 10 percent lower than that of its nearest competitor is responsible for increasing total state or regional economic activity by 1.0 percent.

To assess the importance of coal to state and regional economies in 2015, the authors first estimated the level of coal-based electricity generation in each state in 2015 based on projections by EIA and EPA.[95] They evaluated coal-related impacts according to various assumptions embodied in their scenarios.[96]

[95]They also assumed that the technological structure of the economy, embodied in individual state input-output tables, would remain unchanged over the projection period to 2015.
[96]These are detailed in Appendix B of their report.

Their set of scenarios estimated the positive impact on national and regional economic output, household income, and jobs attributable to the projected levels of coal-fueled electricity in 2015. These scenarios estimated the “existence” value of coal as the key fuel input into electricity generation in the U.S. The economic impacts of coal estimated in the study included two components: 1) the backward linkage, or demand-side multiplier, effects for coal-fueled electricity generation, and 2) the effects of the favorable price differential attributable to the relatively cheaper cost of coal-based electricity.

The authors first used IMPLAN input-output tables to estimate the direct and indirect (multiplier) economic output, household income, and jobs created by coal-fueled electricity generation in each state.[97] They then evaluated the impacts of the favorable price differential attributable to coal-based electricity. Essentially, they measured the economic activity attributable to relatively cheaper coal in contrast to what would take place if a state were dependent on more expensive alternatives, which they assumed would be a combination of oil, natural gas, renewable, and nuclear electricity. They conducted two calculations: 1) an upper-range (“high”) price scenario, and 2) a lower-range (“low”) price scenario. These two scenarios had the same backward linkages effects, but different price differential effects based on their different energy price assumptions. As noted, they estimated the impact of higher electricity prices on state economies using a price elasticity estimate of 0.10.

Finally, they assigned equal weight to each of the two price scenarios to obtain the average “existence” impacts of coal-fueled electricity generation in 2015. They then derived results for each state and region in 2015 that showed that coal, as the low-cost electricity generation option, has significant economic and job benefits and that displacing coal in the generation mix would have severe economic consequences. For example, the study estimated the average impacts of displacing 33 percent of coal-based generation in 2015 at:

- $166 billion (2005$) reduction in gross economic output
- $64 billion reduction of annual household incomes
- 1.2 million job losses

### II.G.2. Elasticity Estimates in the Literature

Numerous studies have developed estimates of the elasticity of GDP with respect to energy and electricity prices.[98] Examples of these are summarized in Table II-5 and are discussed in more detail in Appendix III.

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[97]They estimated only the minimum backward linkage effects for the “multiplier” effects. Their method excluded all forward linkages (all the production that uses coal-fueled electricity directly or indirectly) and focuses only on the factor inputs of coal-based electricity generation, such as fuel and electric generating equipment.

[98]An elasticity of -0.1 implies that a 10 percent increase in the electricity price will result in a one percent decrease in GDP or – in the case of a state – Gross State Product (GSP). Thus, for example, in a state

The meaning and interpretation of these elasticities are discussed below.

As indicated in Table II-5, three decades of rigorous research support elasticity estimates factors of about:

- -0.17 for oil,
- -0.13 for electricity,
- -0.14 for energy, and
- -0.15 for every energy-related study (all of the above).

The meaning and interpretation of these elasticities are discussed in Section II.G.3.

**Table II-5**
**Summary of Energy- and Electricity-GDP Elasticity Estimates**

| Year Analysis Published | Author | Elasticity Estimate |
|---|---|---|
| | | |
| 2010 | Lee and Lee (energy and electricity) | -0.01 and -0.19 |
| 2010 | Brown and Huntington (oil) | -0.01 to -0.08 |
| 2010 | Baumeister, Peersman, and Robays (oil) | -0.35 |
| 2009 | Blumel, Espinoza, and Domper (energy and electricity) | -0.085 to -0.16 |
| 2008 | Kerschner and Hubacek (oil) | -0.03 to -0.17 |
| 2008 | Sparrow (electricity) | -0.3 |
| 2007 | Maeda (energy) | -0.03 to -0.075 |
| 2007 | Citigroup (energy) | -0.3 to -0.37 |
| 2007 | Lescaroux (oil) | -0.1 to -0.6 |
| 2006 | Rose and Wei (electricity) | -0.1 |
| 2006 | Oxford Economic Forecasting (energy) | -0.03 to -0.07 |
| 2006 | Considine (electricity) | -0.3 |
| 2006 | Global Insight (energy) | -0.04 |
| 2004 | IEA (oil) | -0.08 to -0.13 |
| 2002 | Rose and Young (electricity) | -0.14 |
| 2002 | Klein and Kenny (electricity) | -0.06 to -0.13 |
| 2001 | Rose and Ranjan (electricity) | -0.14 |
| 2001 | Rose and Ranjan (energy) | -0.05 to -0.25 |
| 1999 | Brown and Yucel (oil) | -0.05 |
| 1996 | Hewson and Stamberg (electricity) | -0.14 |
| 1996 | Rotemberg and Woodford (energy) | -0.25 |
| 1996 | Gardner and Joutz (energy) | -0.072 |
| 1996 | Hooker (energy) | -0.07 to -0.29 |
| 1995 | Lee and Ratti (oil) | -0.14 |

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such as Arizona where GSP is currently about $270 billion, a 10 percent increase in the electricity price will (other things being equal) likely result in about a $3 billion decrease in Arizona GSP.

| | | |
|---|---|---|
| 1995 | Hewson and Stamberg (electricity) | -0.5 and -0.7 |
| 1982 | Anderson (electricity) | -0.14 |
| 1981 | Rasche and Tatom (energy) | -0.05 to -0.11 |

Source: Management Information Services, Inc.

### II.G.3. The Impact of Electricity Price Increases on the Economy and Jobs

We summarized above some of the major studies that estimated the relationship between the economy and jobs, on the one hand, and the price of energy and electricity on the other, and Appendix III cites over 60 references to studies published over the past three decades. These references pertain to studies published in peer-reviewed international professional and scientific journals, reports prepared by researchers at major universities and research institutes (such as the UK University of Leeds, the Colorado School of Mines, Citigroup Energy, Inc., Duke University, Pennsylvania State University, the National Science Foundation, the OECD, the Federal Reserve Bank, Statistics Norway, etc.), and papers presented at major international scientific conferences.

The sources cited include analyses of the economic and jobs effects of oil price increases, energy price increases, and electricity price increases in both developed and developing countries throughout the world. This breadth of coverage strengthens the analysis and findings.

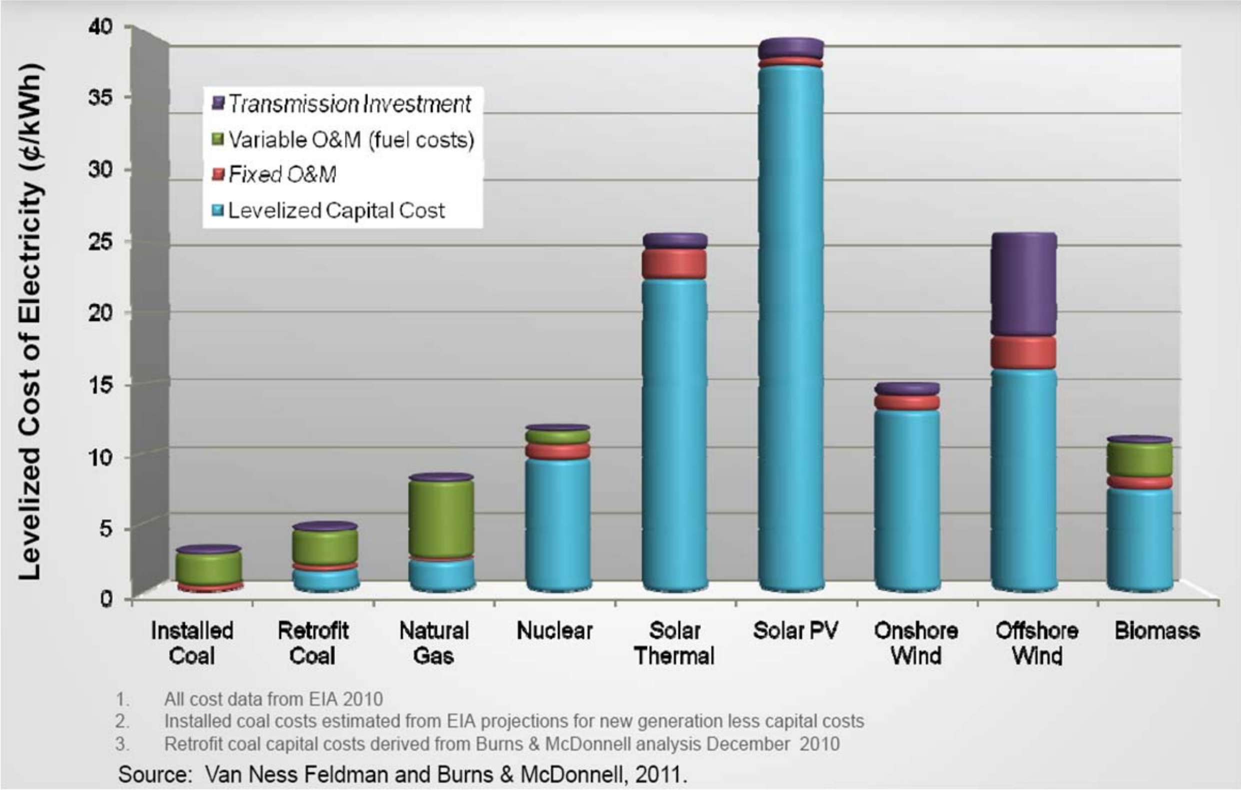
The research discussed here finds that virtually all economists who have analyzed the issue agree that there is a negative relationship between energy price changes and economic activity, but there are significant differences of opinion on the economic mechanisms through which price impacts are felt. Nevertheless, the salient point is that the relationship between energy prices and the economy is negative: Increases in energy and electricity prices harm the economy and decreases in energy and electricity prices benefit the economy. This relationship is important because fossil fuels are currently the low-cost option for generating electricity and are forecast to remain so – as discussed below. The mix of electric generating capacity – existing and new — among the various fossil, nuclear, and renewable sources will significantly affect electricity prices. Estimates of the levelized cost of electricity (LCOE) of existing and, especially, new electricity generating technologies vary by orders of magnitude – see Figure II-16. Nevertheless, it seems clear that coal is the least expensive, followed by natural gas. New builds of nuclear and renewables are the most expensive and, among renewables, geothermal and biomass are the least expensive, followed by onshore wind, offshore wind, solar thermal, and PV.[99]

Basically, energy price increases act like a tax increase on the economy, increasing the outflows of funds and reducing the incomes of energy consumers and ratepayers. In addition, the supply-side impacts from rate increases will depress

[99]No new builds of large hydro are assumed here.

business development and economic output. On the other hand, the consumer cost-savings realized from lower rates increase the disposable incomes of ratepayers and, this income, when used to buy other goods and services, creates additional economic benefits.

**Figure II-16**
**Levelized Costs of Electricity by Generation Sources**




Energy costs have Keynesian economic effects similar to those of taxes:[100]

- Increased energy and utility costs act as a "hidden tax" that have deflationary, economically constrictive impacts; e.g., they decrease sales, GDP, jobs, etc.
- Conversely, decreased energy and utility costs have the effect of a "tax cut" and have economically stimulating effects by putting more money in the hands of consumers and businesses, thus increasing sales, creating jobs, etc.

[100]See Roger H. Bezdek, "Energy Costs: The Unseen Tax? A Case Study of Arizona," presented at the National Taxpayers Conference, Chandler, Arizona, October 2013.

- Like tax increases and decreases, changes in energy costs have both direct and indirect effects on the economy.

Programs and policies that increase electricity prices – in a city, state, region, or nation — over what they would be otherwise will have adverse effects on the economy and jobs. First, businesses currently located in the jurisdiction with the electricity price increase will face increased competitive disadvantages. Second, some businesses currently in the jurisdiction will leave. Third, new businesses will be discouraged from locating in the jurisdiction. Fourth, electric customers will have less money to spend on other things.

Based on studies that estimated the energy price/GDP elasticities (see Table II-5 and Appendix III) we determined that a reasonable electricity elasticity estimate is -0.1, which implies that a 10 percent increase in electricity prices will result in a one percent decrease in GDP. The reported elasticity estimates ranged between -0.85 and -0.01, and most were in the range of about -0.1. This elasticity estimate has been used in rigorous, scholarly studies of these issues, and it is the estimate we use in our research. If anything, we understate the impact of electricity price changes on the economy and jobs.

## III. DIRECT CARBON BENEFITS[101]

Advances in technology and scientific expertise since the Industrial Revolution have led to vast improvements in agricultural yield and production values. More efficient machinery and improved plant cultivars, for example, paved the way for higher crop yields and increased global food production. And with the ever-increasing population of the planet, the increase in food production was a welcome societal benefit. But what remained largely unknown to society at that time was the birth of an ancillary aid to agriculture that would confer great benefits upon future inhabitants of the globe throughout the decades and centuries to come. The source of that aid is atmospheric carbon dioxide ($CO_2$).

Thousands of laboratory and field studies have documented growth-enhancing, water-conserving, and stress-alleviating benefits of atmospheric $CO_2$ enrichment on plants.[102] For a 300-ppm increase in the air's $CO_2$ content, such benefits typically enhance herbaceous plant biomass by around 30 to 35 percent, which represents an important positive externality entirely absent from current state-of-the-art SCC calculations.

Here we provide a quantitative estimate of the direct monetary benefits of atmospheric $CO_2$ enrichment on both historic and future crop production.[103] The incorporation of these estimates into future SCC studies will help to ensure a more realistic assessment of the total net economic impact of rising $CO_2$ concentrations due to both negative and positive externalities.

### III.A. How Increasing Atmospheric $CO_2$ Is a Biospheric Benefit

At a fundamental level, carbon dioxide is the basis of nearly all life on Earth. It is the primary raw material or "food" utilized by the vast majority of plants to produce the organic matter out of which they construct their tissues, which subsequently become the ultimate source of food for nearly all animals and humans. Consequently, the more $CO_2$ there is in the air, the better plants grow, as has been demonstrated in literally thousands of laboratory and field experiments.[104] And the better plants grow, the more food there is available to sustain the entire biosphere.

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[101]This chapter is based on the report by Craig Idso, "The Positive Externalities of Carbon Dioxide," Center for the Study of Carbon Dioxide and Global Change, 2013; © 2013, www.co2science.org, which was commissioned as a part of my previous work on this subject. .

[102]C.D. Idso and Singer, S.F., *Climate Change Reconsidered: 2009 Report of the Nongovernmental International Panel on Climate Change (NIPCC)*. The Heartland Institute, Chicago, Illinois, USA, 2009; C.D. Idso and Idso, S.B., *The Many Benefits of Atmospheric $CO_2$ Enrichment*. Vales Lake Publishing, LLC, Pueblo West, Colorado, USA, 2011.

[103]Determining the net monetary effect of rising atmospheric $CO_2$ is beyond the scope of this analysis; see Section III.E.

[104]Idso and Singer, Ibid.

The idea that an increase in the air's $CO_2$ content may be of benefit to the biosphere can be traced back over 200 years. As early as 1804, for example, de Saussure showed that peas exposed to high $CO_2$ concentrations grew better than control plants in ambient air; and work conducted in the early 1900s significantly increased the number of species in which this growth-enhancing effect of atmospheric $CO_2$ enrichment was observed to occur.[105] In fact, by the time a group of scientists convened at Duke University in 1977 for a workshop on Anticipated Plant Responses to Global Carbon Dioxide Enrichment, an annotated bibliography of 590 scientific studies dealing with $CO_2$ effects on vegetation had been prepared.[106] This body of research demonstrated that increased levels of atmospheric $CO_2$ generally produce increases in plant photosynthesis, decreases in plant water loss by transpiration, increases in leaf area, and increases in plant branch and fruit numbers, to name but a few of the most commonly reported benefits. And five years later, at the International Conference on Rising Atmospheric Carbon Dioxide and Plant Productivity, it was concluded that a doubling of the air's $CO_2$ concentration would likely lead to a 50 percent increase in photosynthesis in $C_3$ plants, a doubling of water use efficiency in both $C_3$ and $C_4$ plants, significant increases in biological nitrogen fixation in almost all biological systems, and an increase in the ability of plants to adapt to a variety of environmental stresses.[107]

Numerous studies conducted on hundreds of different plant species testify to the very real and measurable growth-enhancing, water-saving, and stress-alleviating advantages that elevated atmospheric $CO_2$ concentrations have for Earth's plants.[108] In commenting on these and many other $CO_2$-related benefits, Wittwer wrote that "the 'green revolution' has coincided with the period of recorded rapid increase in concentration of atmospheric carbon dioxide, and it seems likely that some credit for the improved [crop] yields should be laid at the door of the $CO_2$ buildup."[109] Similarly, Allen et al. concluded that yields of soybeans may have been rising since at least 1800 "due to global carbon dioxide increases,"[110] while more recently, Cunniff et al. hypothesized that the rise in atmospheric $CO_2$ following deglaciation of the most recent planetary ice age, was the trigger that launched the global agricultural enterprise.[111]

[105]E. Demoussy, "Sur, La Vegetation Dans Des Atmospheres Riches En Acide Carbonique." *Comptes Rendus Academy of Science Paris* 136: 325-328; 138: 291-293; 139: 883-885, 1902-1904; M.B. Cummings, and Jones, C.H., "*The Aerial Fertilization of Plants With Carbon Dioxide*." Vermont Agricultural Station Bulletin No. 211, 1918.
[106]Strain, B.R., *Report of the Workshop on Anticipated Plant Responses to Global Carbon Dioxide Enrichment*. Department of Botany, Duke University, Durham, NC, 1978.
[107]E.R. Lemon, (Ed.), *$CO_2$ and Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*. Westview Press, Boulder, CO, 1983. $C_3$ plants are those in which photosynthesis takes place throughout the leaf; $C_4$ plants are those in which photosynthesis takes place in inner cells.
[108]Idso and Singer, op. cit.; Idso and Idso, op. cit.
[109]S.H. Wittwer, "Carbon Dioxide and Crop Productivity." *New Scientist* 95: 233-234, 1982.
[110]Allen et al. "Response of Vegetation to Rising Carbon Dioxide: Photosynthesis, Biomass, and Seed Yield of Soybean," *Global Biogeochemical Cycles* 1: 1-14, 1987.
[111]Cunniff et al., "Response of Wild $C_4$ Crop Progenitors to Subambient $CO_2$ Highlights a Possible Role In the Origin of Agriculture." *Global Change Biology* 14: 576-587, 2008.

In a test of this hypothesis, Cunniff et al. designed "a controlled environment experiment using five modern-day representatives of wild $C_4$ crop progenitors, all 'founder crops' from a variety of independent centers," which were grown individually in growth chambers maintained at atmospheric $CO_2$ concentrations of 180, 280 and 380 ppm, characteristic of glacial, post-glacial and modern times, respectively. The results revealed that the 100-ppm increase in $CO_2$ from glacial to postglacial levels (180 to 280 ppm) "caused a significant gain in vegetative biomass of up to 40 percent," together with "a reduction in the transpiration rate via decreases in stomatal conductance of **~**35 percent," which led to "a 70 percent increase in water use efficiency, and a much greater productivity potential in water-limited conditions."[112]

In discussing their results, the five researchers concluded that "these key physiological changes could have greatly enhanced the productivity of wild crop progenitors after deglaciation ... improving the productivity and survival of these wild $C_4$ crop progenitors in early agricultural systems."[113] And in this regard, they note that "the lowered water requirements of $C_4$ crop progenitors under increased $CO_2$ would have been particularly beneficial in the arid climatic regions where these plants were domesticated."[114] For comparative purposes, they also included one $C_3$ species in their study – *Hordeum spontaneum* K. Koch – and they report that it "showed a near-doubling in biomass compared with [the] 40 percent increase in the $C_4$ species under growth treatments equivalent to the postglacial $CO_2$ rise."[115] In light of these and other similar findings,[116] it can be appreciated that the civilizations of the past, which could not have existed without agriculture, were largely made possible by the increase in the air's $CO_2$ content that accompanied deglaciation, and that the peoples of the Earth today are likewise indebted to this phenomenon, as well as the additional 110 ppm of $CO_2$ the atmosphere has subsequently acquired. And as the $CO_2$ concentration of the air continues to rise in the future, this positive externality of enhanced crop production will benefit society in the years, decades, and centuries to come.

## III.B. Data Sets Utilized

In order to estimate the monetary benefit of rising atmospheric $CO_2$ concentrations on historic crop production, a number of different data sets were required. From the United Nations' Food and Agriculture Organization (FAO), annual global crop yield and production data were obtained, as well as the monetary value associated with that production.[117]

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[112]Ibid.
[113]Ibid.
[114]Ibid.
[115]Ibid.
[116]H.S. Mayeux et al., "Yield of Wheat Across a Subambient Carbon Dioxide Gradient." *Global Change Biology* 3: 269-278, 1997.
[117]FAO (Food And Agriculture Organization), FAO Statistics Database. FAO, Rome, Italy, 2012. These data sources are published in the FAO's statistical database FAOSTAT, which is available online at http://faostat.fao.org/site/567/default.aspx#ancor.

For the world as a whole, the FAO's statistical database (FAOSTAT) contains data on these agricultural parameters for over 160 different crops that have been grown and used since 1961. No data are available prior to that time, so the temporal scope of this analysis was limited to the 50-year time window of 1961-2011. In addition, because more than half of the crops in the database each account for less than 0.1 percent of the world's total food production, it was deemed both prudent and adequate to further constrain this analysis to focus on only those crops that accounted for the top 95 percent of global food production. This was accomplished by taking the average 1961-2011 production contribution of the most important crop, adding to that the contribution of the second most important crop, and continuing in like manner until 95 percent of the world's total food production was reached. The results of these procedures produced the list of 45 crops shown in Table III-1.

**Table III-1**
**The Forty-Five Crops That Supplied 95 Percent of Total World Food Production Over the Period 1961-2011**

| Crop | % of Total Production | Crop | % of Total Production |
|---|---|---|---|
| Sugar cane | 20.492 | Rye | 0.556 |
| Wheat | 10.072 | Plantains | 0.528 |
| Maize | 9.971 | Yams | 0.523 |
| Rice, paddy | 9.715 | Groundnuts, with shell | 0.518 |
| Potatoes | 6.154 | Rapeseed | 0.494 |
| Sugar beet | 5.335 | Cucumbers and gherkins | 0.492 |
| Cassava | 3.040 | Mangoes, mangosteens, guavas | 0.406 |
| Barley | 2.989 | Sunflower seed | 0.398 |
| Vegetables fresh nes | 2.901 | Eggplants (aubergines) | 0.340 |
| Sweet potatoes | 2.638 | Beans, dry | 0.331 |
| Soybeans | 2.349 | Fruit Fresh Nes | 0.321 |
| Tomatoes | 1.571 | Carrots and turnips | 0.320 |
| Grapes | 1.260 | Other melons (inc.cantaloupes) | 0.302 |
| Sorghum | 1.255 | Chillies and peppers, green | 0.274 |
| Bananas | 1.052 | Tangerines, mandarins, clem. | 0.264 |
| Watermelons | 0.950 | Lettuce and chicory | 0.262 |
| Oranges | 0.935 | Pumpkins, squash and gourds | 0.248 |
| Cabbages and other brassicas | 0.903 | Pears | 0.243 |
| Apples | 0.886 | Olives | 0.241 |
| Coconuts | 0.843 | Pineapples | 0.230 |
| Oats | 0.810 | Fruit, tropical fresh nes | 0.230 |
| Onions, dry | 0.731 | Peas, dry | 0.228 |
| Millet | 0.593 | | |
| ***Sum of All Crops = 95.2%*** | | | |

Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

Other data needed to conduct the analysis included annual global atmospheric $CO_2$ values since 1961 and plant-specific $CO_2$ growth response factors. The annual global $CO_2$ data were obtained from the most recent United Nations Intergovernmental Panel on Climate Change report, *Annex II: Climate System Scenario Tables - Final Draft Underlying Scientific-Technical Assessment* (IPCC, 2013). The plant-specific $CO_2$ growth response factors – which represent the percent growth enhancement expected for each crop listed in Table III-1 in response to a known rise in atmospheric $CO_2$ – were acquired from the online Plant Growth Database of $CO_2$ Science.[118]

The $CO_2$ Science Plant Growth Database lists the results of thousands of $CO_2$ enrichment experiments conducted on hundreds of different crops growing under varying environmental conditions over the past few decades.[119] This database was used to estimate the mean crop growth response to a 300-ppm increase in atmospheric $CO_2$ concentration for each crop listed in Table III-1. For some crops, however, there were no $CO_2$ enrichment data contained in the database, and in those cases the mean responses of similar plants, or groups of plants, were utilized. Also, there were some instances where the plant category in the FAO database represented more than one plant in the *$CO_2$ Science* Plant Growth Database. For example, the designation *Oranges* represents a single FAO crop category in the FAO database, yet there were two different types of oranges listed in the *$CO_2$ Science* database (*Citrus aurantium, and Citrus reticulata x C. paradisi x C. reticulata*). Thus, in order to produce a single number to represent the $CO_2$-induced growth response for the *Oranges* category, a weighted average from the growth responses of both orange species listed in the *$CO_2$ Science* database was calculated. This procedure was repeated in other such circumstances; and the final results for all crops are listed in Table III-2, which provides the average biomass response by FAO plant category for a 300-ppm increase in the air's $CO_2$ concentration for all 45 crops listed in Table III-1, which values are based upon data downloaded from the *$CO_2$ Science* Plant Growth Database on 1 October 2013.

### III.C. Historical Monetary Benefit Estimates and Results

The first step in determining the monetary benefit of historical atmospheric $CO_2$ enrichment on historic crop production begins by calculating what portion of each crop's annual yield over the period 1961-2011 was due to each year's increase in atmospheric $CO_2$ concentration above the baseline value of 280 ppm that existed at the beginning of the Industrial Revolution.

Illustrating this process for wheat, in 1961 the global yield of wheat from the FAOSTAT database was 10,889 hectograms per hectare (Hg/Ha), the atmospheric $CO_2$ concentration was 317.4 ppm, representing an increase of 37.4 ppm above the 280-ppm baseline, while the $CO_2$ growth response factor for wheat as listed in Table III-2 is 34.9% for a 300-ppm increase in $CO_2$. To determine the impact of the 37.4 ppm rise in atmospheric $CO_2$ on 1961 wheat yields, the wheat-specific $CO_2$ growth response factor of 34.9% per 300 ppm $CO_2$ increase (mathematically written as 34.9%/300 ppm) is multiplied by the 37.4 ppm increase in $CO_2$ that has occurred since the Industrial Revolution. The resultant value of 4.35% indicates the degree by which the 1961 yield was enhanced above the baseline yield value corresponding to an atmospheric $CO_2$

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[118] Center for the Study of Carbon Dioxide and Global Change, *$CO_2$ Science Plant Growth Database*, Http://Www.Co2science.Org/Data/Plant_Growth/Plantgrowth.Php, 2013.
[119] http://www.co2science.org/data/plant_growth/plantgrowth.php.

concentration of 280 ppm. The 1961 yield is then divided by this relative increase (1.0435) to determine the baseline yield in Hg/Ha (10,889/1.0435 = 10,435). The resultant baseline yield amount of 10,435 Hg/Ha is subtracted from the 1961 yield total of 10,889 Hg/Ha, revealing that 454 Hg/Ha of the 1961 yield was due to the 37.4 ppm rise in $CO_2$ since the start of the Industrial Revolution. Similar calculations are then made for each of the remaining years in the 50-year period, as well as for each of the 44 remaining crops accounting for 95% of global food production.

**Table III-2**
**Mean Percentage Yield Increases Produced by a 300-ppm Increase in Atmospheric $CO_2$ Concentration For All Crops Accounting For 95 Percent of Total Food Production**

| Crop | % Biomass Change | Crop | % Biomass Change |
|---|---|---|---|
| Sugar cane | 34.0% | Rye | 38.0% |
| Wheat | 34.9% | Plantains | 44.8% |
| Maize | 24.1% | Yams | 47.0% |
| Rice, paddy | 36.1% | Groundnuts, with shell | 47.0% |
| Potatoes | 31.3% | Rapeseed | 46.9% |
| Sugar beet | 65.7% | Cucumbers and gherkins | 44.8% |
| Cassava | 13.8% | Mangoes, mangosteens, guavas | 36.0% |
| Barley | 35.4% | Sunflower seed | 36.5% |
| Vegetables fresh nes | 41.1% | Eggplants (aubergines) | 41.0% |
| Sweet potatoes | 33.7% | Beans, dry | 61.7% |
| Soybeans | 45.5% | Fruit Fresh Nes | 72.3% |
| Tomatoes | 35.9% | Carrots and turnips | 77.8% |
| Grapes | 68.2% | Other melons (inc.cantaloupes) | 4.7% |
| Sorghum | 19.9% | Chillies and peppers, green | 41.1% |
| Bananas | 44.8% | Tangerines, mandarins, clem. | 29.5% |
| Watermelons | 41.5% | Lettuce and chicory | 18.5% |
| Oranges | 54.9% | Pumpkins, squash and gourds | 41.5% |
| Cabbages and other brassicas | 39.3% | Pears | 44.8% |
| Apples | 44.8% | Olives | 35.2% |
| Coconuts | 44.8% | Pineapples | 5.0% |
| Oats | 34.8% | Fruit, tropical fresh nes | 72.3% |
| Onions, dry | 20.0% | Peas, dry | 29.2% |
| Millet | 44.3% | | |

Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

The next step is to determine what *percentage* of the total annual yield of each crop in each year was due to $CO_2$. This was accomplished by simply taking the results calculated in the previous step and dividing them by the corresponding total annual yields. For example, using the calculations for wheat from above, the 454 Hg/Ha yield due to $CO_2$ in 1961 was divided by the total 10,889 Hg/Ha wheat yield for that year, revealing that 4.17% of the total wheat yield in 1961 was due to the historical rise in atmospheric $CO_2$. Again, such percentage calculations were completed for all crops for each year in the 50-year period 1961-2011.

Knowing the annual percentage influences of $CO_2$ on all crop yields (production per Ha), the next step is to determine how that influence is manifested in total crop production value. This was accomplished by multiplying the $CO_2$-induced yield percentage increases by the corresponding annual production of each crop, and by then multiplying these data by the gross production value (in constant 2004-2006 U.S. dollars) of each crop per metric ton, the data for which were obtained from the FAOSTAT database. The end result of these calculations becomes an estimate of the annual monetary benefit of atmospheric $CO_2$ enrichment (above the baseline of 280 ppm) on crop production since 1961. These monetary values are presented for each of the 45 crops under examination in Table III-3.

**Table III-3**
**The Total Monetary Benefit of Earth's Rising Atmospheric $CO_2$ Concentration on Each of the 45 Crops Listed in Table III-1 For the 1961-2011**
(Values in Constant 2004-2006 U.S. Dollars)

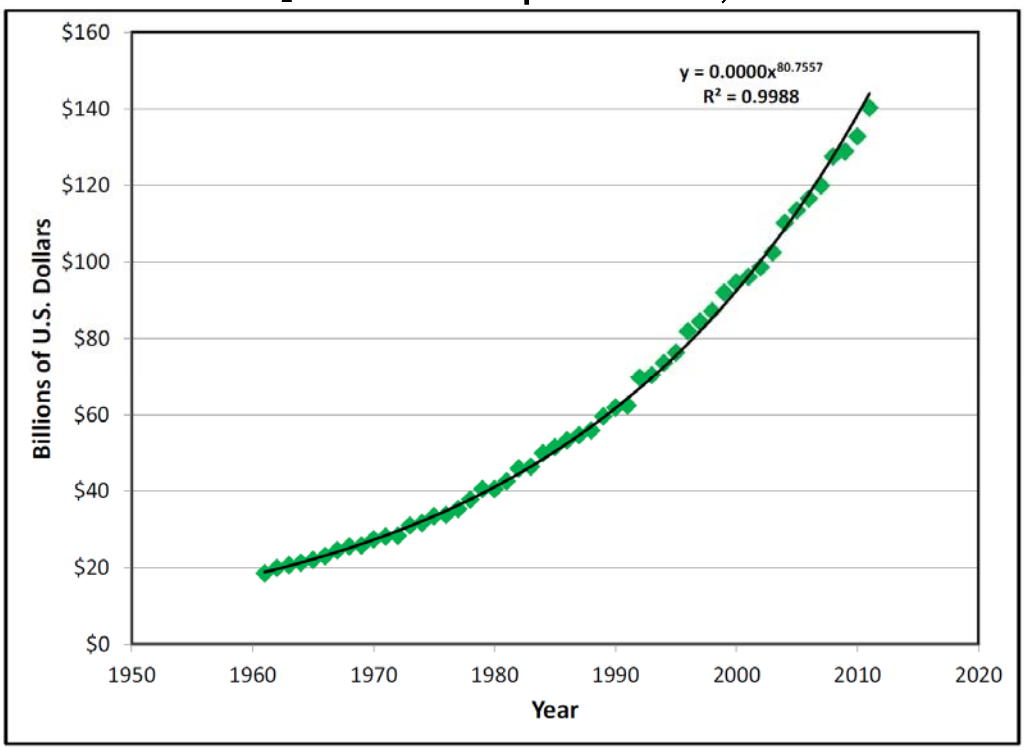
| Crop | Production Rank | Monetary Benefit of $CO_2$ | Crop | Production Rank | Monetary Benefit of $CO_2$ |
|---|---|---|---|---|---|
| Rice, paddy | 4 | $579,013,089,273 | Carrots and turnips | 35 | $36,439,812,318 |
| Wheat | 2 | $274,751,908,146 | Cucumbers and gherkins | 29 | $33,698,222,461 |
| Grapes | 13 | $270,993,488,618 | Watermelons | 16 | $32,553,055,795 |
| Maize | 3 | $182,372,524,324 | Pears | 41 | $31,577,067,767 |
| Soybeans | 11 | $148,757,417,756 | Fruit Fresh Nes | 34 | $29,182,817,600 |
| Potatoes | 5 | $147,862,516,739 | Fruit, tropical fresh nes | 44 | $28,837,991,342 |
| Vegetables fresh nes | 9 | $143,295,147,644 | Millet | 23 | $24,748,422,190 |
| Tomatoes | 12 | $140,893,704,588 | Eggplants (aubergines) | 32 | $22,794,746,004 |
| Sugar cane | 1 | $107,420,713,630 | Cassava | 7 | $21,850,017,436 |
| Apples | 19 | $98,329,393,797 | Onions, dry | 22 | $20,793,394,925 |
| Sugar beet | 6 | $69,247,223,819 | Sorghum | 14 | $20,579,850,257 |
| Barley | 8 | $63,046,887,462 | Tangerines, mandarins, clem. | 38 | $18,822,174,419 |
| Bananas | 15 | $58,264,644,460 | Coconuts | 20 | $17,949,253,896 |
| Yams | 26 | $56,163,446,226 | Sunflower seed | 31 | $17,585,395,685 |
| Groundnuts, with shell | 27 | $51,076,843,461 | Plantains | 25 | $17,384,141,669 |
| Olives | 42 | $50,604,186,875 | Lettuce and chicory | 39 | $15,029,691,577 |
| Oranges | 17 | $50,173,178,154 | Pumpkins, squash and gourds | 40 | $13,140,422,653 |
| Beans, dry | 33 | $47,240,266,167 | Oats | 21 | $12,615,396,815 |
| Mangoes, mangosteens, guavas | 30 | $40,731,776,757 | Rye | 24 | $8,981,587,998 |
| Sweet potatoes | 10 | $39,889,080,598 | Peas, dry | 45 | $5,667,935,087 |
| Chillies and peppers, green | 37 | $39,813,008,532 | Other melons (inc.cantaloupes) | 36 | $2,477,799,109 |
| Rapeseed | 28 | $38,121,172,234 | Pineapples | 43 | $1,779,091,848 |
| Cabbages and other brassicas | 18 | $37,501,047,431 | **Sum of all crops = $3,170,050,955,544** | | |

Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

As can be seen from Table III-3, the financial benefit of Earth's rising atmospheric $CO_2$ concentration on global food production is enormous. Such benefits over the period 1961-2011 have amounted to at least $1 billion for each of the 45 crops examined; and for nine of the crops the monetary increase due to $CO_2$ over this period is well over $100 billion. The largest of these benefits is noted for rice, wheat and grapes, which saw increases of $579 billion, $274 billion and $270 billion, respectively.

Another interesting aspect of these calculations can be seen in Figure III-1, which shows the annual total monetary value of the $CO_2$ benefit for all 45 crops over the 50-year period 1961-2011. As seen there, the annual value of the $CO_2$ benefit has increased over time. Whereas it amounted to approximately $18.5 billion in 1961, by 2011 it had grown to over $140 billion annually. In summing these annual benefits across the entire 50-year time period, the total $CO_2$-induced benefit on global food production since 1961 amounts to $3.2 trillion.

**Figure III-1**
**Total Annual Monetary Value of the**
**Direct $CO_2$ Benefit on Crop Production, 1961-2011**




Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

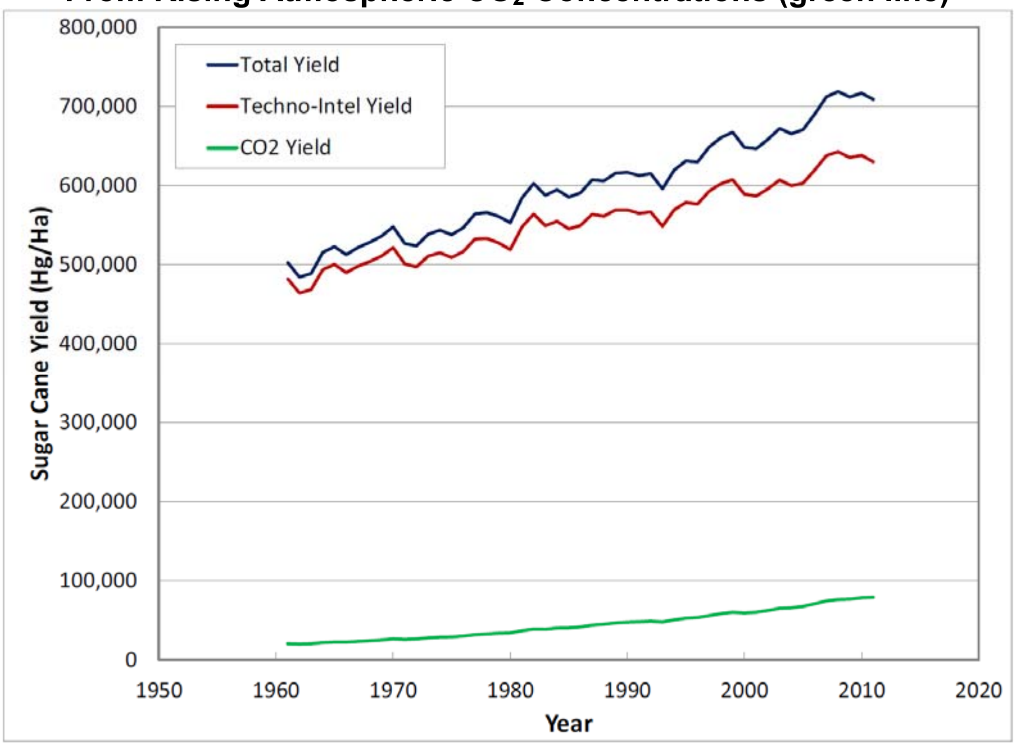
## III.D. Future Monetary Benefit Estimates and Results

The methods of estimating future monetary benefits of rising atmospheric $CO_2$ concentrations on crop production were slightly different from those used in calculating the historic values of the previous section. In explaining these methods, sugar cane will serve as the example.

First, the 1961-2011 historic yield data for sugar cane are plotted as the solid blue line in Figure III-2. Next, that portion of each year's annual yield that was due to rising carbon dioxide, as per calculations described in the prior section (the solid green line), was subtracted out. The resultant values are depicted as the solid red line in

Figure III-2. These yield values represent the net effect of everything else that tended to influence crop yield over that time period. Although many factors play a role in determining the magnitude of this latter effect, it is referred to here as the *techno-intel effect*, as it derives primarily from continuing advancements in agricultural technology and scientific research that expand our knowledge or intelligence base.

**Figure III-2**
**Plot of the Total Yield of Sugar Cane, 1961-2011 (blue line), Along With Plots of That Portion of the Total Yield Attributed to Advances in Agricultural Technology and Scientific Research (Techno-Intel Effect, red line) and Productivity Increases From Rising Atmospheric $CO_2$ Concentrations (green line)**



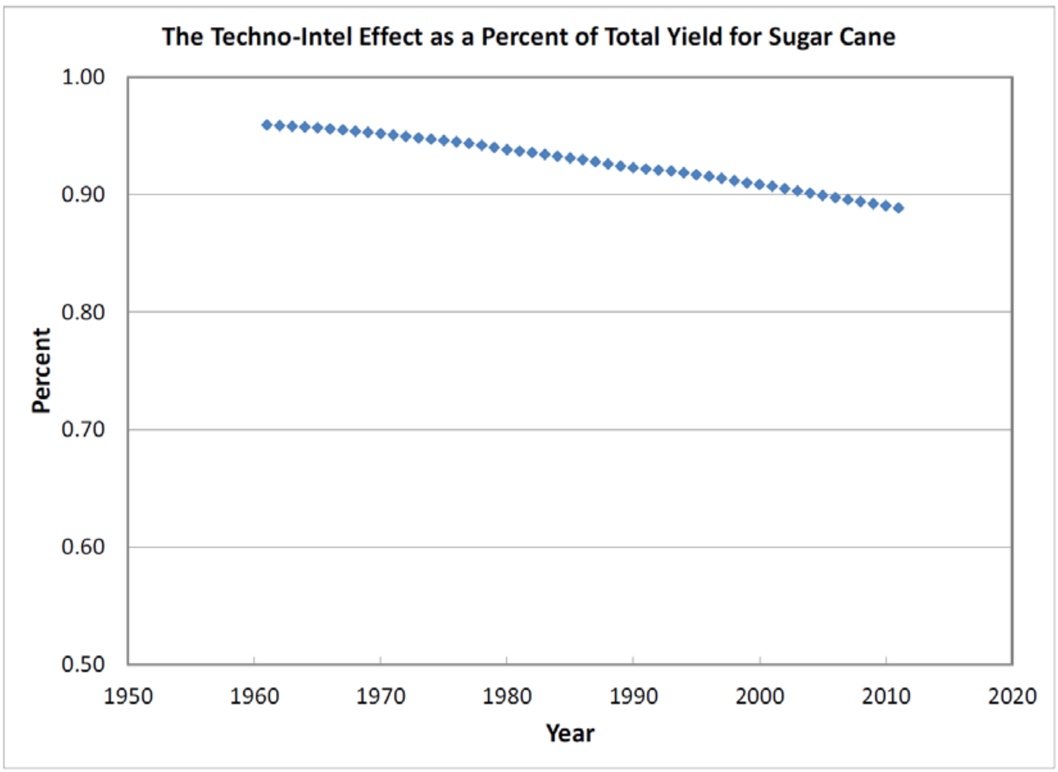

Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

The difference between the techno-intel line and the observed yield line above it represents the annual yield contribution due to rising atmospheric $CO_2$, which difference is also plotted in Figure III-2 as the green line. As depicted there, the relative influence of atmospheric $CO_2$ on the total yield of sugar cane is increasing with time. This fact is further borne out in Figure III-3, where techno-intel yield values are plotted as a percentage of total sugar cane yield. Whereas the influence of technology and intelligence accounted for approximately 96 percent of the observed yield values in the early 1960s, by the end of record in 2011 it accounted for only 89 percent.[120]

[120]The methodology utilized here has been reviewed and validated by independent researchers.

Focusing on the future, the 1961-2011 linear trend of the techno-intel yield line is next projected forward to the year 2050. Depicted as the dashed red line in Figure III-4, this line represents the best estimate that can be made of the effect of technology and innovation on future sugar cane crop yields. Following this step, a second-order polynomial has been fitted to the data depicted in Figure III-3, and this relationship is projected forward in time (Figure III-5) to obtain an estimate of the annual contribution of the techno-intel effect on the total yield through 2050. Next, the total yield for each year between 2012 and 2050 can be calculated by dividing the linear projection of the techno-intel line in Figure III-4 (dashed red line) by the corresponding yearly forecasted percentage contribution of the techo-intel line to the total yield, as depicted by the polynomial projection fit to the data and extended through 2050 in Figure III-5. These resultant values, plotted in Figure III-4 as the dashed blue line, provide an estimate of the total annual crop yield from 2012 through 2050. By knowing the annual total yield, as well as the portion of the annual total yield that is due to the techno-intel effect between 2012 and 2050, the part of the total yield that is due to $CO_2$ can be calculated by subtracting the difference between them. These values are also plotted in Figure III-4 as the dashed green line.

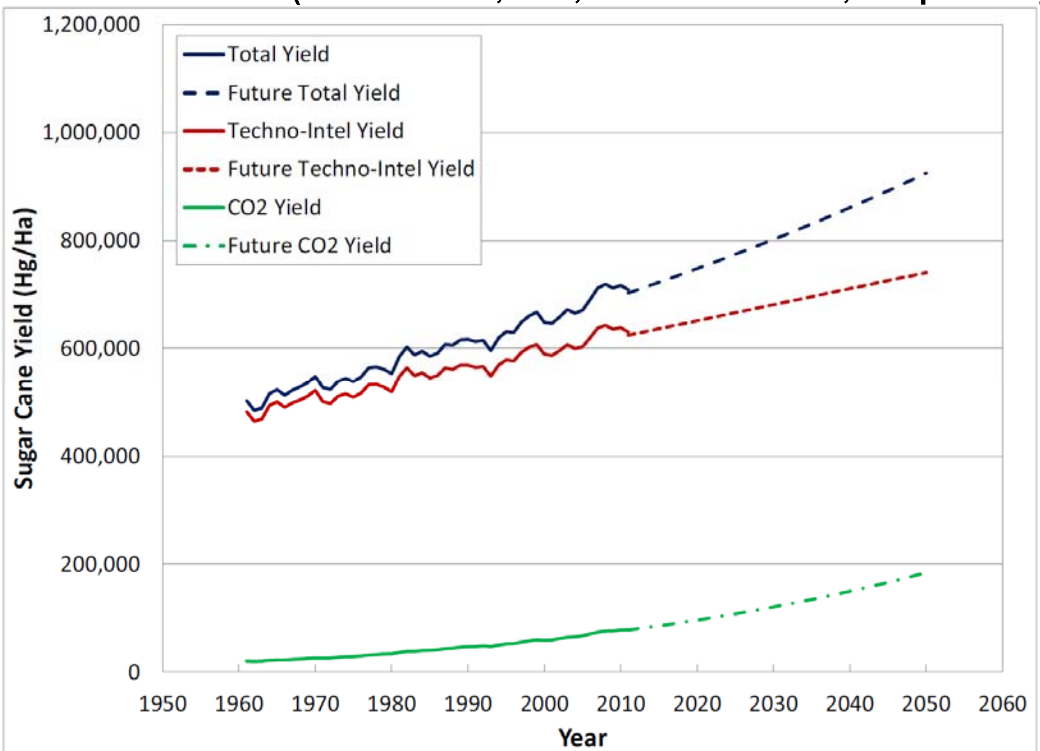
**Figure III-3**
**The Percentage of the Total Annual Yield of Sugar Cane 1961-2011 That Is Attributed to the Techno-Intel Effect**




Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

In order to apply the future estimates of the $CO_2$ influence on crop yields to future estimates of crop production, linear trends in each of the 45 crops' 1961-2011 production data were extended forward in time to provide projections of annual production values through 2050. As with the historical calculations discussed in the previous section, these production values were multiplied by the corresponding annual percentage influence of $CO_2$ on 2012-2050 projected crop yields. The resultant values were then multiplied by an estimated gross production value (in constant 2004-2006 U.S. dollars) for each crop per metric ton. And as there are several potential unknowns that may influence the future production value assigned to each crop, a simple 50-year average of the observed gross production values was applied over the period 1961-2011. The ensuing monetary values for each of the 45 crops over the 2012 through 2050 period are listed in Table III-4.

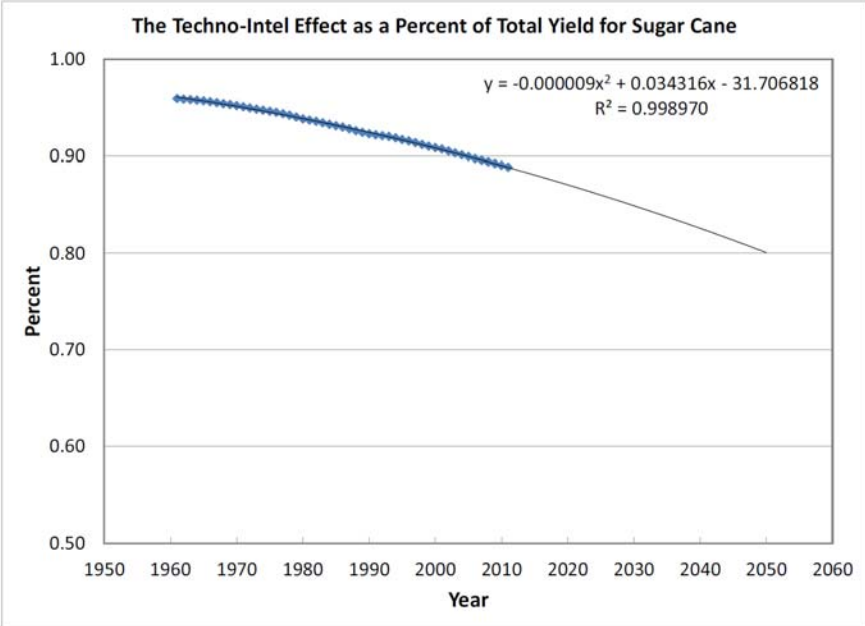
**Figure III-4**
**Same as Figure III-2, but With the Added Projections of the Total Yield and the Portion of the Total Yield Due to the Techno-Intel and $CO_2$ Effects Estimated For the Period 2012-2050 (Dashed Blue, Red, and Green Lines, Respectively).**




Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

The results of the above set of calculations once again reveal a very substantial financial benefit resulting from the effect of Earth's rising atmospheric $CO_2$ concentration on global food production. Over the period 2012 through 2050, the projected benefit amounts to \$9.8 trillion, far surpassing the \$3.2 trillion that was observed in the longer 50-year historic period of 1961-2011.

**Figure III-5**
**Same as Figure III-3, But With a Second Order Polynomial Equation Fit to the 1961-2011 Data, Projecting the Data Forward Through 2050**




Source: Craig Idso, "The Positive Externalities of Carbon Dioxide," 2013.

**Table III-4**
**The Total Monetary Benefit of Earth's Rising Atmospheric $CO_2$ Concentration on Each of the Forty-Five Crops Listed in Table III-1 For the Period 2012-2050**
(Values in Constant 2004-2006 U.S. Dollars)

| Crop | Production Rank | Monetary Benefit of $CO_2$ | Crop | Production Rank | Monetary Benefit of $CO_2$ |
|---|---|---|---|---|---|
| Rice, paddy | 4 | $1,847,162,847,355 | Beans, dry | 33 | $121,672,752,990 |
| Wheat | 2 | $731,810,134,138 | Eggplants (aubergines) | 32 | $121,040,127,404 |
| Soybeans | 11 | $622,840,779,401 | Sugar beet | 6 | $118,016,992,389 |
| Vegetables fresh nes | 9 | $603,158,136,300 | Pears | 41 | $106,648,093,649 |
| Maize | 3 | $582,352,695,047 | Fruit Fresh Nes | 34 | $96,939,989,779 |
| Tomatoes | 12 | $538,622,004,026 | Tangerines, mandarins, clem. | 38 | $94,049,613,976 |
| Grapes | 13 | $507,943,670,190 | Fruit, tropical fresh nes | 44 | $92,676,868,053 |
| Sugar cane | 1 | $366,333,858,080 | Onions, dry | 22 | $83,094,062,469 |
| Apples | 19 | $306,866,752,703 | Sweet potatoes | 10 | $70,623,018,596 |
| Potatoes | 5 | $268,944,859,065 | Cassava | 7 | $66,454,408,155 |
| Yams | 26 | $206,504,638,016 | Pumpkins, squash and gourds | 40 | $65,141,087,416 |
| Bananas | 15 | $200,878,216,972 | Lettuce and chicory | 39 | $54,406,821,316 |
| Rapeseed | 28 | $176,560,583,707 | Coconuts | 20 | $52,278,524,212 |
| Cucumbers and gherkins | 29 | $165,126,686,871 | Sunflower seed | 31 | $50,554,512,301 |
| Oranges | 17 | $165,014,960,801 | Plantains | 25 | $45,996,854,219 |
| Chillies and peppers, green | 37 | $162,527,401,900 | Millet | 23 | $43,337,359,355 |
| Olives | 42 | $157,323,187,194 | Sorghum | 14 | $38,314,226,074 |
| Groundnuts, with shell | 27 | $148,440,689,387 | Other melons (inc.cantaloupes) | 36 | $11,163,081,357 |
| Watermelons | 16 | $144,909,503,686 | Peas, dry | 45 | $10,484,435,272 |
| Barley | 8 | $127,842,645,165 | Pineapples | 43 | $6,926,670,057 |
| Carrots and turnips | 35 | $126,282,174,308 | Rye | 24 | $5,804,121,850 |
| Mangoes, mangosteens, guavas | 30 | $124,067,842,115 | Oats | 21 | $4,904,374,119 |
| Cabbages and other brassicas | 18 | $122,664,616,192 | **Sum of all crops = $9,764,706,877,630** | | |

Source: Craig Idso, “The Positive Externalities of Carbon Dioxide,” 2013.

### III.E. Future $CO_2$ Benefits or Damages: Which is More Likely to Occur?

Although determining the net monetary effect of rising atmospheric $CO_2$ is beyond the scope of this analysis, some general comments can be made with respect to the likelihood of damages or benefits occurring as a result of higher $CO_2$ concentrations in the future.

With respect to damages, as discussed in Chapter IV, it is important to note that all SCC studies rely heavily on computer model projections of future climate and climate-related indices. Analyses of such state-of-the-art models, however, have consistently revealed multiple problems in their abilities to accurately represent and simulate reality.[121] Spencer, for example, has highlighted an important model vs. observation discrepancy that exists for temperatures in the tropical troposphere.[122] In written testimony before the U.S. Environment and Public Works Committee, he noted that the magnitude of global-average atmospheric warming between 1979 and 2012 is only about 50 percent of that predicted by the climate models. He also reported that the temperature trend over the most recent 15-year period was not significantly different from zero (meaning that there has been no temperature rise), despite this being the period of greatest greenhouse gas concentration increase. Lastly, he notes that the level of observed tropical atmospheric warming since 1979 is dramatically below that predicted by climate models. With respect to this last point, Spencer’s graph of mid-tropospheric temperature variations for the tropics (20°N to 20°S) in 73 current (CMIP5) climate models versus measurements made from two satellite and four weather balloon datasets is plotted here as Figure III-6.

The level of disagreement between the models and observations of tropical mid-tropospheric temperatures in Figure III-6 is quite striking. It reveals, for example, that the models’ projected average values are 0.5°C higher than observations at the end of the record. Although these data are restricted to the tropics (from 20°N to 20°S), Spencer notes that “this is where almost 50 percent of the solar energy absorbed by the Earth enters the climate system.”

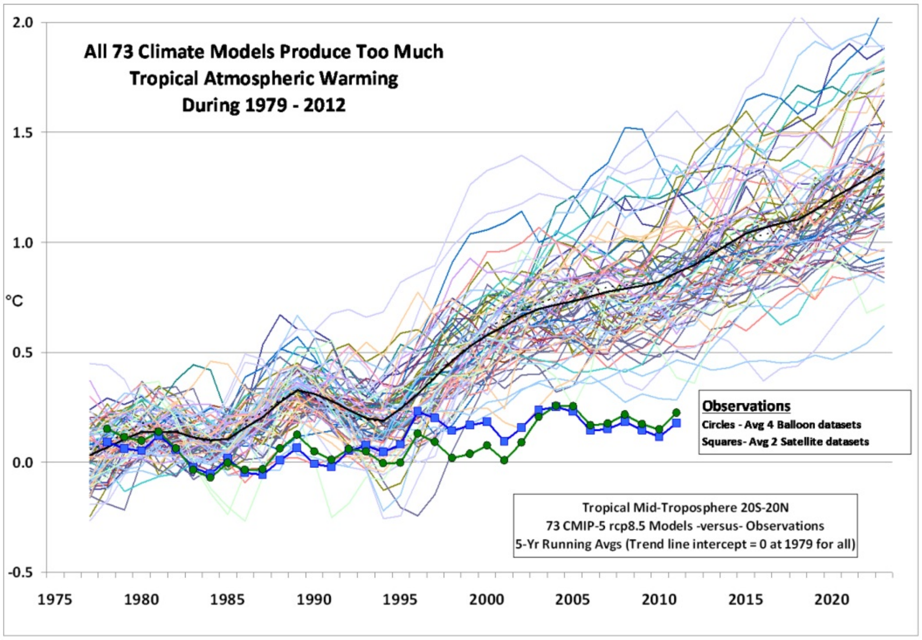
The sensitivity of temperature to carbon dioxide, which is the amount of total warming for a nominal doubling of atmospheric carbon dioxide, is the core parameter that ultimately drives climate model temperature projections. The magnitude of this parameter used in the models is likely the reason for their overestimation of recent (and likely future) projections of temperature observations. Although most models incorporate a mean sensitivity of 3.4°C (range of 2.1 to 4.7°C), several recent studies

[121] A. Lupo and Kininmonth, W., “Global Climate Models and Their Limitations.” In: *Climate Change Reconsidered II: Physical Science.* C.D. Idso, R.M. Carter And S.F. Singer, (Eds.). Chicago, IL: The Heartland Institute, 2013.

[122] R.W. Spencer, “Statement to the Environment and Public Works Committee,” 19 July 2013, Washington, DC.

indicate the true sensitivity is much lower.[123] Until such problems are resolved, SCC damage estimates relying on future temperature projections should be considered to be significantly inflated.

**Figure III-6**
**Mid-tropospheric Temperature Variations For the Tropics (20°N To 20°S) in 73 Current (CMIP5) Climate Models Versus Measurements From Two Satellite Datasets and Four Weather Balloon Datasets**




Source: Spencer, 2013.

In concluding his discussion of the topic, Spencer states "It is time for scientists to entertain the possibility that there is something wrong with the assumptions built into

[123]Annan, J.D. and Hargreaves, J.D., "On the Generation and Interpretation of Probabilistic Estimates of Climate Sensitivity." *Climatic Change* 104: 324-436, 2011; R.S. Lindzen and Choi, Y.-S., "On the Observational Determination of Climate Sensitivity and Its Implications." *Asia-Pacific Journal of Atmospheric Science* 47: 377-390, 2011; A. Schmittner et al., "Climate Sensitivity Estimated From Temperature Reconstructions of the Last Glacial Maximum." *Science* 334: 1385-1388, 2011; Holden M. Aldrin et al., "Bayesian Estimation of Climate Sensitivity Based on a Simple Climate Model Fitted To Observations of Hemispheric Temperature and Global Ocean Heat Content," *Environmetrics* 23: 253-271, 2012; J.C. Hargreaves et al., "Can The Last Glacial Maximum Constrain Climate Sensitivity?" *Geophysical Research Letters* 39: L24702, Doi: 10.1029/ 2012GL053872, 2012; M.J. Ring et al., "Causes of the Global Warming Observed Since the 19th Century." *Atmospheric and Climate Sciences* 2: 401-415, 2012; J.H. Van Hateren, "A Fractal Climate Response Function Can Simulate Global Average Temperature Trends of the Modern Era and the Past Millennium." *Climate Dynamics,* Doi: 10.1007/S00382-012-1375-3, 2012; Lewis, N., "An Objective Bayesian, Improved Approach for Applying Optimal Fingerprint Techniques to Estimate Climate Sensitivity." *Journal of Climate*, Doi: 10.1175/JCLI-D-12-00473.1, 2013; Masters, T., "Observational Estimates of Climate Sensitivity From Changes in the Rate of Ocean Heat Uptake and Comparison to CMIP5 Models. *Climate Dynamics*, Doi:101007/S00382-013-1770-4, 2013; A. Otto et al., "Energy Budget Constraints on Climate Response." *Nature Geoscience* 6, 415-416, 2013.

their climate models. The fact that all of the models have been peer reviewed does not mean that any of them have been deemed to have any skill for predicting future temperatures. In the parlance of the *Daubert* standard for rules of scientific evidence, the models have not been successfully field tested for predicting climate change, and so far their error rate should preclude their use for predicting future climate change."[124]

A somewhat related problem with SCC calculations is their inclusion of costs due to sea level rise. Here, it is presumed that rising temperatures from $CO_2$-induced global warming will result in an acceleration of sea level rise that will result in a host of economic damages. There are two problems with this projection. First, temperatures are not rising in the manner or degree projected by the models. Second, observations reveal no acceleration of sea level rise over the past century. In fact, just the opposite appears to be occurring. For example, Holgate derived a mean global sea level history over the period 1904-2003.[125] According to his calculations, the mean rate of global sea level rise was "larger in the early part of the last century (2.03 ± 0.35 mm/year 1904-1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954-2003)." In other words, contrary to model projections, the mean rate of global sea level rise (SLR) has not accelerated over the recent past. If anything, it has done just the opposite. Such observations are striking, especially considering they have occurred over a period of time when many have claimed that (1) the Earth warmed to a degree that is unprecedented over many millennia, (2) the warming resulted in a net accelerated melting of the vast majority of the world's mountain glaciers and polar ice caps, and (3) global sea level rose at an ever increasing rate.

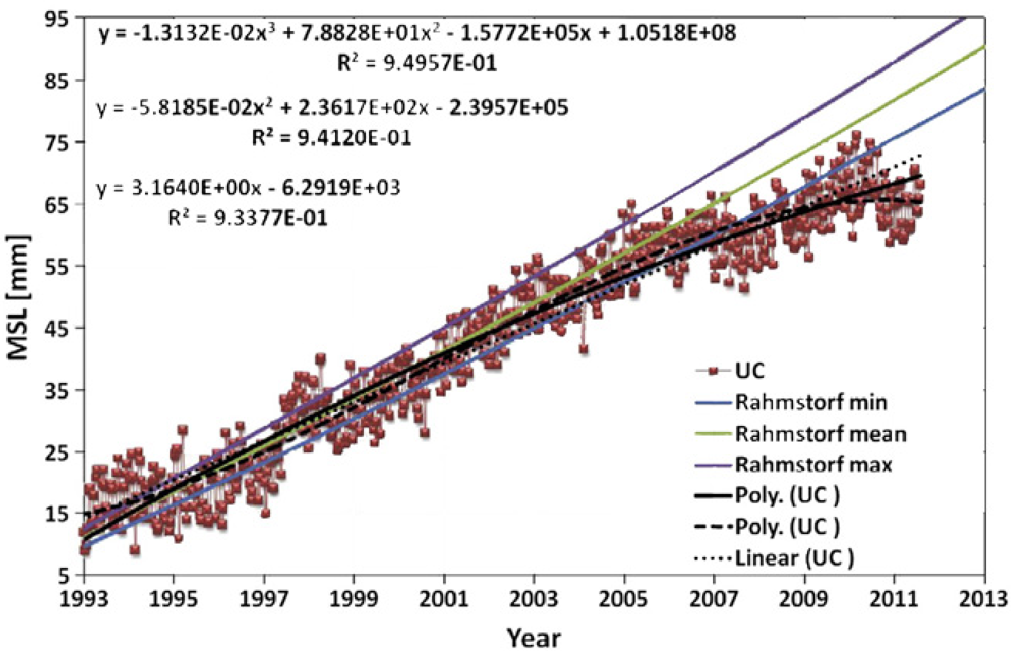
In another paper, Boretti applied simple statistics to the two decades of information contained in the TOPEX and Jason series of satellite radar altimeter data to "better understand if the SLR is accelerating, stable or decelerating." In doing so, the Australian scientist reports that the rate of SLR is reducing over the measurement period at a rate of -0.11637 mm/year$^2$, and that this *de*celeration is *also* "reducing" at a rate of -0.078792 mm/year$^3$ — Figure III-7.[126] In light of such observations, Boretti concludes that the huge deceleration of SLR over the last 10 years "is clearly the opposite of what is being predicted by the models," and that "the SLR's reduction is even more pronounced during the last 5 years."[127] To further illustrate the importance of his findings, he notes that "in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the SLR must be almost 11 mm/year every year for the next 89 years," but he notes that "since the SLR is dropping, the predictions become increasingly unlikely," especially in view of the facts that (1) "not once in the past 20 years has the SLR of 11 mm/year ever been achieved," and that (2) "the average SLR

[124]B.E. Harlow, and Spencer, R.W., "An Inconvenient Burden of Proof? $CO_2$ Nuisance Plaintiffs Will Face Challenges in Meeting the Daubert Standard." *Energy Law Journal* 32: 459-496, 2011.
[125]Holgate, S.J., "On the Decadal Rates of Sea Level Change During the Twentieth Century." *Geophysical Research Letters* 34: 10.1029/2006GL028492, 2007.
[126]Boretti, A.A., "Short Term Comparison of Climate Model Predictions and Satellite Altimeter Measurements of Sea Levels." *Coastal Engineering* 60: 319-322, 2012.
[127]Ibid.

of 3.1640 mm/year is only 20 percent of the SLR needed for the prediction of a one meter rise to be correct."[128]

The real world, data-based results of Holgate and Boretti, as well as those of other researchers, all suggest that rising atmospheric $CO_2$ emissions are exerting no discernible influence on the rate of sea level rise.[129] Clearly, SCC damages that are based on model projections of a $CO_2$-induced acceleration of SLR must be considered inflated and unreliable.

**Figure III-7**
**Comparison of Mean Sea Level (MSL) Predictions From Rahmstorf (2007) With Measurements From the TOPEX and Jason Series***




*Adapted from Boretti (2012) who states in the figure caption that "the model predictions [of Rahmstorf (2007)] clearly do not agree with the experimental evidence in the short term."

Additional observations apply to other model-based projections of economic damages resulting from various climate- and extreme weather-related maladies. As reported in the most recent assessment of the Nongovernmental International Panel on Climate Change, in almost all instances model projections of climate and climate-related

[128]Ibid.
[129]N.A. Morner, "Estimating Future Sea Level Changes From Past Records." *Global and Planetary Change* 40: 49-54, 2004; S. Jevrejeva et al., "Nonlinear Trends and Multiyear Cycles in Sea Level Records." *Journal of Geophysical Research* 111: 10.1029/ 2005JC003229, 2006; G. Wöppelmann et al., "Rates of Sea-Level Change Over the Past Century in a Geocentric Reference Frame." *Geophysical Research Letters* 36: 10.1029/2009GL0 38720, 2009; J.R. Houston, and Dean, R.G., "Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses." *Journal of Coastal Research* 27: 409-417, 2001.

catastrophes are not borne out by observational data.[130] Thus, SCC estimates, which are based on (and even necessitated by) the fulfillment of such computer-projected catastrophes, must be considered highly suspect and inflated. In contrast, the monetary benefits of rising carbon dioxide estimated here are far more likely to result, because they are based on hundreds of laboratory and field observations. It should also be noted that the benefit estimates derived here, although very large, may yet be found to be conservative.

Recognizing these positive impacts of rising $CO_2$ concentrations, some researchers have begun to explore ways in which to increase the influence of atmospheric $CO_2$ on crop yields even more. Many of these efforts are devoted to identifying "super" hybrid cultivars.[131] For example, De Costa et al., for example, grew 16 genotypes of rice (*Oryza sativa* L.) under standard lowland paddy culture with adequate water and nutrients within open-top chambers maintained at either the ambient atmospheric $CO_2$ concentration (370 ppm) or at an elevated $CO_2$ concentration (570 ppm).[132] Their results indicated that the $CO_2$-induced enhancement of the light-saturated net photosynthetic rates of the 16 different genotypes during the grain-filling period of growth ranged from +2 percent to +185 percent in the yala season (May to August) and from +22 percent to +320 percent in the maha season (November to March). Similarly, they found that the $CO_2$-induced enhancement of the grain yields of the 16 different genotypes ranged from +4 percent to +175 percent in the yala season and from -5 percent to +64 percent in the maha season.

In commenting on the findings, the five Sri Lanka researchers say their results "demonstrate the significant genotypic variation that exists within the rice germplasm, in the response to increased atmospheric $CO_2$ of yield and its correlated physiological parameters," and they suggest that "the significant genotypic variation in this response means that genotypes that are highly responsive to elevated $CO_2$ may be selected and incorporated into breeding programs to produce new rice varieties which would be higher yielding in a future high $CO_2$ climate."[133] Selecting such genotypes, as per the results experienced in the De Costa et al. study, has the potential to increase the $CO_2$ monetary benefit per ton of rice by a factor of four or more.

Atmospheric $CO_2$ enrichment also tends to enhance growth and improve plant functions in the face of environmental constraints. For example, Conway and Toenniessen, describe how ameliorating four such impediments to plant productivity – soil infertility, weeds, insects and diseases, and drought – significantly increases crop

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[130] C.D. Idso et al., (Eds.) *Climate Change Reconsidered II: Physical Science.* Chicago, IL: The Heartland Institute, 2013.
[131] L. Yang et al., "Yield Formation of $CO_2$-Enriched Inter-Subspecific Hybrid Rice Cultivar Liangyoupeijiu Under Fully Open-Air Condition in a Warm Sub-Tropical Climate." *Agriculture, Ecosystems and Environment* 129: 193-200, 2009.
[132] W.A. De Costa et al. "Genotypic Variation in the Response of Rice (*Oryza Sativa* L.) to Increased Atmospheric Carbon Dioxide and Its Physiological Basis." *Journal of Agronomy & Crop Science* 193: 117-130, 2007.
[133] Ibid.

yields.[134] Therefore, reducing the negative consequences of each of these yield-reducing factors via human ingenuity should boost crop productivity in an additive manner. And a continuation of the historical increase in the air's $CO_2$ content should boost crop productivity even more.

In the case of soil infertility, many experiments have demonstrated that even when important nutrients are present in the soil in less than optimal amounts, enriching the air with $CO_2$ still boosts crop yields. With respect to the soil of an African farm where their "genetic and agro-ecological technologies" have been applied, for example, Conway and Toenniessen speak of "a severe lack of phosphorus and shortages of nitrogen." Yet even in such adverse situations, atmospheric $CO_2$ enrichment has been reported to enhance plant growth.[135] And if supplemental fertilization is provided as described by Conway and Toenniessen, even larger $CO_2$-induced benefits above and beyond those provided by the extra nitrogen and phosphorus applied to the soil would likely be realized.

In the case of weeds, Conway and Toenniessen speak of one of Africa's staple crops, maize, being "attacked by the parasitic weed Striga (*Striga hermonthica*), which sucks nutrients from roots." This weed also infects many other $C_4$ crops of the semi-arid tropics, such as sorghum, sugar cane and millet, as well as the $C_3$ crop rice, particularly throughout much of Africa, where it is currently one of the region's most economically damaging parasitic weeds. Here, too, studies have shown that atmospheric $CO_2$ enrichment greatly reduces the damage done by this devastating weed.[136]

In the case of insects and plant diseases, atmospheric $CO_2$ enrichment also helps prevent crop losses. For example, in a study of diseased tomato plants infected with the fungal pathogen *Phytophthora parasitica*, which attacks plant roots inducing water stress that decreases yields, the growth-promoting effect of a doubling of the air's $CO_2$ content completely counterbalanced the yield-reducing effect of the pathogen.[137] Similarly, in a review of impacts and responses of herbivorous insects maintained for relatively long periods of time in $CO_2$-enriched environments, as described in some 30-

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[134] G. Conway and G. Toenniessen, "Science for African Food Security." *Science* 299: 1187-1188, 2003.

[135] D.J. Barrett, Richardson, A.E. and Gifford, R.M., "Elevated Atmospheric $CO_2$ Concentrations Increase Wheat Root Phosphatase Activity When Growth is Limited by Phosphorus," *Australian Journal of Plant Physiology,* 25: 87-93, 1998; P.A. Niklaus, Leadley, P.W., Stocklin, J. and Korner, C., "Nutrient Relations in Calcareous Grassland Under Elevated $CO_2$," *Oecologia,* 116: 67-75, 1998; H.Y. Kim, Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M.W. and Gumpertz, M., "Effects of Free-Air CO2 Enrichment And Nitrogen Supply On The Yield Of Temperate Paddy Rice Crops," *Field Crops Research* 83: 261-270, 2003; A. Rogers, Gibon, Y., Stitt, M., Morgan, P.B., Bernacchi, C.J., Ort, D.R. and Long, S.P., "Increased C Availability at Elevated Carbon Dioxide Concentration Improves N Assimilation in a Legume," *Plant, Cell and Environment* 29: 1651-1658, 2006.

[136] J.R. Watling and Press, M.C., "How is the Relationship Between the $C_4$ Cereal *Sorghum Bicolor* and the $C_3$ Root Hemi-Parasites *Striga Hermonthica* and *Striga Asiatica* Affected by Elevated $CO_2$?" *Plant, Cell and Environment* 20: 1292-1300, 1997; J.R. Watling, and Press, M.C., "Infection With the Parasitic Angiosperm *Striga Hermonthica* Influences the Response of the $C_3$ Cereal *Oryza Sativa* to Elevated $CO_2$." *Global Change Biology* 6: 919-930, 2000.

[137] N.S. Jwa, and Walling, L.L., "Influence of Elevated $CO_2$ Concentration on Disease Development in Tomato." *New Phytologist* 149: 509-518, 2001.

plus different studies, Whittaker noted that insect populations, on average, have been unaffected by the extra $CO_2$.[138] And since plant growth is nearly universally stimulated in air of elevated $CO_2$ concentration, Earth's crops should therefore gain a relative advantage over herbivorous insects in a high-$CO_2$ world of the future.

Finally, in the case of drought, there is a nearly universal bettering of plant water use efficiency that is induced by atmospheric $CO_2$ enrichment. For example, Fleisher et al., for example, grew potato plants (*Solanum tuberosum* cv. Kennebec) from "seed tubers" in soil-plant-atmosphere research chambers maintained at daytime atmospheric $CO_2$ concentrations of either 370 or 740 ppm under well-watered and progressively water-stressed conditions.[139] And in doing so, they found that "total biomass, yield, and water use efficiency increased under elevated $CO_2$, with the largest percent increases occurring at irrigations that induced the most water stress." In addition, they report that "water use efficiency was nearly doubled under enriched $CO_2$ when expressed on a tuber fresh weight basis." These results indicate, in the words of the three researchers, that "increases in potato gas exchange, dry matter production and yield with elevated $CO_2$ are consistent at various levels of water stress as compared with ambient $CO_2$," providing what is currently required and what will be even more urgently required as the world's population continues to grow: Significantly enhanced food production per unit of water used.[140]

The same situation exists with respect to excessive heat, ozone pollution, light stress, soil toxicity and most any other environmental constraints. Atmospheric $CO_2$ enrichment generally tends to enhance growth and improve plant functions to minimize or overcome such challenges.[141] As researchers continue to explore these benefits and farmers select cultivars to maximize them, the monetary value of this positive externality of raising the global $CO_2$ concentration of the atmosphere will increase.

It is thus far more likely to expect the monetary benefits of rising atmospheric $CO_2$ to accrue in the future than it is to expect the accrual of monetary damages and that the modern rise in the air's $CO_2$ content is providing a significant economic benefit to global crop production. As Sylvan Wittwer, the father of agricultural research on this topic, so eloquently stated nearly two decades ago:

> "The rising level of atmospheric $CO_2$ could be the one global natural resource that is progressively increasing food production and total biological output, in a

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[138] J.B. Whittaker, "Impacts and Responses at Population Level of Herbivorous Insects to Elevated $CO_2$." *European Journal of Entomology* 96: 149-156, 1999.

[139] D.H. Fleisher et al., "Elevated Carbon Dioxide and Water Stress Effects on Potato Canopy Gas Exchange, Water Use, and Productivity." *Agricultural and Forest Meteorology* 148: 1109-1122, 2008.

[140] There are numerous studies that have produced similar results, including (J. De Luis et al., "Elevated $CO_2$ Enhances Plant Growth in Droughted N2-Fixing Alfalfa Without Improving Water Stress." *Physiologia Plantarum* 107: 84-89, 1999; S. Kyei-Boahen, et al., "Gas Exchange of Carrot Leaves in Response to Elevated $CO_2$ Concentration. *Photosynthetica* 41: 597-603, 2003. 2003; S.H. Kim et al., "Canopy Photosynthesis, Evapotranspiration, Leaf Nitrogen, and Transcription Profiles of Maize in Response to $CO_2$ Enrichment. *Global Change Biology* 12: 588-600, 2003.

[141] Idso and Singer, 2009, op. cit.; Idso and Idso, op. cit.

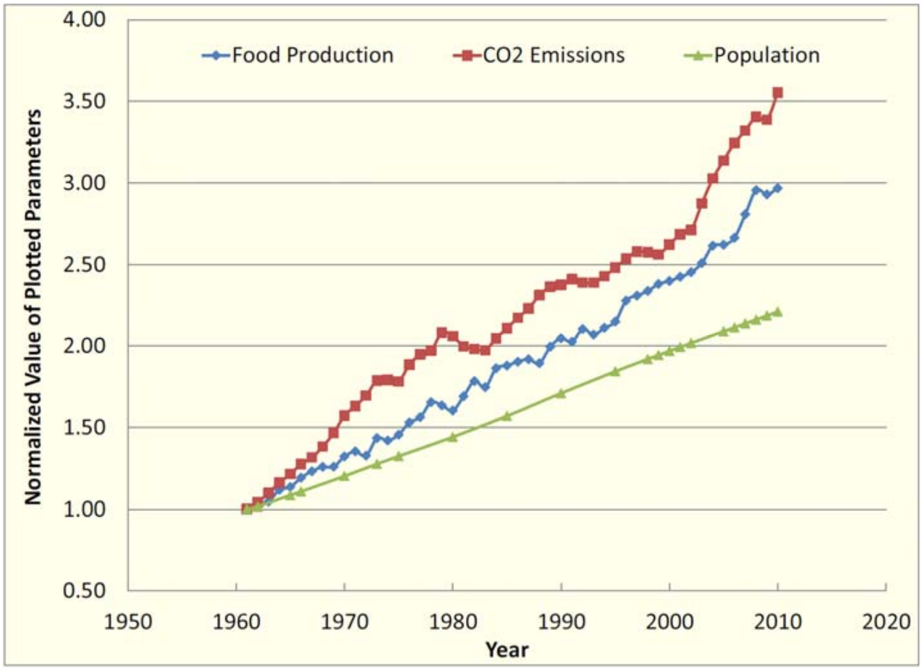
world of otherwise diminishing natural resources of land, water, energy, minerals, and fertilizer. It is a means of inadvertently increasing the productivity of farming systems and other photosynthetically active ecosystems. The effects know no boundaries and both developing and developed countries are, and will be, sharing equally," for "the rising level of atmospheric $CO_2$ is a universally free premium, gaining in magnitude with time, on which we all can reckon for the foreseeable future".[142]

The relationship described above by Wittwer is illustrated below in Figure III-8, where data pertaining to atmospheric $CO_2$ emissions, food production, and human population are plotted. Standardized to a value of unity in 1961, each of these datasets has experienced rapid and interlinked growth over the past five decades. Rising global population has led to rising $CO_2$ emissions and rising $CO_2$ emissions have benefited food production.

The very real positive externality of inadvertent atmospheric $CO_2$ enrichment must be considered in all studies examining the SCC, and its observationally-deduced effects must be given premier weighting over the speculative negative externalities presumed to occur in computer model projections of global warming. Until that time, little if any weight should be placed on current SCC estimates and dire predictions derived from them.

**Figure III-8**
**Global Population, $CO_2$ Emissions, and Food Production Data Over the Period 1961-2010, Normalized to a Value of Unity at 1961***

[142]S.H. Wittwer, "*Food, Climate, and Carbon Dioxide: The Global Environment and World Food Production*." Lewis Publishers, Boca Raton, FL, 1995.



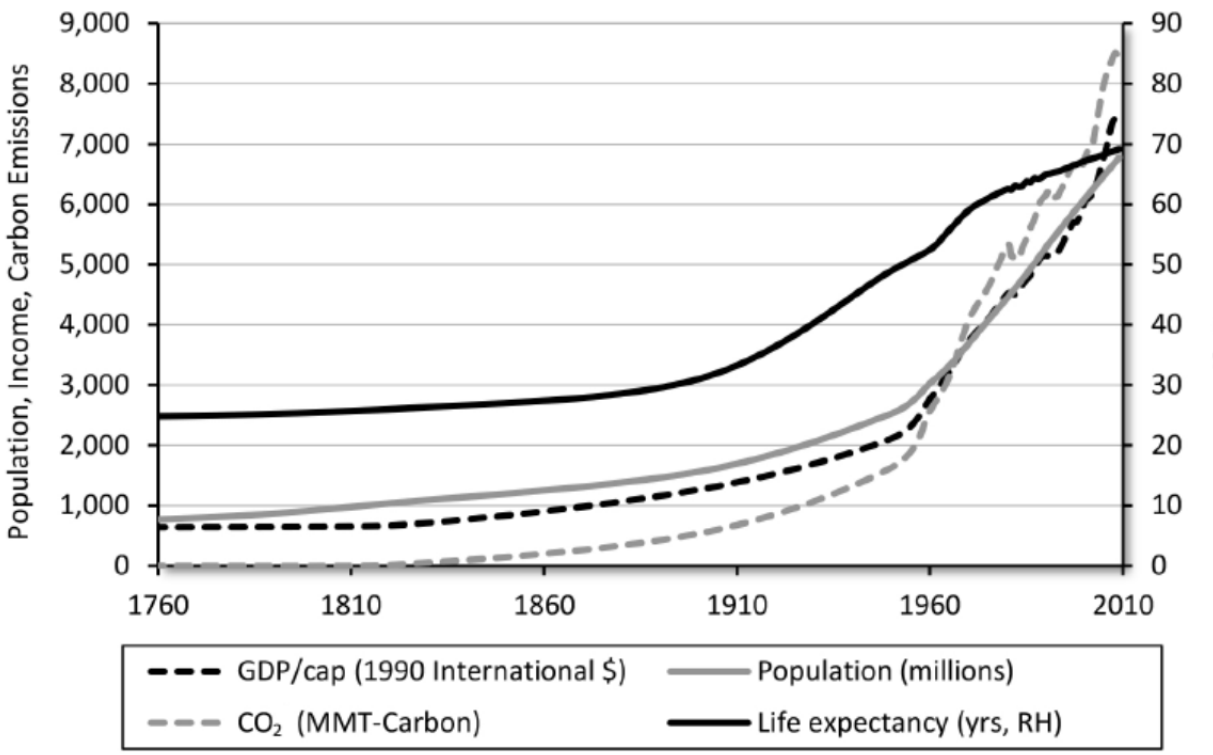

*Food production data represent the total production values of the forty-five crops that supplied 95% of the total world food production over the period 1961-2011, as listed in Table III-1.

# IV. CARBON BENEFITS COMPARED TO CARBON COSTS

## IV.A. Fossil Fuels, $CO_2$, and World GDP

In Chapter II, we noted the critical role played by fossil fuels in the development of the world economy over the past two centuries.[143] This was summarized in Figure II-5, reproduced below as Figure IV-1, which illustrates the relationship between GDP per capita and the $CO_2$ emissions resulting from fossil fuel utilization.

**Figure IV-1**
**Global Progress, 1760–2009 — as Indicated by Trends in World Population, GDP Per Capita, Life Expectancy, and $CO_2$ Emissions From Fossil Fuels**




Source: Goklany, 2012.

There may be an imperfect link between fossil fuel consumption and GDP and, as discussed in Section IV.D, marginal benefits differ from average benefits and not all energy is fossil-based. Nevertheless:

[143]As noted in Section II.B, not all of future world energy will be derived from fossil fuels. See the discussion in Section IV.D.

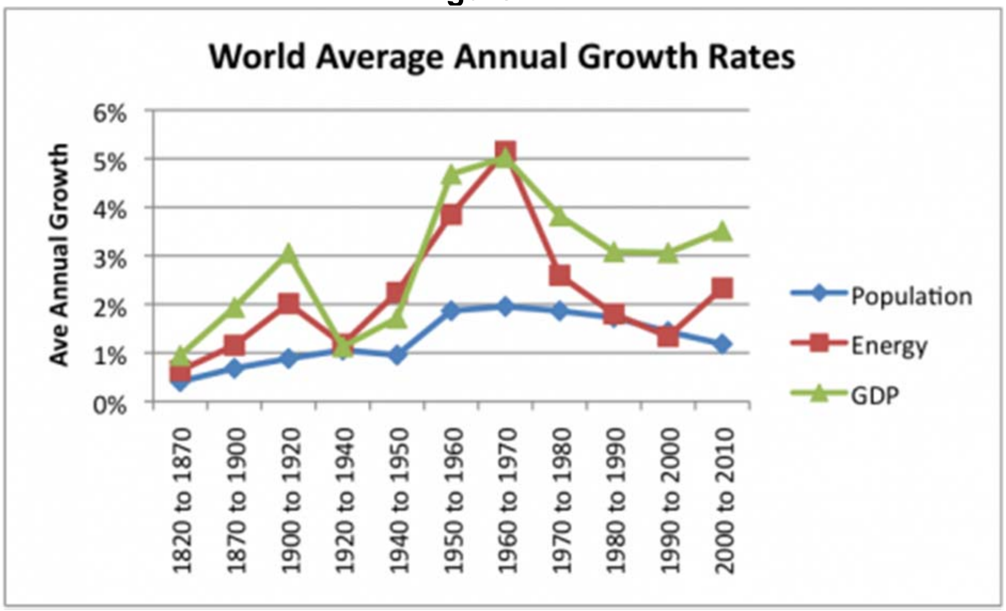
- As Vaclav Smil states: "The most fundamental attribute of modern society is simply this: Ours is a high energy civilization based largely on combustion of fossil fuels."[144]
- As Robert Ayres concludes: "The rather standard assumption that economic growth is independent of energy availability must be discarded absolutely. It is not tenable. It implies, wrongly, that energy-related emissions (GHGs) can be reduced or eliminated without consequences for growth."[145]
- As James Brown, et al. conclude: "The bottom line is that an enormous increase in energy supply will be required to meet the demands of projected population growth and lift the developing world out of poverty without jeopardizing current standards of living in the most developed countries."[146]
- As David Stern finds, "The theoretical and empirical evidence indicates that energy use and output are tightly coupled, with energy availability playing a key role in enabling growth. Energy is important for growth because production is a function of capital, labor, and energy, not just the former two or just the latter as mainstream growth models or some biophysical production models taken literally would indicate."[147]
- And Robert Ayres and Benjamin Warr find that economic growth in the past has been driven primarily not by "technological progress" in some general and undefined sense, but specifically by the availability of ever cheaper energy – and useful work – from coal, petroleum, or gas."[148]

Gail Tverberg notes that historical estimates of energy consumption, population, and GDP are available for many years, and she also found a close connection between energy growth, population growth, and economic growth.[149] She utilized the population and GDP estimates of Angus Maddison and the energy estimates of Vaclav Smil, BP, EIA, and other sources to estimate average annual growth rates for various historical periods – Figure IV-2. Using these data, she explored the implications of reducing fossil fuel use by 80 percent by 2050 and rapidly ramping up renewables at the same time –

[144]Vaclav Smil, *Energy at the Crossroads: Global Perspectives and Uncertainties*, MIT Press, 2005.
[145]Robert U. Ayres, Jeroen C.J.M. van don Bergh, Dietmar Lindenberger, and Benjamin Warr, "The Underestimated Contribution of Energy to Economic Growth," INSEAD, Fontainebleau, France, 2013.
[146]James H. Brown, William R. Burnside, Ana D. Davidson, John P. DeLong, William C. Dunn, Marcus J. Hamilton, Jeffrey C. Nekola, Jordan G. Okie, Norman Mercado-Silva, William H. Woodruff, and Wenyun Zuo, "Energetic Limits to Economic Growth," *BioScience*, January 2011, Vol. 61, No. 1.
[147]David I. Stern, "The Role of Energy in Economic Growth," The United States Association for Energy Economics and the International Association for Energy Economics, USAEE-IAEE WP 10-055, November 2010.
[148]Robert U. Ayres and Benjamin Warr, *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*, Northampton, MA: Edward Elgar. 2009.
[149]Gail Tverberg, "An Energy/GDP Forecast to 2050," http://www.resilience.org/stories/2012-08-14/energygdp-forecast-2050.

an unrealistic, but widely advocated goal.[150] The question she posed is "If we did this, what would such a change mean for GDP, based on historical energy and GDP relationships back to 1820?"[151]

**Figure IV-2**




Source: Tverberg, 2012

She utilized regression analysis to create what she termed a "best-case" estimate of future GDP if a decrease in energy supply of the magnitude hypothesized were to take place. She considered it a best-case scenario because it assumes that the patterns observed on the up-slope of the trends will continue on the down-slope. For example, it assumes that financial systems will continue to operate as currently, international trade will continue as in the past, and that there will not be major problems with overthrown governments or interruptions to electrical power. It also assumes that the world will continue to transition to a service economy, and that there will be continued growth in energy efficiency.

Her results are sobering. Specifically, based on her regression analysis she found that, with the assumptions made:[152]

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[150]The idea of reducing world fossil fuel use 80 percent by 2050 may be unrealistic, but it is a widely advocated goal. See, for example: European Commission, "Roadmap For Moving to a Low-Carbon Economy in 2050," Brussels, March 2011; Jane C. S. Long and Jeffery Greenblatt, "The 80% Solution: Radical Carbon Emission Cuts for California," *Issues in Science and Technology*, September 2012; U.S. National Academies of Science, *Transitions to Alternative Vehicles and Fuels*, Washington, D.C., National Academies Press, 2013; World Energy Council, "Goal of Fossil Fuel Independence by 2050," 2013, www. worldenergy.org/wp-content/uploads/2013/09/ Pack-Leaders-goals-A4.pdf.
[151]Tverberg, op. cit.
[152]Ibid.

- World per capita energy consumption in 2050 would be about equal to world per capita energy consumption in 1905.
- World economic growth would average a negative 0.59 percent per year between 2012 and 2050, meaning that the world would be more or less in perpetual recession through 2050. Given past relationships, this would be especially the case for Europe and the U.S.
- Per capita GDP would decline by 42 percent for the world between 2010 and 2050, on average.
- The decrease in per capita GDP would likely be greater in higher income countries, such as the U.S. and Europe, because a more equitable sharing of resources between rich and poor nations would be needed, if the poor nations are to have enough of the basics.

Since, as noted, these are optimistic best case estimates, it is likely that fossil fuel reductions of this magnitude by 2050 would more likely result in decreases in world per capita GDP in the range of 50 – 70 percent. As Tverberg notes, "The issue of whether we can really continue transitioning to a service economy when much less fuel in total is available is also debatable. If people are poorer, they will cut back on discretionary items. Many goods are necessities: Food, clothing, basic transportation. Services tend to be more optional — getting one's hair cut more frequently, attending additional years at a university, or sending grandma to an Assisted Living Center. So the direction for the future may be toward a mix that includes fewer, rather than more, services, and so will be more energy intensive."[153]

Further, she asks "If our per capita energy consumption drops to the level it was in 1905, can we realistically expect to have robust international trade, and will other systems hold together? While it is easy to make estimates that make the transition sound easy, when a person looks at the historical data, making the transition to using less fuel looks quite difficult, even in a best-case scenario." She concludes that such a worldwide reduction in fossil fuels is "very unlikely."[154]

Using similar data, Robert Zubrin analyzed the relationship between global GDP per capita and carbon use from 1800 through 2010.[155] He found that the relationship is generally linear, with GDP per capita and carbon use both increasing by a factor of ten between 1910 and 2010. What is even more important, however, is the fact that the carbon-use benefits identified are enormous. Zubrin notes that just in the past 55 years — well within living memory — in line with a fourfold increase in carbon use, the average global GDP per capita has quadrupled. Accordingly, "That is an economic

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[153] Ibid.

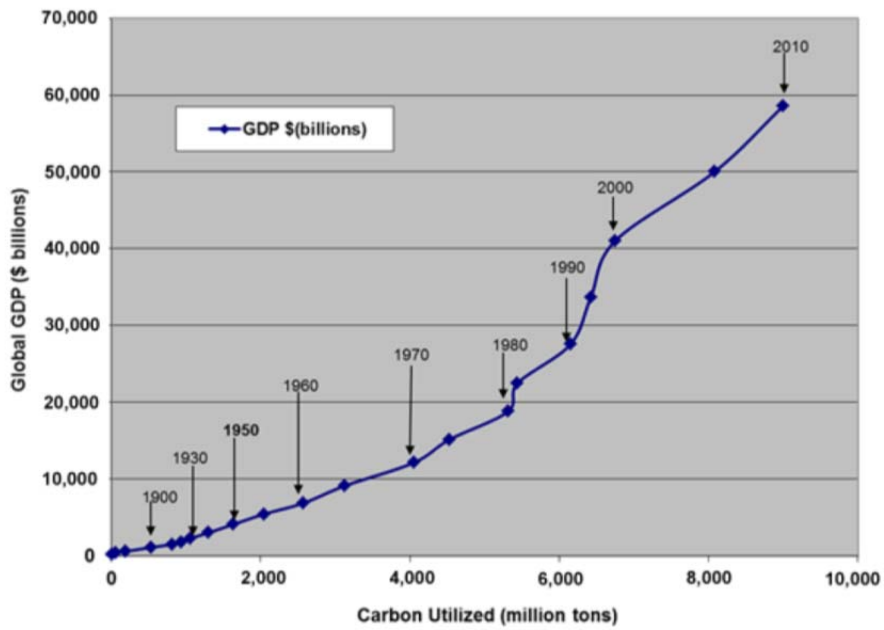
[154] Ibid. For an illustration of the difficulties of implementing even minimally restrictive carbon policies, see Roger H. Bezdek, "Carbon Policy Around the Globe: Degrees of Disaster," presented at The Energy Council 2013 Global Energy and Environmental Issues Conference, Lake Louise, Alberta, Canada, December 2013.

[155] Robert Zubrin, "The Cost of Carbon Denial," *National Review*, July 31, 2013.

miracle that has lifted billions of people out of hopeless poverty — and not just in the Third World."[156]

To assess the economic value of fossil fuels in dollar terms, Zubrin compared absolute GDP to carbon utilization — Figure IV-3. This illustrates that "The relationship between GDP and carbon utilization is not merely linear, but is more nearly quadratic, with total economic output rising as roughly the square of carbon use."[157] For example, Zubrin estimates that since 1975, carbon use has doubled, in conjunction with a quadrupling of global GDP. Further, taking the ratio of current global GDP to carbon use and dividing it out indicates that, at present, each ton of carbon used produces about $6,700 of global GDP.[158]

**Figure IV-3**
**Global GDP vs. Carbon Utilization, 1800 - 2010**
(2010 Dollars)




Source: Zubrin, 2013.

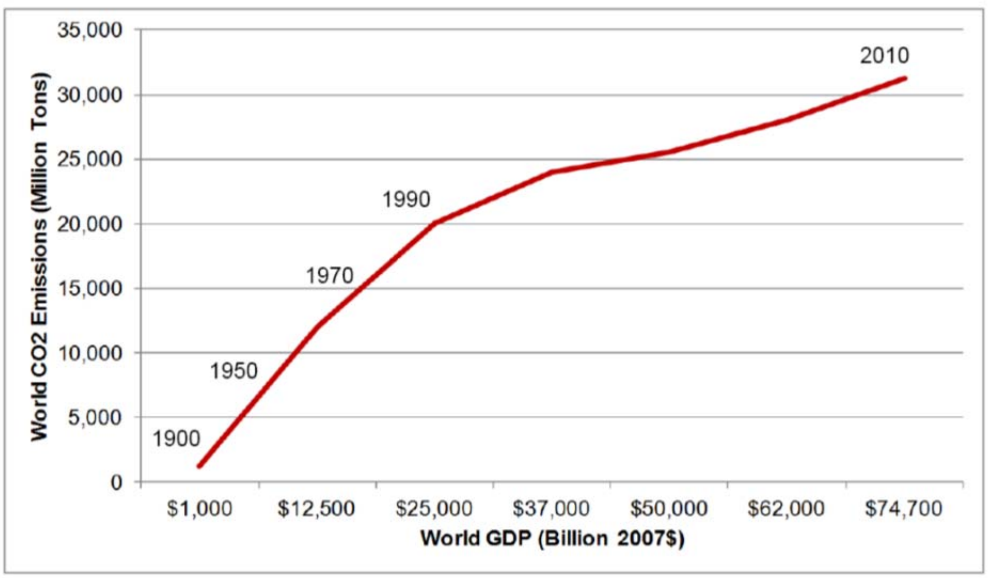
Zubrin thus estimates that each ton of carbon denied to the world economy destroys about $6,700 worth of wealth, and: "That is the difference between life and death for a Third World family. Seven tons denied corresponds to a loss of $47,000, or

[156]Zubrin concludes: "To claim that this came at a comparable "social cost," one would have to show that there has been a climatic catastrophe. Has there? How much better was the weather in the 1950s than it is today? If you don't know, there are plenty of people who were around then whom you can ask. But I'll save you the trouble. The answer is: Not at all. So there was no climatic social cost to the carbon-driven miracle of the 20th century, but there would have been economic cost of genocidal dimensions had carbon deniers been around and able to prevent it." Ibid.
[157]Zubrin, ibid.
[158]Specifically, Zubrin used the ratio of a recent estimate of global GDP ($60 trillion) to carbon use (9 billion tons) to derive the estimate of about $6,700. Ibid.

a good American job. Since 2007, the combination of high oil prices and a depressed economy has reduced the United States' use of carbon in the form of oil by about 130 million tons per year. At a rate of $6,700 per ton, this corresponds to a GDP loss of $870 billion, equivalent to losing 8.7 million jobs, at $100,000 per year each. Were we to implement the program of the Kyoto treaty, and constrict global carbon use to 1990 levels, we would cut global GDP by $30 trillion per year, destroying an amount of wealth equal to the livelihood of half of the world's population. Such are the costs of carbon denial."[159]

In this chapter we are concerned with comparing the Social Cost of Carbon (SCC) as defined by the IWG[160] with the social or economic benefits produced by the fossil fuels which generate $CO_2$. Accordingly, to conform to IWG conventions we use $CO_2$ emissions rather than carbon emissions,[161] and we utilize EIA and IEA economic data normalized to 2007 dollars to be consistent with the base year dollars used by the IWG in developing its SCC estimates. The relationship between world GDP and $CO_2$ emissions over the past century is illustrated in Figure IV-4. This figure shows a similar strong relationship between world GDP and the $CO_2$ emissions from fossil fuels as indicated in Figures IV-1 through IV-3.

**Figure IV-4**
**Relationship Between World GDP and $CO_2$ Emissions**




Source: U.S. Energy Information Administration, International Energy Agency, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

[159]Ibid.
[160]U.S. Government Interagency Working Group, 2010 and 2013, op. cit.
[161]A ton of $CO_2$ contains 0.2727 tons of carbon.

## IV.B. $CO_2$ Benefits and Costs in 2010

Basically, Figure IV-4 shows that in 2010, expressed in 2007 dollars, a ton of $CO_2$ resulting from fossil fuel utilization “created” about $2,400 in world GDP. This is a reasonable and defensible estimate of the indirect benefit of $CO_2$ – indirect because it is the result of the energy produced by the fossil fuels from which the $CO_2$ derives.[162] It thus does not include the direct $CO_2$ benefits discussed in Chapter III. We can compare these indirect benefits with the SCC estimates derived by the IWG.

As discussed in Chapter V, the SCC is an estimate of the monetized damages associated with an incremental increase in carbon (or $CO_2$) emissions in a given year. That is, it is the increase in aggregate income that would make society just as well off as a one unit decrease in carbon emissions in a particular year.[163] The IWG selected four SCC values for use in regulatory analyses, and the benefits from reduced $CO_2$ emissions can be estimated by multiplying changes in emissions in any year by the SCC value for that year.[164] To estimate SCC, the IWG used three discount rates to span a range of “certainty-equivalent” constant discount rates:

- 2.5 percent per year, which was selected to incorporate concern that interest rates are highly uncertain over time,
- 3.0 percent per year, which was selected because it is consistent with estimates in the economics literature and OMB Circular A-4 guidance for the consumption rate of interest,[165] and
- 5.0 percent per year, which was selected to represent the possibility climate damages are positively correlated with market returns.

In addition, the IWG included a fourth extreme value: “The 95th percentile at a 3.0 percent discount rate, representing higher than-expected economic impacts further out in the tails of the distribution.”[166]

As discussed in Chapter V, the first IWG SCC estimates were published in February 2010, but these were subsequently revised significantly upward in May 2013.[167] The most recent SCC estimates are given in Table IV-1 and the original

[162]See the discussion at the beginning of Section IV.A.

[163]It includes (but is not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. See Interagency Working Group on Social Cost of Carbon, United States Government, “Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866,” May 2013; Interagency Working Group on Social Cost of Carbon, United States Government, “Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866,” February 2010; and Charles Griffiths, “The Social Cost of Carbon for Regulatory Impact Analyses, the National Center for Environmental Economics, February 17, 2011.

[164]Ibid.

[165]U.S. Office of Management and Budget, “Regulatory Impact Analysis: A Primer,” Circular A-4, September 17, 2003.

[166]Interagency Working Group, op. cit.

[167]Prior to 2010 the “official” U.S. government SCC estimate was, presumably, zero.

estimates are given in Table IV-2. Table IV-I shows that the revised (2013) SCC estimates for 2010 are (in 2007 dollars):

- 5.0% — $11,
- 3.0% — $33,
- 2.5% — $52, and
- 3.0% 95th — $90.

Table IV-2 shows that the original (2010) SCC estimates for 2010 are (in 2007 dollars):

- 5.0% — $4.7,
- 3.0% — $21.4,
- 2.5% — $35.1, and
- 3.0% 95th — $64.9.

**Table IV-1**
**Revised (2013) Social Cost of CO2, 2010 – 2050**
(In 2007 dollars per metric ton of $CO_2$)

| Discount Rate Year | 5.0% Avg | 3.0% Avg | 2.5% Avg | 3.0% 95th |
|---|---|---|---|---|
| 2010 | 11 | 33 | 52 | 90 |
| 2015 | 12 | 38 | 58 | 109 |
| 2020 | 12 | 43 | 65 | 129 |
| 2025 | 14 | 48 | 70 | 144 |
| 2030 | 16 | 52 | 76 | 159 |
| 2035 | 19 | 57 | 81 | 176 |
| 2040 | 21 | 62 | 87 | 192 |
| 2045 | 24 | 66 | 92 | 206 |
| 2050 | 27 | 71 | 98 | 221 |

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2013.

**Table IV-2**
**Original (2010) Social Cost of CO2, 2010 – 2050**
(In 2007 dollars per metric ton of $CO_2$)

| Discount Rate<br>Year | 5%<br>Avg | 3%<br>Avg | 2.5%<br>Avg | 3%<br>95th |
|---|---|---|---|---|
| 2010 | 4.7 | 21.4 | 35.1 | 64.9 |
| 2015 | 5.7 | 23.8 | 38.4 | 72.8 |
| 2020 | 6.8 | 26.3 | 41.7 | 80.7 |
| 2025 | 8.2 | 29.6 | 45.9 | 90.4 |
| 2030 | 9.7 | 32.8 | 50.0 | 100.0 |
| 2035 | 11.2 | 36.0 | 54.2 | 109.7 |
| 2040 | 12.7 | 39.2 | 58.4 | 119.3 |
| 2045 | 14.2 | 42.1 | 61.7 | 127.8 |
| 2050 | 15.7 | 44.9 | 65.0 | 136.2 |

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2010.

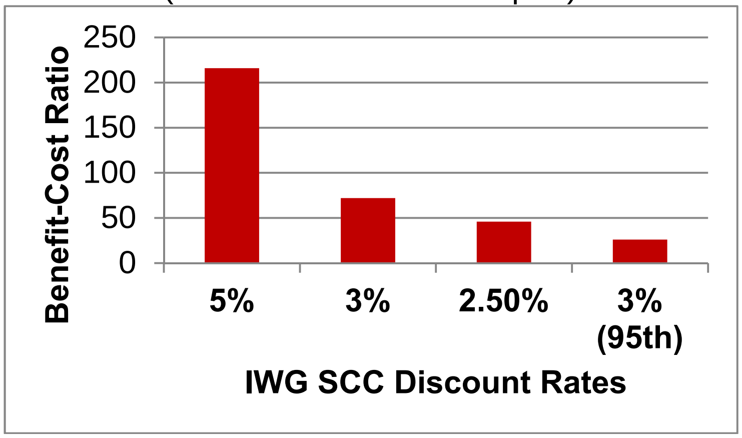
Combining this information with that shown in Figure IV-4 permits the derivation of $CO_2$ benefit-cost (B-C) ratios, which are simply the ratio of $CO_2$ benefits to $CO_2$ costs in a particular year. A B-C ratio is derived by dividing the benefit estimate by the cost estimate: A ratio of less than 1.0 indicates that costs outweigh benefits, and a B-C ratio greater than one indicates that benefits exceed costs.[168]

The $CO_2$ B-C ratios for 2010 based on the 2013 IWG report are shown in Figure IV-5 and the $CO_2$ B-C ratios for 2010 based on the 2010 IWG report are shown in Figure IV-6. These figures indicate that $CO_2$ benefits exceed any estimates of $CO_2$ costs by – literally — orders of magnitude:

- Based on the 2013 IWG report, the B-C ratios for the three discount rates range between about 50-to-1 and 250-to-1.
- Based on the 2010 IWG report, the B-C ratios for the three discount rates range between about 70-to-1 and 500-to-1.
- Even using the extreme 3.0% 95$^{th}$ estimates, the B-C ratios range between about 30-to-1 and 40-to-1.

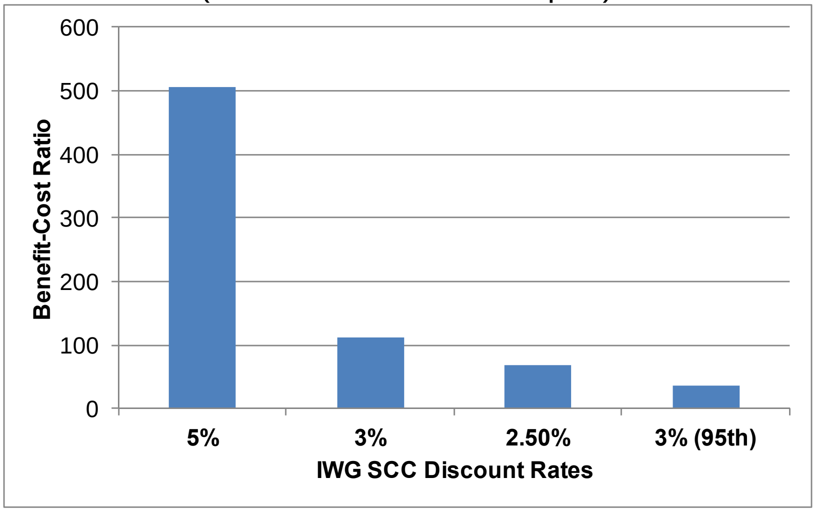
[168]See, for example, Gerald Shively and Marta Galopin, "An Overview of Benefit-Cost Analysis," Purdue University, www.agecon.purdue.edu/staff/shively/COURSES/AGEC406/reviews/bca.htm.

**Figure IV-5**
**2010 $CO_2$ Benefit-Cost Ratios**
(Based on 2013 IWG Report)




Sources: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

**Figure IV-6**
**2010 $CO_2$ Benefit-Cost Ratios**
(Based on 2010 IWG Report)




Sources: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

It should be noted that, normally, B-C ratios in the range of 2-to-1 or 3-to-1 are considered very favorable.[169] Thus, in other words, the 2010 benefits of $CO_2$ overwhelmingly outweigh the estimated $CO_2$ costs no matter which IWG report or discount rates are used. In fact, for 2010, any of the IWG SCC estimates are relatively so small as to be in the statistical noise of the estimated $CO_2$ benefits.

### IV.C. Future $CO_2$ Costs and Benefits

Section IV.B indicates that recent and current $CO_2$ benefits are orders of magnitude larger than any SCC estimates. Since much of the relevant SCC debate concerns future emissions, future potential costs, and future policies, here we analyze forecast $CO_2$ benefits compared to available SCC forecasts. We thus examine forecasts of world economic growth, fossil fuel utilization, and $CO_2$ emissions.

IEA notes that its forecasts are highly sensitive to the underlying assumptions about the rate of growth of GDP; that is, GDP growth requires energy and energy demand is driven by economic growth.[170] IEA assumes that world GDP, in purchasing power parity (PPP), will grow by an average of 3.5 percent annually over the period 2010-2035.[171] It finds that most forecasts of economic growth at the world level and regional levels over the long terms fall within a relatively narrow range, even if there may be significant divergence between countries.[172]

Similarly, as shown in Figure IV-7, EIA forecasts that from 2010 to 2040, real world GDP growth averages 3.6 percent in its Reference case.[173] The growth rate slows over the period, peaking at 4.0 percent between 2015 and 2020 and declining to 3.5 percent between 2020 and 2040. Global economic growth in the Reference case is led by the emerging economies: Real GDP growth from 2010 to 2040 averages 4.7 percent for the non-OECD region, compared with 2.1 percent for the OECD region — Figure IV-8. Slower global economic growth after 2020 is primarily a result of slower growth in the emerging economies, particularly China.

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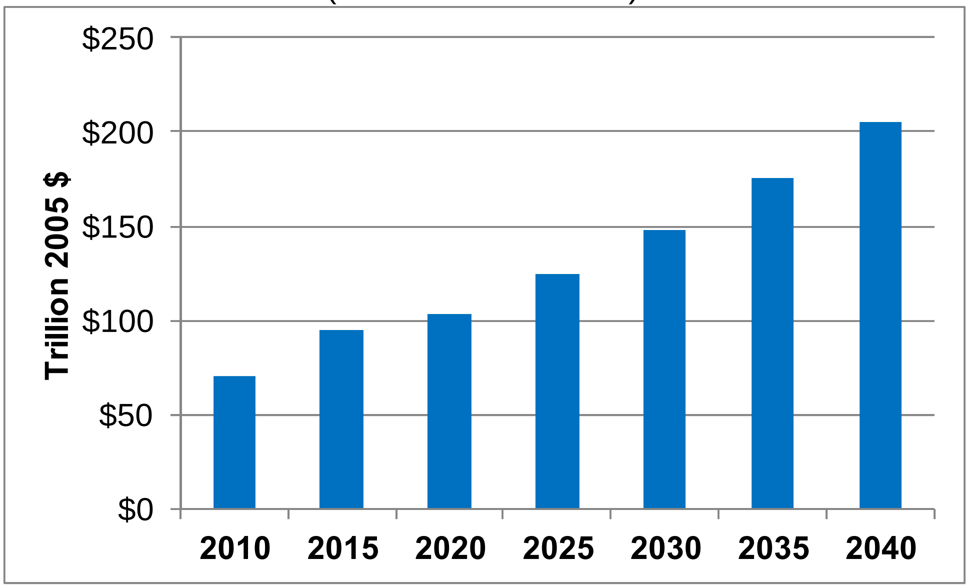
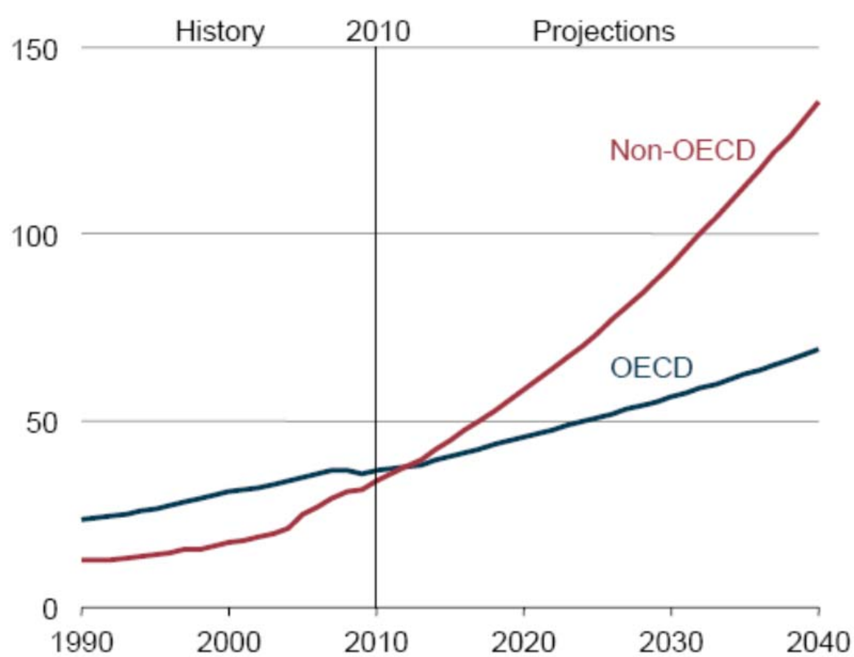
[169]Ibid.
[170]International Energy Agency, *World Energy Outlook*, 2012, op. cit.
[171]Ibid.
[172]IEA bases its medium-term GDP growth assumptions primarily on IMF forecasts, and its longer term GDP assumptions are based on forecasts made by various economic forecasting organizations, as well as IEA's assessment of prospects for the growth in labor supply and improvements in productivity.
[173]On a purchasing power parity (PPP) basis. U.S. Energy Information Administration, *International Energy Outlook*, op. cit.

**Figure IV-7**
**World GDP Forecast**
(EIA Reference Case)




Source: U.S. Energy Information Administration.

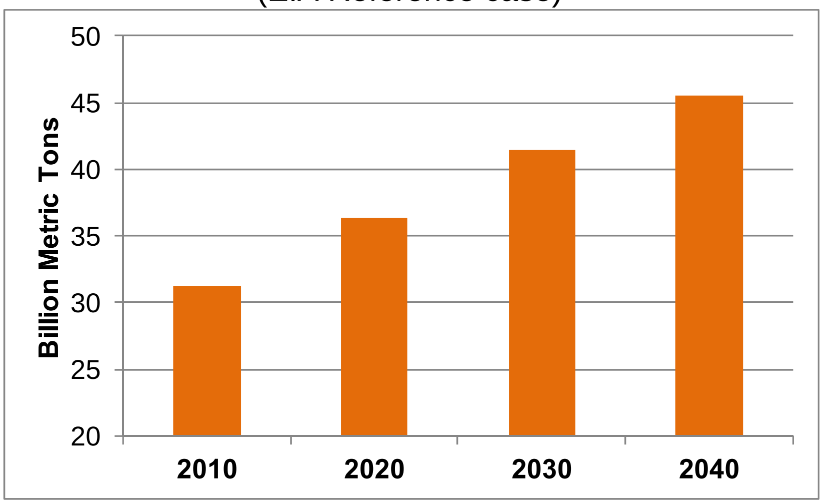
**Figure IV-8**
**World total GDP by Region 1990-2040**
(Trillion 2005 dollars — EIA Reference Case)




Source: U.S. Energy Information Administration.

EIA notes that energy-related carbon dioxide emissions — emissions produced through the combustion of liquid fuels, natural gas, and coal — account for much of the world's anthropogenic greenhouse gas emissions (GHG).[174] And, as a result, energy consumption is an important component of the global climate change debate. In the EIA *IEO 2013* Reference case, which does not assume new policies to limit GHG, world energy-related carbon dioxide emissions increase from 31.2 billion metric tons in 2010 to 36.4 billion metric tons in 2020 and to 45.5 billion metric tons in 2040 – Figure IV-9.

**Figure IV-9**
**Forecast World Energy-related $CO_2$ Emissions**
(EIA Reference case)




Source: U.S. Energy Information Administration.

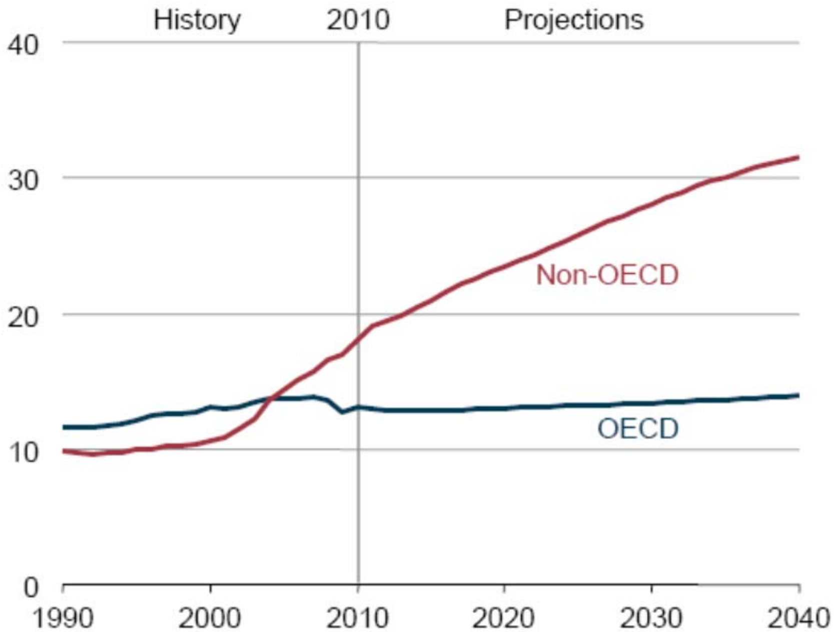
As shown in Figure IV-10, EIA forecasts that much of the growth in $CO_2$ emissions is attributed to the developing non-OECD nations that continue to rely heavily on fossil fuels to meet rapidly growing energy demand. Non-OECD carbon dioxide emissions total 31.6 billion metric tons in 2040, or 69 percent of the world total. In comparison, OECD $CO_2$ emissions total 13.9 billion metric tons in 2040 — 31 percent of the world total. EIA also cautions that near-term events can have a substantial impact on year-to-year changes in energy use and the corresponding $CO_2$ emissions, and notes that recent years have seen fluctuations in economic growth and, as a result, energy demand and $CO_2$ emissions.[175]

During the 2008-2009 global economic recession, world energy consumption contracted, and as a result total world carbon dioxide emissions in 2009 were about one percent lower than in 2008. In 2010, as the world economy rebounded — especially among the emerging economies – total $CO_2$ emissions increased by about 5.1 percent.

[174]Ibid.

[175]The *IEO 2013* Reference case projections are, to the extent possible, based on existing laws and policies, and EIA notes that projections for carbon dioxide emissions could change significantly if new laws and policies aimed at reducing greenhouse gas emissions were implemented in the future.

**Figure IV-10**
**World Energy-related $CO_2$ Emissions, 1990-2040**
(Billion metric tons – EIA Reference case)



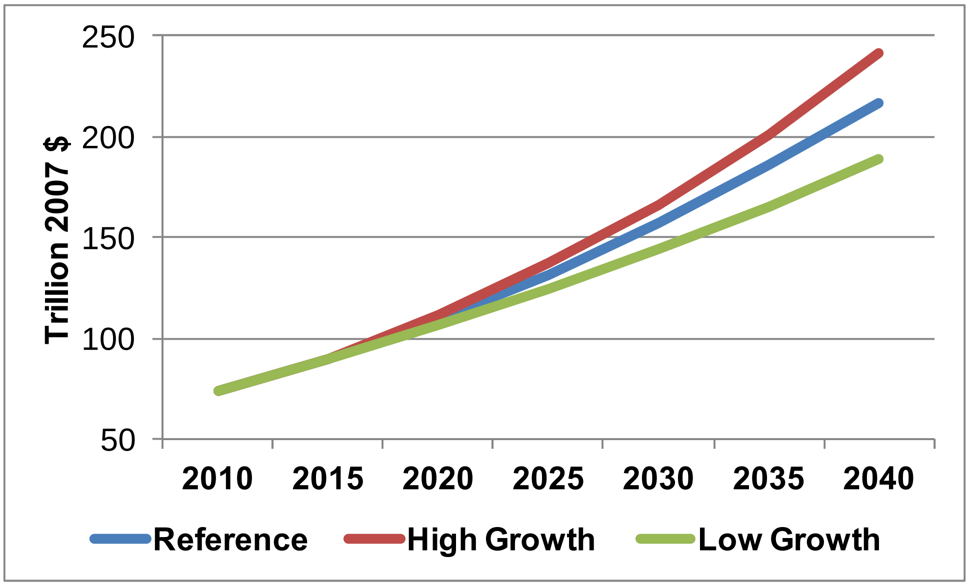

Source: U.S. Energy Information Administration.

As is the case with IEA, for EIA expectations of future rates of economic growth are a major source of uncertainty in the *IEO 2013* projections. To illustrate the uncertainties associated with economic growth trends, IEA's *IEO2013* includes a High Economic Growth case and a Low Economic Growth case in addition to the Reference case — Figure IV-11. The two alternative growth cases use different assumptions about future economic growth paths, while maintaining the oil price path of the *IEO 2013* Reference case.[176]

In the High Economic Growth case, real GDP in the OECD region increases by 2.3 percent per year from 2010 to 2040, as compared with 2.1 percent per year in the Reference case. In the non-OECD region — where uncertainty about future growth is higher than in the developed OECD economies, the High Economic Growth case assumes GDP growth of 5.2 percent per year, or 0.5 percentage points higher than in the Reference case. In the Low Economic Growth case, OECD GDP increases by 1.9 percent per year, or 0.3 percentage points lower than in the Reference case. GDP growth in the non-OECD region is assumed to average 4.1 percent per year, or 0.6 percentage points lower than in the Reference case.

[176]U.S/ Energy Information Administration, *International Energy Outlook*, op. cit.

**Figure IV-11**
**Alternate Forecasts of Word GDP: 2010 - 2040**

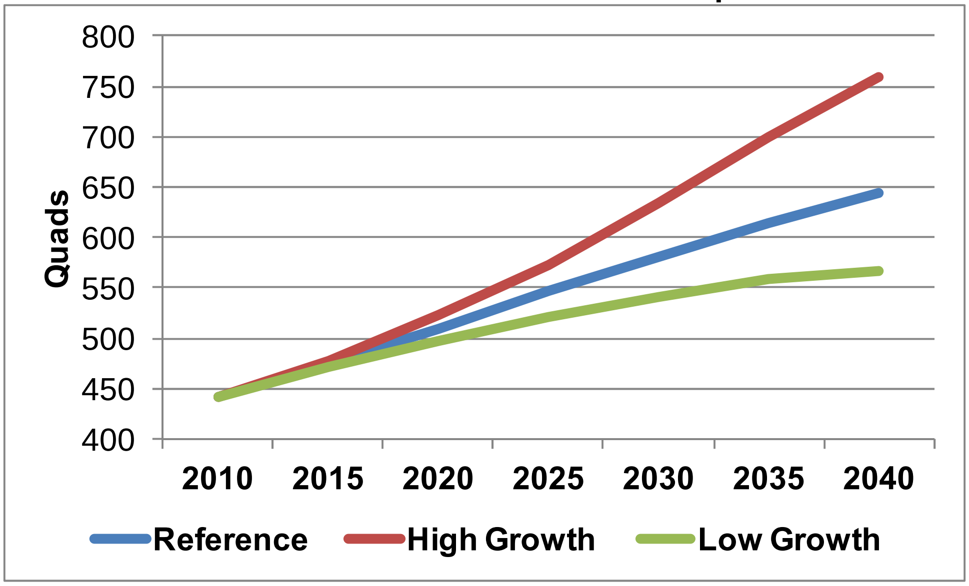



Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

As shown in Figure IV-12, in the Reference case world energy consumption totals 820 Quads in 2040 — 285 Quads in the OECD countries and 535 Quads in the non-OECD countries. In the High Economic Growth case, world energy use in 2040 is 760 Quads — 127 Quads (about 63 million barrels oil equivalent per day) higher than in the Reference case. In the Low Growth Case, total world energy use in 2040 is 733 Quads — 87 Quads (about 43 million barrels oil equivalent per day) lower than in the Reference case.[177] Thus, the projections for 2040 in the High and Low Economic Growth cases span a range of uncertainty equal to 213 Quads, equivalent to 41 percent of total world energy consumption in 2010. These EIA forecasts illustrate, once again, that future fossil fuel consumption is determined by future economic growth and that future economic growth will be critically dependent on fossil fuel utilization.[178]

[177] Ibid.
[178] Ibid

**Figure IV-12**
**Alternate Forecasts of Word Fossil Fuel Consumption: 2010 - 2040**

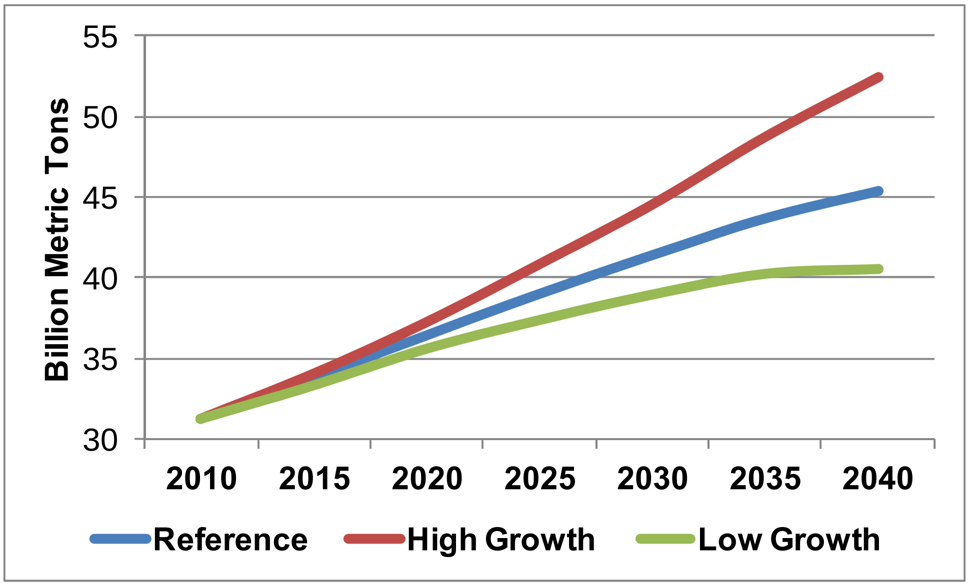



Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

EIA does not publish alternate $CO_2$ emissions forecasts corresponding to the high economic growth and low economic growth cases. Here we derived these alternate forecasts by assuming that the relationship between fossil fuel consumption and $CO_2$ emissions forecast by EIA for the Reference case would be about the same in the high growth and the low growth scenarios. Our results are given in Figure IV-13, which shows that:

- In 2020, $CO_2$ emissions total over 37 billion tons in the high growth case and about 35.5 billion tons in the low growth case.
- In 2030, $CO_2$ emissions total over 44 billion tons in the high growth case and about 39 billion tons in the low growth case.
- In 2040, $CO_2$ emissions total over 52 billion tons in the high growth case and less than 41 billion tons in the low growth case.
- Thus, by 2040 the difference in world $CO_2$ emissions between the high growth and the low growth cases totals about 11 billion tons.

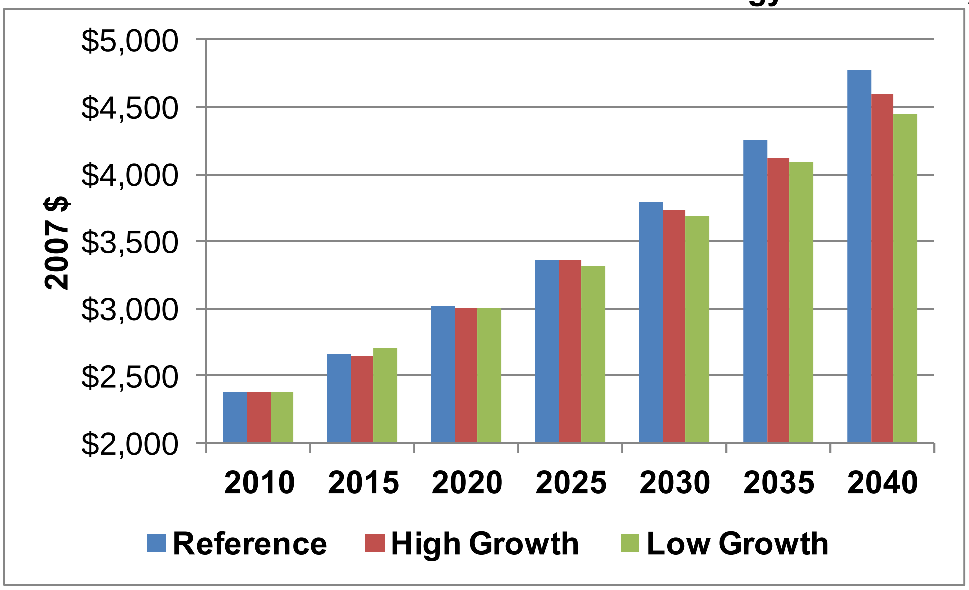
**Figure IV-13**
**Alternate Forecasts of World $CO_2$ Emissions: 2010 - 2040**




Source: U.S. Energy Information Administration and Management Information Services, Inc.

The preceding information allows us to forecast world GDP (2007 dollars) per ton of energy-related $CO_2$ according to each of the three scenarios – Figure IV-14. Because both world GDP and world $CO_2$ emissions are forecast to change over time, this figure indicates that the ratios of GDP to $CO_2$ emissions do not vary significantly until about 2035. Therefore, in the analyses below we use the forecast Reference case ratios.

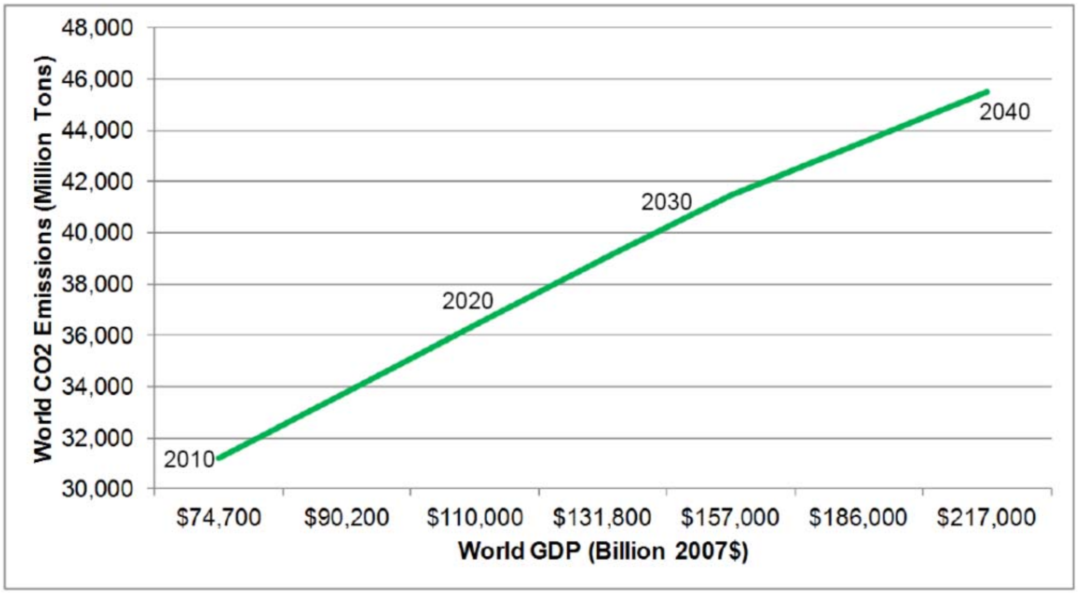
**Figure IV-14**
**Alternate Forecasts of World GDP Per Ton of Energy-Related $CO_2$**




Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

Figure IV-15 is analogous to Figure IV-4 and shows the forecast relationship between world GDP and $CO_2$ emissions in the EIA reference case through 2040. This figure indicates that the relationship is forecast to be roughly linear.

**Figure IV-15**
**Forecast Relationship Between World GDP and $CO_2$ Emissions**
(EIA Reference Case)



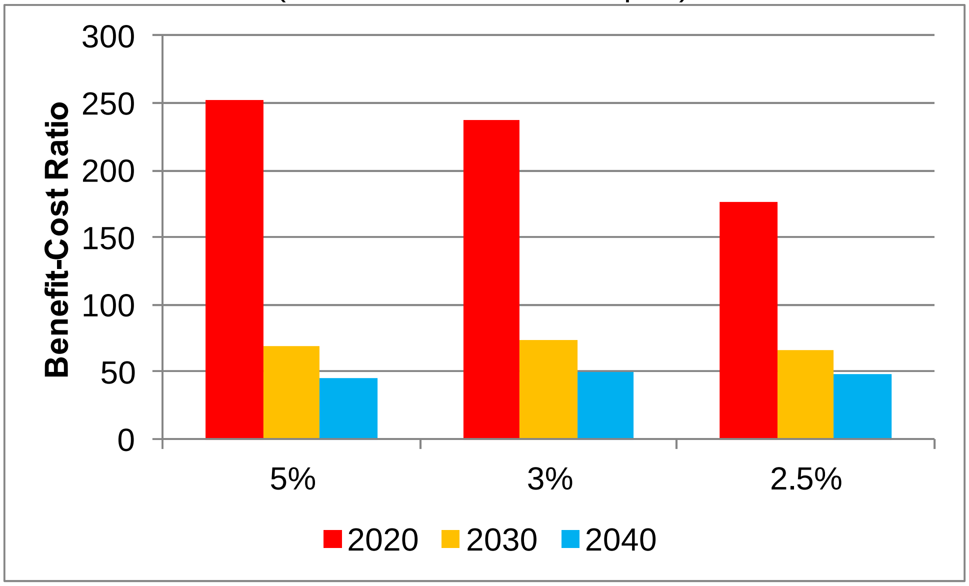

Source: U.S. Energy Information Administration, International Energy Agency, U.S. Bureau of Economic Analysis, and Management Information Services, Inc.

We can utilize the information shown in Figure IV-15 with the forecast SCC estimates given in Tables IV-1 and IV-2 to develop estimated future $CO_2$ B-C ratios. These reference case estimates are shown for the three 2013 IWG report discount rates in Figure IV-16.

This figure indicates that the $CO_2$ B-C ratios remain extremely high through 2040 using each of the three discount rates:

- With a 5.0% discount rate, over the forecast period the B-C ratios range from about 180-to-1 to about 250-to-1.
- With a 3.0% discount rate, over the forecast period the B-C ratios are about 70-to-1.
- With a 2.5% discount rate, over the forecast period the B-C ratios are about 50-to-1.

**Figure IV-16**
**Forecast Reference Case $CO_2$ Benefit-Cost Ratios**
(Based on 2013 IWG Report)

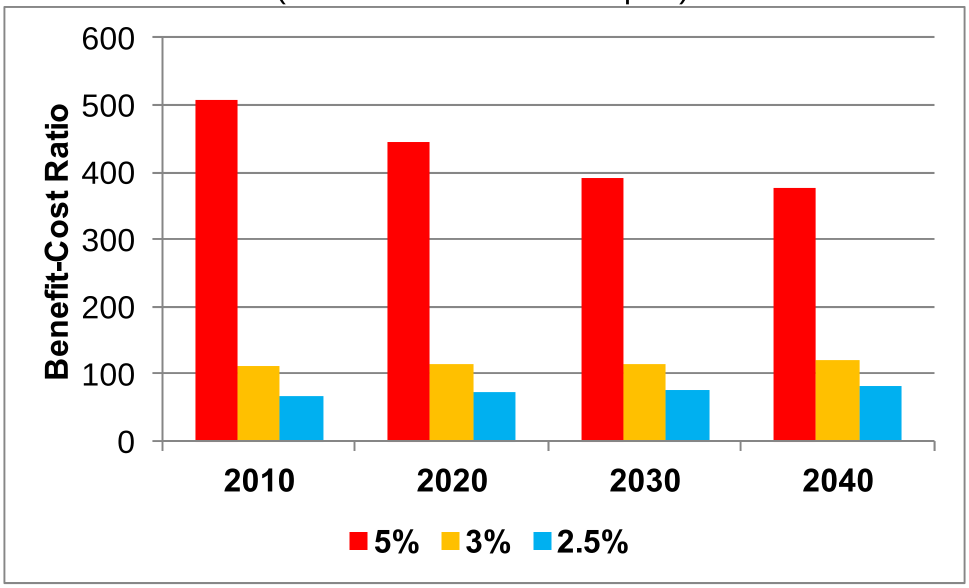



Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

The reference case estimates are shown for the three 2010 IWG report discount rates in Figure IV-17. This figure indicates that, using the 2010 SCC estimates, the $CO_2$ B-C ratios are even higher through 2040 under each of the three discount rates:

- With a 5.0% discount rate, over the forecast period the B-C ratios range from nearly 400-to-1 to about 500-to-1.
- With a 3.0% discount rate, over the forecast period the B-C ratios are in the range of about 110-to-1 to about 120-to-1.
- With a 2.5% discount rate, over the forecast period the B-C ratios are in the range of about 70-to-1 to about 80-to-1.

**Figure IV-17**
**2010 and Forecast Reference Case $CO_2$ Benefit-Cost Ratios**
(Based on 2010 IWG Report)




Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

## IV.D. Average, Marginal, and Differential Benefits

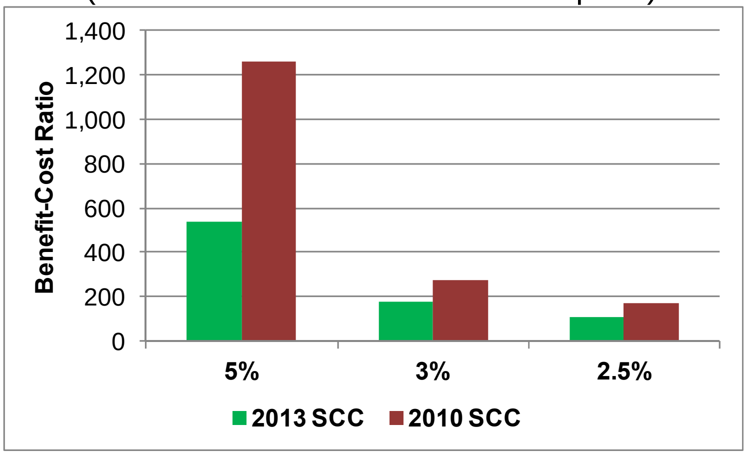
Figures IV-16 and IV-17 may be somewhat misleading because they indicate, basically, the average $CO_2$ B-C ratio for each year. The question thus arises of how marginal $CO_2$ benefits may compare to marginal costs. To estimate this, using the EIA reference case we computed the marginal $CO_2$-related change in world GDP, 2010-2011, and compared this with the 2010 SCC estimates from the 2013 and 2010 IWG reports. The results are shown in Figure IV-18. As anticipated, these "marginal" B-C ratios are larger than those given in Figures IV-5 and IV-6 or Figures IV-16 and IV-17. Specifically, Figure IV-18 shows that:

- Using the 5.0% discount rate, the B-C estimates range from about 540-to-1 to about 1,260-to-1.
- Using the 3.0% discount rate, the B-C estimates range from about 180-to-1 to about 290-to-1.
- Using the 2.5% discount rate, the B-C estimates range from about 110-to-1 to about 170-to-1.

Thus, the marginal $CO_2$ B-C ratios are significantly higher than those estimated above.[179]

[179]The estimated marginal $CO_2$ benefits will change over time depending on the forecast period, but the argument remains valid.

**Figure IV-18**
**2010-2011 Reference Case Marginal $CO_2$ Benefit-Cost Ratios**
(Based on 2010 and 2013 IWG Reports)




Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

In our work thus far, we have essentially attributed all of the increase in world GDP to increases in fossil fuel utilization. This approach can be criticized because not all of the world's energy is derived from fossil fuels: In 2010 about 81 percent of world energy was comprised of fossil fuels, while forecasts indicate that in 2040 somewhere between 75 percent and 80 percent of world energy will be comprised of fossil fuels – see the discussion in Sections II.B and II.C. To determine how this may affect the B-C estimates, we developed a scenario where the portion of world energy comprised of fossil fuels decreased gradually from 80 percent in 2010 to 75 percent in 2040. Thus, under this scenario in the EIA reference case:

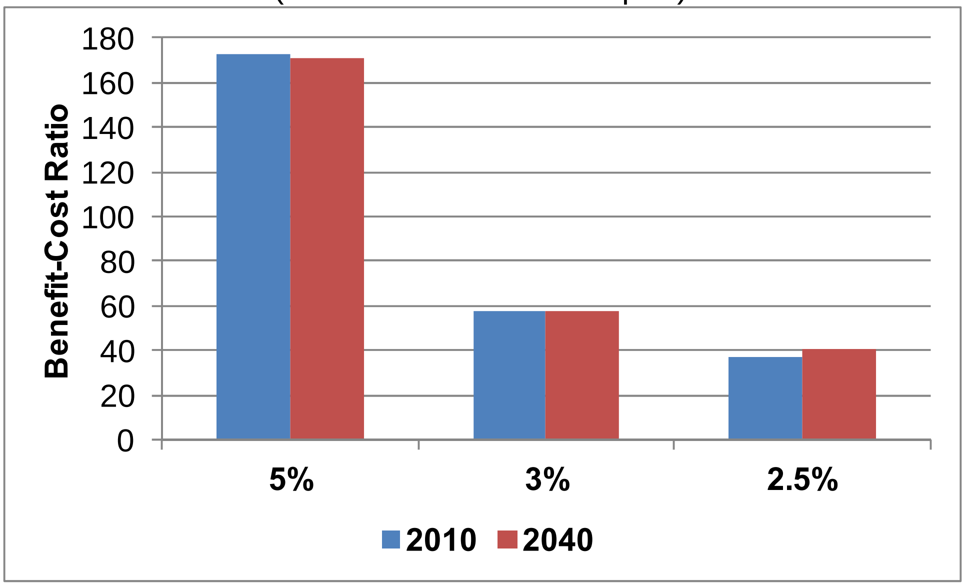
- In 2010, 80 percent of total world GDP is attributed to fossil fuels – approximately $59.8 trillion in 2007 dollars.
- In 2040, 75 percent of total world GDP is attributed to fossil fuels – approximately $162.8 trillion in 2007 dollars.

The results of this simulation are shown in Figure IV-19, based on the SCC estimates from the IWG 2013 report, and in Figure IV-20, based on the SCC estimates from the IWG 2010 report. These figures indicate that, while the scaling of $CO_2$ benefit estimates somewhat decreases the B-C ratios, the ratios remain very high. Specifically, Figure V-19 shows that, on the basis of the SCC estimates from the IWG 2013 report:

- Using the 5.0% discount rate, the B-C estimates for both 2010 and 2040 are in the range of about 170-to-1.
- Using the 3.0% discount rate, the B-C estimates for both 2010 and 2040 are in the range of about 60-to-1.

- Using the 2.5% discount rate, the B-C estimates for both 2010 and 2040 are in the range of about 40-to-1.

**Figure IV-19**
**2010 and Forecast 2040 Reference Case Scaled $CO_2$ Benefit-Cost Ratios**
(Based on 2013 IWG Report)

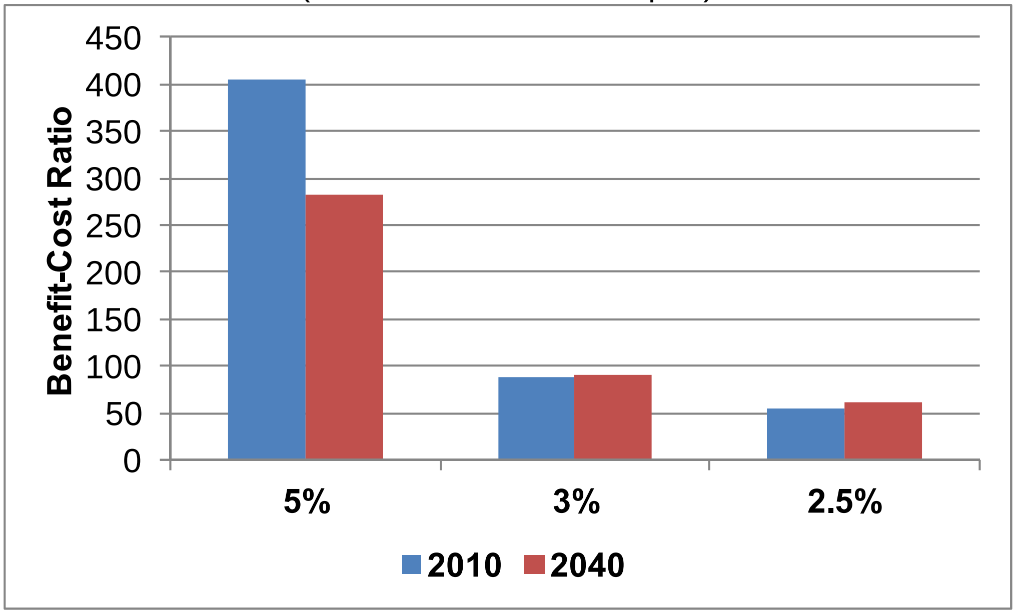



Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

Figure IV-20 shows that, on the basis of the SCC estimates from the IWG 2010 report:

- Using the 5.0% discount rate, the B-C estimate for both 2010 is about 170-to-1 and for 2040 is about 280-to-1.
- Using the 3.0% discount rate, the B-C estimates for both 2010 and 2040 are in the range of nearly 100-to-1.
- Using the 2.5% discount rate, the B-C estimates for both 2010 and 2040 are in the range of about 50-to-1.

**Figure IV-20**
**2010 and Forecast 2040 Reference Case Scaled $CO_2$ Benefit-Cost Ratios**
(Based on 2010 IWG Report)




Source: U.S. Energy Information Administration, U.S. Bureau of Economic Analysis, U.S. Interagency Working Group, and Management Information Services, Inc.

In other words, even assuming that by 2040 fossil fuels represent a somewhat smaller portion of total world energy supply, the benefits of carbon based energy still exceed the IWG SCC estimates by orders of magnitude. This is true even given the questionable validity of the IWG SCC estimates and, as discussed in Section IV.A, it may not even be possible to significantly reduce future fossil fuel utilization without causing unacceptable reductions in world economic growth and standards of living.

# V. THE FEDERAL INTERAGENCY WORKING GROUP REPORTS

## V.A. The Federal Interagency Working Group

The Federal Interagency Working Group (IWG) on Social Cost of Carbon is comprised of the following 12 agencies: Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Transportation, Environmental Protection Agency, National Economic Council, Office of Energy and Climate Change, Office of Management and Budget, Office of Science and Technology Policy, and Department of the Treasury. The process it used to develop the SCC estimates involved technical experts from numerous agencies meeting on a regular basis to consider public comments, exploring the technical literature in relevant fields, and discussing key model inputs and assumptions. The objective was to develop a range of SCC values using a defensible set of input assumptions grounded in the existing scientific and economic literatures. In this way, the IWG felt that key uncertainties and model differences transparently and consistently inform the range of SCC estimates used in the rulemaking process.[180]

The first IWG report was published in February 2010 and it contained four SCC values for use in regulatory analyses – Table V-1. Three values are based on the average SCC from three integrated assessment models (IAMs) — DICE, PAGE, and FUND, at discount rates of 2.5, 3, and 5 percent. The fourth value, which represents the 95$^{th}$ percentile SCC estimate across all three models at a 3 percent discount rate, was included to represent higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.[181]

In May 2013, the IWG published an updated report which contained SCC estimates, shown in Table V-2, based on new versions of each IAM. It did not revisit other interagency modeling decisions (e.g., with regard to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity. Changes in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves in the peer-reviewed literature.[182]

The 2013 SCC estimates using the updated versions of the models are higher than those in the 2010 report. By way of comparison, the four 2020 SCC estimates reported in the 2010 TSD were $7, $26, $42 and $81 (2007$). The corresponding four updated SCC estimates for 2020 are $12, $43, $65, and $129 (2007$).[183]

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[180] Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," February 2010.
[181] Ibid.
[182] Interagency Working Group on Social Cost of Carbon, United States Government, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013.
[183] Ibid.

**Table V-1**
**Original (2010) Social Cost of CO2, 2010 – 2050**
(In 2007 dollars per metric ton of $CO_2$)

| Discount Rate<br>Year | 5%<br>Avg | 3%<br>Avg | 2.5%<br>Avg | 3%<br>95th |
|---|---|---|---|---|
| 2010 | 4.7 | 21.4 | 35.1 | 64.9 |
| 2015 | 5.7 | 23.8 | 38.4 | 72.8 |
| 2020 | 6.8 | 26.3 | 41.7 | 80.7 |
| 2025 | 8.2 | 29.6 | 45.9 | 90.4 |
| 2030 | 9.7 | 32.8 | 50.0 | 100.0 |
| 2035 | 11.2 | 36.0 | 54.2 | 109.7 |
| 2040 | 12.7 | 39.2 | 58.4 | 119.3 |
| 2045 | 14.2 | 42.1 | 61.7 | 127.8 |
| 2050 | 15.7 | 44.9 | 65.0 | 136.2 |

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2010.

**Table V-2**
**Revised (2013) Social Cost of CO2, 2010 – 2050**
(In 2007 dollars per metric ton of $CO_2$)

| Discount Rate<br>Year | 5.0%<br>Avg | 3.0%<br>Avg | 2.5%<br>Avg | 3.0%<br>95th |
|---|---|---|---|---|
| 2010 | 11 | 33 | 52 | 90 |
| 2015 | 12 | 38 | 58 | 109 |
| 2020 | 12 | 43 | 65 | 129 |
| 2025 | 14 | 48 | 70 | 144 |
| 2030 | 16 | 52 | 76 | 159 |
| 2035 | 19 | 57 | 81 | 176 |
| 2040 | 21 | 62 | 87 | 192 |
| 2045 | 24 | 66 | 92 | 206 |
| 2050 | 27 | 71 | 98 | 221 |

Source: Interagency Working Group on Social Cost of Carbon, United States Government, 2013.

The model updates relevant to the SCC estimates included an explicit representation of sea level rise damages in the DICE and PAGE models; updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages in the PAGE model; an updated carbon cycle in the DICE model; and updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of methane emissions in the FUND model. Of these changes, only the inclusion in the FUND model of impacts on the agricultural sector and impacts from reduced space heating requirements represent attempts to include any potential positive impacts from higher concentrations of $CO_2$ and warmer global temperatures.

### V.B. Analysis of the IWG Methodology

IAMs form the basis for the IWG SCC estimates, and the IWG ran simulations of three different IAMs, with a range of parameter values, discount rates, and assumptions regarding GHG emissions, to derive its SCC estimates.[184] However, as Pindyck notes the IAM models "are so deeply flawed as to be close to useless as tools for policy analysis. Worse yet, their use suggests a level of knowledge and precision that is simply illusory, and can be highly misleading."[185] In his 2008 Richard T. Ely lecture at the annual meeting of the American Economic Association, Sir Nicholas Stern stated:[186]

> However, as the Stern Review stressed, such analysis (IAM) has very serious weaknesses and must not be taken too literally. It is generally forced to aggregate into a single good, and in so doing misses a great deal of the crucial detail of impacts — on different dimensions and in different locations — which should guide risk analysis. It is forced to make assumptions about rates and structures of growth over many centuries. Further, it will be sensitive to the specification of ethical frameworks and parameters. Thus its estimates of marginal social costs of damages provide a very weak foundation for policy. This type of modeling does have an important supplementary place in an analysis, but all too often it has been applied naively and transformed into the central plank of an argument.

As discussed below, the IWG methodology requires that a large number of assumptions be made to complete the linkages between levels of human activity, today and in the future, and the environmental consequences of that activity today and for generations to come. However, even small variations in the size of the assumed inputs

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[184]For a detailed review and analysis of IAMs, see Richard S.J. Tol, "Integrated Assessment Modeling," Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany, Working Paper FNU-102, 2006, https://fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/efieaiamwp.pdf, and Edward Parson and Karen Fisher-Vanden, "Integrated Assessment Models of Global Climate Change," *Annual Review of Energy and the Environment 1997*, 22:589–628.

[185]Robert S. Pindyck, "Climate Change Policy: What Do The Models Tell Us?" National Bureau of Economic Research, Working Paper 19244, July 2013; © 2013 by Robert S. Pindyck.

[186]Stern is professor of economics at the London School of Economics and Political Science and the lead author on the 2006 Stern Report on Global Warming. The source for this quote is found in Stern, "The Economics of Climate Change," *American Economic Review: Papers and Proceedings*, Vol. 98, No. 2, p. 3, 2008.

can lead to very large and significant differences in the results produced by the IWG's methodology — differences in results that are so great as to leave the IWG's policy recommendations highly questionable. Below, we briefly outline the structure of IAMs, and then describe the strengths and weaknesses of the models. One of the more important conclusions about these models, as discerned through a review of the literature, it that they are not yet robust enough to play a role in environmental or regulatory policy formulation.

### V.B.1. What are IAMs?

IAMs are constructed for different purposes and emphasize different aspects of the global climate change issue, and there are currently about 50 IAMs.[187] Some of their major limitations include:[188]

- The simplicity in their approach, using only one or two equations associating aggregate damage to one climate variable, in most cases temperature change, which does not recognize interactions between different impacts,
- Capturing only a limited number of impacts, often omitting those difficult to quantify and those showing high levels of uncertainty,
- Presenting damage in terms of loss of income, without recognizing capital implications, and
- The application of willingness to pay quantification, which could lead to relatively low results in the context of developing countries.

The description and purposes of IAMs have changed little over the two decades since their use became common in the analysis of global climate change. In an early description and review of these models John Weyant and colleagues concluded that integrated assessments are convenient frameworks for combining knowledge from a wide range of disciplines.[189] These efforts address three goals:

- Coordinated exploration of possible future trajectories of human and natural systems,
- Development of insights into key questions of policy formation, and

[187]Elizabeth Stanton, et al, "Inside the Integrated Assessment Models: Four Issues in Climate Economics," *Climate and Development*, 1 (2009). P.168.
[188]Swenja Surminski, Ana Lopez, Joern Birkmann, and Thorsten Welle, "Current Knowledge on Relevant Methodologies and Data Requirements as Well as Lessons Learned and Gaps Identified at Different Levels, in Assessing the Risk of Loss and Damage Associated With the Adverse Effects Of Climate Change," technical paper, FCCC/TP/2012/1. 2012, United Nations Framework Convention on Climate Change, Bonn, Germany, p. 23, http://unfccc.int/resource/docs/2012/tp/01.pdf.
[189]See Tol, op. cit.; Stanton, op. cit.; and John P. Weyant, et.al, "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," p. 371, in J. P. Bruce, et al. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, Cambridge, 1996.

- Prioritization of research needs in order to enhance our ability to identify robust policy options — the integration process helps the analyst coordinate assumptions from different disciplines and introduce feedbacks absent in conclusions available from individual disciplinary fields.

Prior to the use of mathematical computer models (IAMs) to link knowledge from divergent disciplines together using explicit behavior assumptions, questions involving cross-disciplinary issues were usually addressed by convening panels or commissions of experts from the various fields to provide their collective judgment on the issue at hand. The first application of a formal IAM effort on a global environmental issue was the Climate Impacts Assessment Program (CIAP) at the U.S. Department of Transportation to examine the potential environmental impacts of supersonic flight in the early 1970s. Other efforts to assess global issues using IAM's followed, but it was not until the 1990's that IAMs to address climate change began to proliferate.[190]

As described above, the primary goal of these models is to assess a broad range of science across several disciplines to provide policy makers with answers to questions involving the potential problems of global climate change. The models can be relegated to two broad classes of models: i. policy optimization models and ii. policy evaluation models.

In climate research, policy optimization models solve for an optimal policy that trades off expected costs and benefits to maximize, for example, social welfare. Alternatively, optimization models can be used to find the optimal (least cost) approach to reaching a particular goal, e.g. a future, stable level of climate $CO_{2.}$ Policy evaluation models, on the other hand, are used to assess the impact of a particular policy variable on the environment. Importantly, the models differ in the degree of complexity found in their respective sectors. Policy evaluation models tend to be much more complex, especially in their treatment of the physical sciences, whereas policy optimization models contain economic and climate sectors that are relatively simple.[191]

Figures V-1 and V-2 illustrate the basic integrated assessment model showing both economic and climate modules and the interactions between them.[192] The four-module structure depicted in Figure V-2 contains the basic "building blocks" for an IAM. The "Economic Dynamics" block contains the human activities that generate carbon emissions. This block usually contains a fairly robust energy sector as well as a sector representing agriculture forestry and livestock. The "Carbon Cycle" block contains a model of the carbon cycle which estimates the net increase of carbon in the atmosphere (carbon atmosphere concentration). Changes in carbon concentrations are then used

[190]See Wayant, op cit. p. 376.
[191]See David L. Kelly and Charles D.Kolstad, "Integrated Assessment Models For Climate Change Control," US Department of Energy grant number DE-FG03-96ER62277, www.econ.ucsb.edu/papers/wp31-98.pdf.
[192]From N. Edwards, H. Grepin, A. Haurie and L. Viguier, "Linking Climate and Economic Dynamics," in *The Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment*, Alain Haurie and Laurent Viguier (eds), Amsterdam: Springer, 2005.

as an input into a "Climate Dynamics" module that predicts changes in temperature. Next, changes in temperature impact economic sectors are determined by the "Damage Function" module. Finally, any adverse impacts on GDP are fed back into the Economic Dynamic module, resulting in a lower starting level of GDP for calculating impacts in the next period.

**Figure V-1**
**Simplified schematic of a typical IAM**[193]

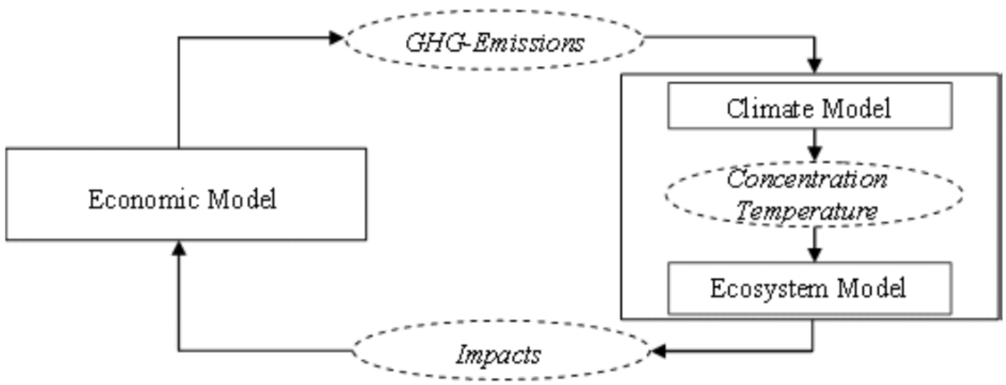
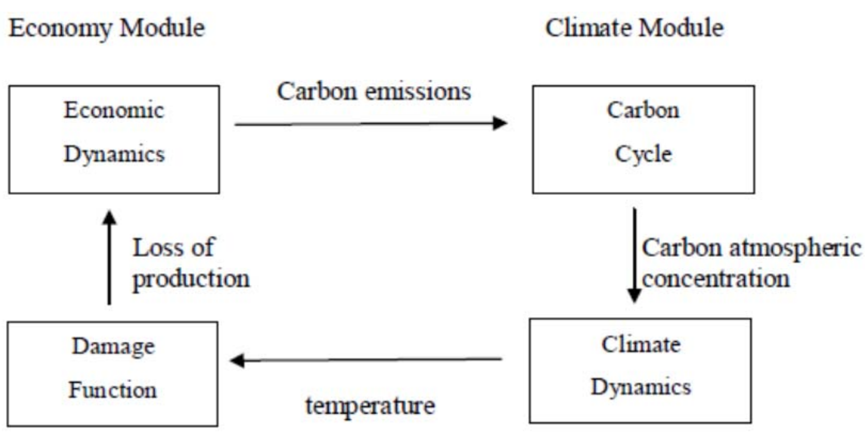



**Figure V-2**
**Representation of a Basic Integrated Assessment Model**
**Showing Interactions Between Economic and Climate Systems.**[194]




More sophisticated models will contain more elements in each model as well as additional feedback effects – see Figure V-3 and V-4. For example, the Carbon Cycle

[193]Christoph Böhringer, Andreas Löschel and Thomas F. Rutherford, *Decomposing the Integrated Assessment Climate Change,* Centre for European Economic Research, Discussion Paper No. 05-07, p. 3. ftp://ftp.zew.de/pub/zew-docs/dp/dp0507.pdf.
[194]From Edwards, N.; H.Grepin, A.Haurie and L.Viguier, "Linking Climate and Economic Dynamics", In *The Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment*, Alain Haurie and Laurent Viguier (eds), Amsterdam: Springer. 2005.

module may contain an Ocean Carbon Cycle model as well as an atmospheric model. Climate Dynamics modules may contain ocean temperature and sea level models as well. Conceptually, there is no limit to the degree of sophistication that can be built into the models. Computational limits, however, are another matter and these weigh heavily in fully integrated optimization IAMs based on CGE (computable general equilibrium) economic modules, such as the DICE model, which compute optimal growth paths by computing thousands of iterations over hundreds of periods.

**Figure V-3**
**Simplified Schematic of a Typical Welfare Optimizing IAM**[195]

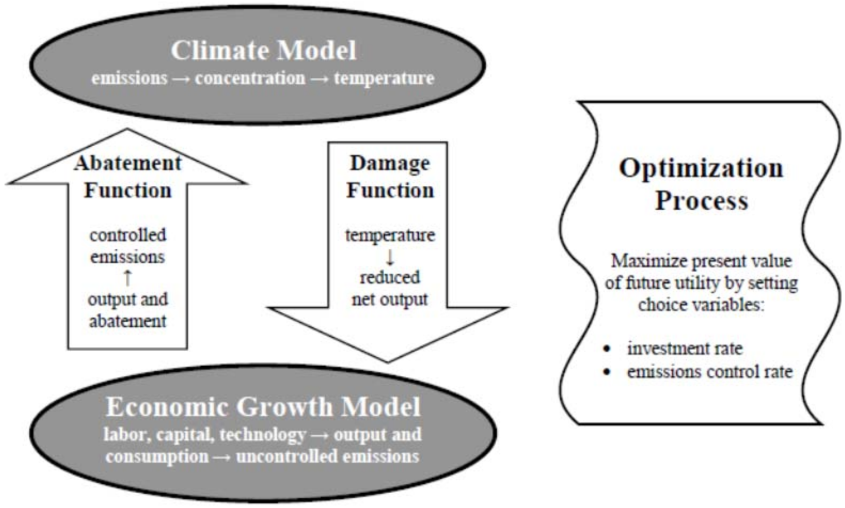



**Figure V-4**
**Key Components of Full Scale IAMs**[196]

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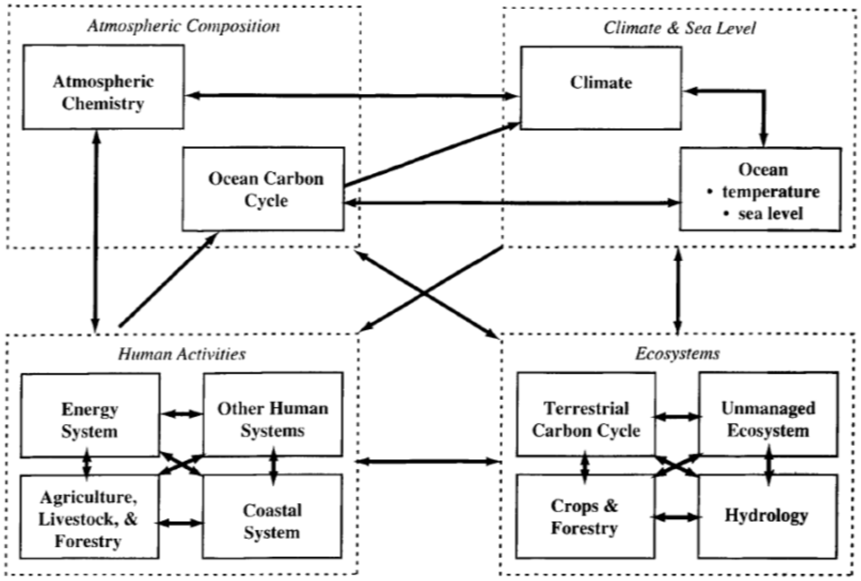
[195]From Elizabeth Stanton, et al, Inside the Integrated Assessment Models: Four Issues in Climate Economics," *Climate and Development*, 1 (2009). p.168.

[196]From John p. Weyant, et.al, "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," p. 377 in *Climate Change 1995: Economic and Social Dimensions of Climate Change*, op. cit.


Atmospheric Composition
Atmospheric Chemistry
Ocean Carbon Cycle
Climate & Sea Level
Climate
Ocean
• temperature
• sea level
Human Activities
Energy System
Other Human Systems
Agriculture, Livestock, & Forestry
Coastal System
Ecosystems
Terrestrial Carbon Cycle
Unmanaged Ecosystem
Crops & Forestry
Hydrology

James Risbey and colleagues likened the art of building an IAM to building a house where the blocks represent the substantive knowledge found in the different disciplines that are represented in the various modules while the mortar that links the modules together:

> . . . . frequently takes the form of the practitioner's subjective judgments linking the disparate knowledge blocks. Unfortunately, while the bricks may be quite sound and well described, the subjective judgments (glue) are often never made explicit. As a result, it is difficult to judge the stability of the structure that has been constructed. Thus, in the case of integrated assessment, not only do we need criteria for assessing the quality of the individual components of the analysis, we also need criteria that are applicable to the glue or the subjective judgments of the analyst, as also for the analysis as a whole. While criteria for adequacy for the individual components may be obtained from the individual disciplines, a similar situation does not exist for the "glue'' in the analysis.[197]

In reality, it is not only the "mortar" that is suspect in the building of IAMs, but the content of the blocks themselves. Below we highlight the most problematic parts of a typical IAM, beginning with the estimates of carbon emissions through each step up to and including the estimation of the economic costs and benefits of those emissions. Troubling and unresolved issues at each stage of an IAM include: [198]

- What is the rate of carbon emissions, from natural and human sources?
- How is the carbon cycle specified: The processes that impact the net change of the amount of carbon in the atmosphere? If more carbon enters the atmosphere than is absorbed by ocean and terrestrial carbon "sinks", then the concentration of carbon will increase.
- How does the concentration of carbon in the atmosphere impact the climate, e.g. climate dynamics? What are the interactions between climate and oceans, between climate and land mass?
- How do changes in temperature impact the oceans and the land?

[197]See James Risbey, et al, "Assessing Integrated Assessments," *Climatic Change*, 1996, Volume 34, Issue 3-4, pp 369-395.

[198]This list is based on an analysis of various studies of the issue, but draws most heavily from Risbey, op. cit.; and Stephen H. Schneider, "Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool For Policy Making or Opaque Screen Hiding Value-Laden Assumptions?" *Environmental Modeling and Assessment*, Issue 2, October 1997, pp. 229-49. http://stephenschneider.stanford.edu/Publications/PDF_Papers/Integr_Ass.pdf; and J. Weyant, et al, "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," pp. 367-439 in J. P. Bruce, et al. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, Cambridge (1996). http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1.

- What evidence is there that increasing temperatures will cause damages?
- How much will those damages impact current and future rates of growth?
- Finally, if there are expected damages to future economic growth and output, how do we compare the current, or present value of those future damages to the costs — present and future — of slowing or stopping, (i.e., "mitigating") the emission of carbon into the atmosphere. This issue hinges on the very sensitive and controversial question of selecting the "correct" discount rate to convert future costs and benefits into current costs and benefits in order to establish an SCC.

In his critique of the use of IAMs for policy decision making, Stern focused on several of the above issues.[199] Of the key elements in the parameters of IAMs he broadly classified them into two groups which he labeled structural elements and ethical elements. Among the former he considered the following structural parameters to be crucial: The flow of emissions; "climate sensitivity", the link between carbon stocks and temperature changes; the functioning of the carbon cycle that links carbon flows to carbon stocks – the concentration level of carbon in the atmosphere; and the estimation of damages from temperature changes. As far as the ethical elements that concern Stern, his argument is that they are far broader than the one or two issues that are "shoehorned" into the standard economic growth module of a typical IAM.

The structural elements of major concern include:

- The flow of carbon into the atmosphere,
- Climate sensitivity and the functioning of the carbon cycle, and
- Damage estimates – the damage functions.

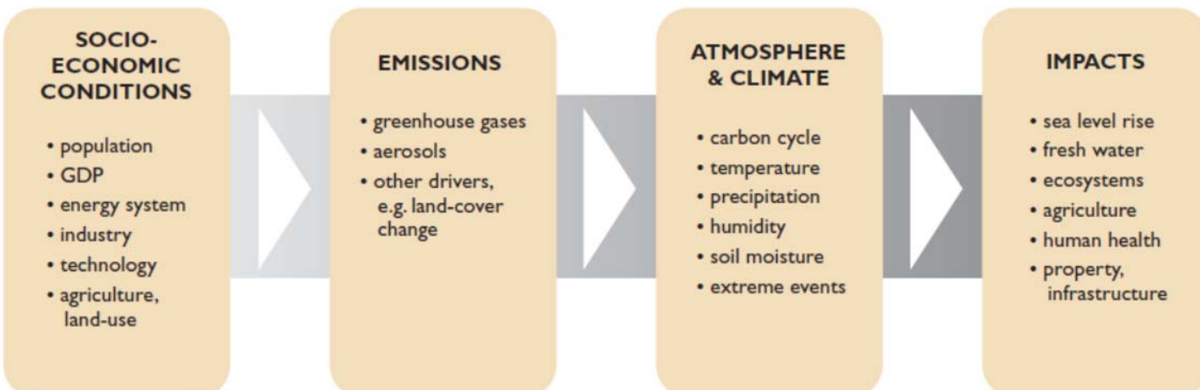
### V.B.2. The Flow of Carbon Into the Atmosphere

The assessment of potential impacts of climate change in an IAM begins with an emission stream generated by a scenario of economic growth, and the IWG selected five different scenarios developed by the Energy Modeling Forum (EMF) at Stanford University.[200] Figure V-5 shows several areas of climate research that are often subject to the creation of "scenarios" – essentially "what if" exercises based on sets of assumptions about the structure of the models within the socio-economic module and variables that drive the creation of various climate model scenarios.[201] In the case of

[199] See Nicholas Stern, "The Economics of Climate Change," op. cit., pp. 17-18.
[200] A description of the specific EMF scenarios selected by the IWG can be found in Michael Greenstone, et al., "Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation", *Review of Environmental and Economic Policy* (Winter 2013) 7 (1): 23-46.
[201] Found in Edward Parson, et al, "Global-Change Scenarios: Their Development and Use", U.S. Department of Energy, 2007, p. 23.

emission scenarios, exogenously determined trends for economic growth, population growth, and technological change are inputs into the socio-economic module to create scenarios of emissions that are compatible with the structure of the energy system. The remaining sectors in the diagram – "Atmosphere & Climate" and "Impacts" are modeled as part of the IAMs. The scenarios are not to be considered forecasts of future emissions, but are developed to create a range of plausible trends for future emissions given the underlying assumptions about economic and population growth and technological change.

**Figure V-5**
**Anthropogenic Climate Change: Simplified Linear Causal Chain**[202]




In critiques of the socio-economic scenario creation for IAM calculations, attention has been focused primarily on the assumed rate of economic growth, on the treatment of technological change, the treatment of non-$CO_2$ sources of GHG emissions, and the treatment on non-anthropogenic sources of GHG emissions. In the scenarios of economic growth from the EMF, compound annual rates of global economic growth between 1995 and 2100 ranged between a low of 1.48% and a high of 2.45%. The average "reference" (baseline) rate of growth was 2.17%.[203] These rates of growth are not particularly high, especially when compared to global growth rates over the last fifty years, but they are typical of scenario modeling at the EMF as well as at other organizations. Projected slowing rates of population growth and of technological improvements over coming decades are responsible for this trend.[204]

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[202] Found in Ibid.
[203]Spreadsheets with the various parameters for the created scenarios can be found at the Energy Modeling Forum website, http://emf.stanford.edu/.
[204]A 2012 paper by Robert J. Gordon is especially pessimistic with regard to future technology leading to much if any productivity gain and economic growth. See Gordon, "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds", op. cit.

Of the three IAM models used by the IWG in their computations of SCC, the FUND and PAGE models treat economic growth as an exogenous variable, while the DICE model uses an optimal growth model based on a Cobb-Douglas production function to forecast GDP. Technological change is treated exogenously in all three models. Critics of IAMs consistently cite the failure of IAMs to treat technological change (productivity) as well as population growth as endogenous variables as an important weakness in these models.[205]

### V.B.3. Climate Sensitivity

The term "Climate Sensitivity" refers to the change in global temperature in reaction to changes in the atmospheric content of Greenhouse Gases (GHG). This component is composed of at least three elements

- First, the long-term increase in global temperature given an increase in GHG. Usually this reaction is expressed in terms of the change in global temperature relative to a pre-industrial base temperature, given a doubling of the concentration of $CO_2$ in the atmosphere.
- Second, the rate at which the temperature changes over the period being assessed.
- Third, the assessment of potential feedback effects that occur because of climate change – feedbacks that may either increase or decrease the concentration of atmospheric GHGs and thereby either speed or slow the rate of GHG concentration and the subsequent impact on global temperature.

The long-term change in global temperature in reaction to changes in atmospheric $CO_2$ concentration is one of the first important uncertainties related to climate science and IAM efforts to model the causal linkage between anthropogenic activities and possible adverse economic and/or ecological impacts. In 2007 the Intergovernmental Panel on Climate Change (IPCC) reported its estimate of climate sensitivity – the change in predicted temperature change given a doubling of $CO_2$ — at between $2.0^o$ and $4.5^o$ C, with a best estimate of $3.0^o$ C.[206] The IPCC range of estimates resulted from a peer review of over twenty individual studies of climate sensitivity.[207] IAM modelers who have tested for impact of climate change generally

[205] A description and evaluation of the three IAMs used by the IWG as well as other IAMs can be found in Ramon Arigoni Ortiz and Anil Markandya, "Integrated Impact Assessment Models of Climate Change with an Emphasis on Damage Functions: a Literature Review," BC3 Working Paper Series 2009-06, Basque Center for Climate Change (BC3), October 2009. http://www.bc3research.org/d7H9dfT3Re2/2009102002 04231130584436.pdf.

[206] IPCC, "2.3 Climate Sensitivity and Feedbacks". In R.K. Pachauri and Reisinger, A. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2007.

[207] See Pindyck, op. cit., p.9.

have experimented with different change values, usually within the IPCC estimated range.

The speed at which global temperatures increase toward their estimated equilibrium temperature is also very important in the estimation of the total impact. A slower path toward equilibrium will result in lower estimated impact costs, since the discounted present value of more immediate increases (and impacts) would be lower — as would the more distant impacts. Although impacts in the far future would be more severe, their present value would be reduced owing to their value being discounted over a more lengthy time period. IAM modelers have addressed this issue through assuming different time paths and comparing results, again, with no solid data or science to indicate what the actual path might be.

Further, the rate at which $CO_2$ is emitted is not the rate at which it enters into and increases the GHG concentration in the atmosphere owing to the natural action of the carbon cycle, which immediately acts to remove some emitted carbon while more dissipates over time into ocean and agricultural sinks. While sophisticated global climate models often incorporate elaborately calibrated carbon cycles within their models, most IAMs deal with the problem by utilizing simplifying assumptions about how much and how rapidly emitted $CO_2$ is subtracted from the current emission flows. While the limiting factor in an IAM model is computational time, it is important to note that there is significant uncertainty among climate science as to how the current cycle operates and how it will continue to operate in the future under increasing emissions of $CO_2$.

Thus, in this first step of an IAM impact estimation, there are significant unknowns for which science is unable to provide answers. When IAM modelers craft various assumptions about the impact of $CO_2$ emissions on global temperatures, their assumptions can produce a wide range of impact values depending on those assumptions and upon the structure of the individual IAMs that they employ.

### V.B.4. IAM Damage Functions

One of the most contentious elements of IAM SCC estimates concerns how estimates of damage are related to projected global temperature changes. In general, most IAMs relate damages to increases in temperature, T, using a quadratic equation that calculates damages as a function of temperature changes. There is no economic basis for using a quadratic equation, nor is there any scientific justification for the parameters of the equations that determine how fast damages increase as temperatures climb. The result is that the structural of these equations contain the unstated assumption that damages increase at an increasing rate as temperatures increase. In their review of IAMs, Rachel Warren and her colleagues concluded that: “The assumption of a quadratic dependence of damage on temperature rise is even less grounded in any empirical evidence. Our review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function – although the practice is endemic in IAMs.[208] Similarly, in his review of IAMs Pindyck also noted that the "loss functions" are not based on any economic theory, but, rather, "They are just arbitrary functions, made up to describe how GDP goes down when T goes up."[209]

The damage functions used by the three models used by the IWG – DICE, FUND and PAGE – have little or no disaggregation with regard to sectors and/or regions in their estimations. For example, the DICE model uses a single total damage function based on estimates of temperature related damages in several sectors including agriculture, forestry, coastal vulnerability, health, and outdoor recreation to name a few. The PAGE model includes three damage functions that cover economic sectors, noneconomic sectors, and potential climate discontinuities. The damage function in the FUND model is the most disaggregated of the three and it includes damage functions for several sectors: Agriculture, forestry, water resources, sea level increases, health, and several others. In addition, the FUND model includes regional impacts for the various sectors.[210]

While the simplicity and arbitrariness of the structure of the damage functions raises concerns regarding their accuracy, also troubling is the fact that these functions are usually based on only one country or region because the literature on the topic of environmentally induced costs (or benefits) is very limited, except in agriculture. For example, as described by Mastrandrea:[211]

> Market and non-market damages in DICE are based on studies of impacts on the United States that are then scaled up or down for application to other regions. Many of the estimates to which market damages in PAGE are calibrated are also based on an extrapolation of studies of the United States. Only FUND uses regional and sector-specific estimates. However, in some sectors these estimates also originate in one country, or may be dominated by estimates from one region. For example, in the energy sector, the sector which accounts for most of the economic damages in FUND, estimates for the UK are scaled across the world.

In short, we are asked to accept that very limited assessments of damages to one sector in one region, for example the energy sector in the UK, can be extrapolated to assess the impact on the same sector in other regions without acknowledging first, that the structure of these sectors differ significantly from one region to another and that, second, global climate science cannot predict with any accuracy at all what

[208]Also see Rachel Warren, et al, "Spotlighting Impacts Functions in Integrated Assessment," Research Report Prepared for the Stern Review on the Economics of Climate Change, Tyndall Centre for Climate Change Research Working Paper 91, September 2006, p. 172.
[209]Pindyck, op cit. p. 11.
[210]A more complete description of the damage functions in the three models can be found on pp. 13-21 in Michael D. Mastrandrea, *Calculating the Benefits of Climate Policy: Examining the Assumptions of Integrated Assessment Models,* The Pew Center on Global Climate Change, 2009. Also see Rachel Warren, et al, Spotlighting Impacts Functions in Integrated Assessment, op cit.
[211]Mastrandrea, op. cit., p. 17.

countries or regions may be impacted more or less than any others, given an increase in average global temperatures.

While some progress is being made in estimating the potential damages from climate change, at present the research is still so limited that one would be hard pressed to describe the results as little more than educated guesses. Or, as Mastrandrea states: "Although the differences in formulation across models do not allow a perfectly parallel comparison, it is clear that the relationship between temperature increase and climate damages varies significantly among IAMs."[212]

Finally, Pindyck notes that while the IAM damage functions relate changes in GDP levels to changes in global temperature, a more persuasive argument is that temperature changes would impact the rate of GDP growth and not the level. Currently most IAMs estimate an impact on income, but not capital. Concerning this issue, Pindyck states:

> First, some effects of warming will be permanent; e.g., destruction of ecosystems and deaths from weather extremes. A growth rate effect allows warming to have a permanent impact. Second, the resources needed to counter the impact of warming will reduce those available for R&D and capital investment, reducing growth. Third, there is some empirical support for a growth rate effect. Using data on temperatures and precipitation over 50 years for a panel of 136 countries, Dell, Jones and Olken have shown that higher temperatures reduce GDP growth rates but not levels. Likewise, using data for 147 countries during 1950 to 2007, Bansal and Ochoa show that increases in temperature have a negative impact on economic growth.[213]

Elizabeth Stanton and her colleagues[214] also note that subtracting damages from output with no effect on capital, production or consumption in following periods is an "unrealistic assumption." Specifically:

> In recognition of the fact that the parameters of the damage functions are questionable at best, IAM models increasingly include probability distributions of the parameters to explicitly address the issue of uncertainty. While the use of probability distributions – using a range of values around a norm – serves to acknowledge that we have no real scientific evidence to support one value over another – their use introduces another bias into IAM results. Since the structure of the damage functions are quadratic equations, the results of using probability distributions of equation parameters results in so-called "fat tail" impacts that are larger for higher temperature increases than for lower increases.[215]

[212]Mastrandrea, Op cit. p. 20.
[213]Pindyck, op cit., p. 12.
[214]See Elizabeth Stanton, et al, op. cit.
[215]Mastrandrea, op cit., p. 48.

As for the fact that the models include only a limited number of sectors in their assessments, the modelers argue that any unrepresented sectors would result in even greater damage assessment if included. Also, admitting that that there may be some positive impacts from climate change, most modelers argue that any positive impacts would undoubtedly be outweighed by the negatives.[216] However, little evidence is presented to support these claims.

An interesting example of the uncertainty and arbitrariness of damage functions can be shown in a comparison of the results of IAM impact studies conducted by Joseph Aldy and his colleagues. They found that there was a significant amount of consistency among several disparate studies of the economic impact of a 2.5C$^o$ warming of average global temperatures, compared to pre-industrial levels, by 2100: Five different models predicted economic damages of between 1% and 2% of global GDP. However, although the gross damages estimates were similar, there were huge differences in the studies' estimates of the sources of the damages, as shown in Figure V-6.[217] As illustrated, the total damages, although similar, reveal large differences in the source of the damages – market impacts, non-market impacts, or catastrophic impact[218] Thus, it must be concluded that the similar results for the total damage estimates occurs because the selection of damage structures and parameters for the different sectors – economic and noneconomic – in the five model results just happened to aggregate to similar total damage values.

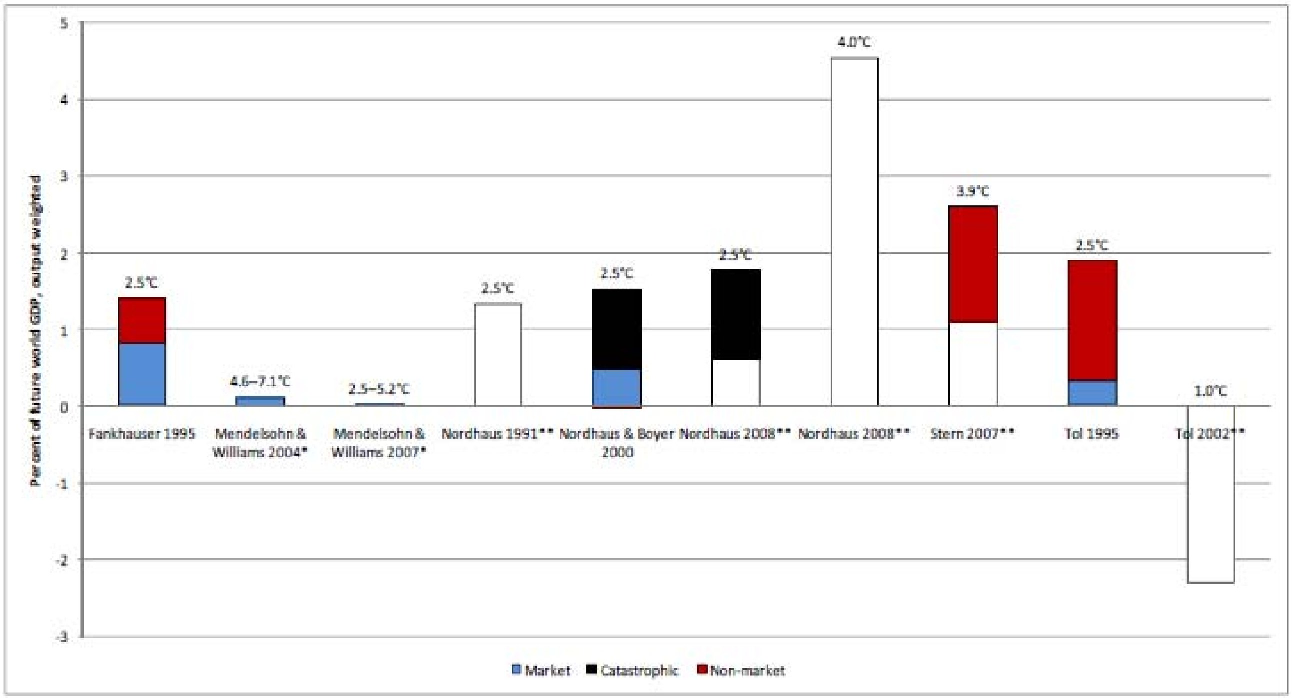
### V.B.5. The Discount Rate:

Of the many parameters found in IAMs, including everything from decisions about model structure to the value of key variables, none attracts as much attention and criticism as the choice of the discount rate used to estimate the present value of future impacts. The discount rate is a lightening-rod for criticism, first, because of the heavy ethical baggage that it carries. Unlike the majority of benefit-cost studies that use discount rates to assess values only a few years or even decades into the future, IAMs that are developed to evaluate the impacts of climate change must look generations ahead. This characteristic of IAMs raises important ethical issues, and one of the most basic ethical arguments is that to use any rate of discount other than zero would be a violation of intergenerational neutrality. That is, a positive value of the discount rate is an indication that future generations are held to be less valuable than the current or "present" one.[219] Second, and more important, in simulations of the sensitivity of IAM

[216]See, for example, Richard S.J. Tol, "Why Worry About Climate Change? A Research Agenda," *Environmental Values*, 17 (2008): 437–470, p.448.
[217]Only market damages were estimated in these studies, and the figure is the midpoint of a range of damage estimates. Damage categories are not precisely de-lineated in these studies.
[218]The figure and related discussion are included here to illustrate that, in general, IAM's produce inconsistent results (as to where and why damages might occur) even though there may be an (apparent) consistency in the level of the overall level of damages calculated by the different models.
[219]The arguments on this issue are long and involved. See Stern, op. cit., 2009, pp. 12-17 for his arguments of the justification for using a low discount rate in "The Stern Review of the Economics of

results using different variable values, the choice of the values of the discount rate causes greater variation in model results than do other model parameters.

**Figure V-6**
**Selected Estimates of Contemporaneous World GDP Damages From Global Warming Occurring Around 2100**[220]
(Estimates derived by indicated researchers)




For example, in the summary of results of the latest IWG report, the ranges of estimated SCC values are huge even though the range of discount rates tested is not.[221] For the three discount rates considered (2.5%, 3% and 5%) using the PAGE IAM and the IMAGE scenario (for projections of economic growth and $CO_2$ emissions), the model results extended over a range of average values for the SCC of from $28 per metric ton of $CO_2$ at a 5% discount rate to $129 at a 2.5% rate. Using the FUND model and the same IMAGE scenario of growth, the results ranged from $3 (at 5%) to $44 (at 2.5%). The results in these two examples show that cutting the discount rate in half, from 5% to 2.5%, produces SCC values that range from five times to twelve times as large when computed at 2.5% rather than 5%.

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Climate Change" and a rebuttal by William D. Nordhaus, "A Review of the Stern review on the Economics of Climate Change," *Journal of Economic Literature*, V. XLV, September 2007, pp. 689-97.

[220]See Joseph E. Aldy, et al, "Designing Climate Mitigation Policy", Resources For the Future, RFF DP 08-16, May 2009. P. 50. http://www.rff.org/RFF/Documents/RFF-DP-08-16.pdf.

[221]See "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis," Interagency Working Group on the Social Cost of Carbon, The White House, the United States Government, Under Executive Order 12866, Washington, D.C., May 2013, pp. 19-20.

The question thus arises, if relatively small changes in the discount rate produce such large differences in the estimated values of the SCC, why not settle on a value for the discount rate that is closest to the “correct” value? On this point the entire enterprise of using IAMs to set policy targets is revealed for what it is: A sophisticated and opaque exercise in creating forecasts far into the future that are based on guesses and subjective assumptions. Literally hundreds of papers have been written that address the issue of how to select the “correct” discount rate, but there is no “correct” answer.

In their initial estimation of the SCC, the IWG devoted nearly a quarter of their “Technical Support Document” to the subject of the discount rate.[222] In this long section the IWG explains and justifies their choice of the three rates that they used, 2.5%, 3% and 5%, but only two short paragraphs[223] on why they did not use a 7% rate that should have been considered according to OMB Circular A-4 — which is the directive that provides official guidance on how federal government regulatory benefit-cost analysis should be conducted.[224] Unstated, but clearly a factor, is that if the IWG had used a 7% discount rate in their analysis, much smaller estimates of the value of the SCC would have resulted. Instead, the IWG defends its use of the 3% rate as the “central value” in its analysis because it “...is consistent with estimates provided in the economics literature and OMB’s Circular A-4 guidance for the consumption rate of interest.”[225]

However, almost nothing in the literature of IAMs could be less certain than having a discount rate that is “consistent with estimates provided in the economics literature.” Rather, the choice of the discount rate is the most contentious issue in the IAM literature. In 2007 when Nicholas Stern published “The Economics of Climate Change: The Stern Review,”[226] the report was notable because it was the first major report from a well-respected economist that forcefully argued for immediate and major actions to slow the growth of $CO_2$ emissions. The report was met with a barrage of criticism, most of which pointed out that the major reason for the report’s conclusions was it has used a discount rate near zero to generate its gloomy outlook.[227]

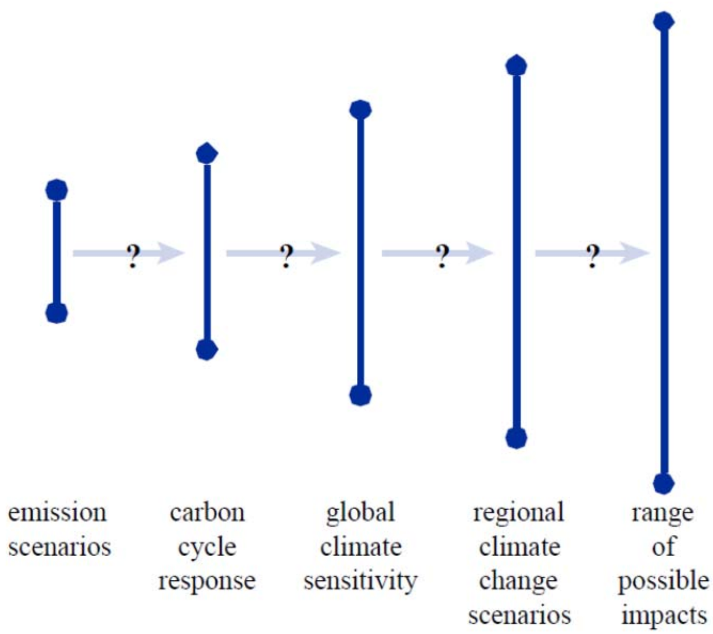
## V.C. Aggregation and the Cascade of Uncertainty

While some progress has been made in global science and in the understanding of how human activity interacts with and impacts the biosphere, the remaining areas of uncertainty are significant, especially and obviously because of the inability to foresee

[222]See “Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis”, Interagency Working Group on the Social Cost of Carbon, The White House, the United States Government, Under Executive Order 12866, Washington, D.C., February 2010, pp. 17-23.
[223]Op cit., IWG, 2010, p.19.
[224]Regulatory Planning and Review, Executive Order 12866 of September 30, 1993,” op. cit.
[225]Op cit., IWG, 2010, p. 23.
[226]Nicholas Stern, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, U.K. 2007.
[227]See William Nordhaus, “A Review of the Stern Review on the Economics of Climate Change”, op. cit. for an good example of a rebuttal to the Stern Review’s conclusions.

future developments. With respect to integrated assessment modeling, the uncertainties confronted at each stage of the process are magnified as the uncertainties surrounding each variable in the chain of computations are compounded by the uncertainties found in the next step, creating a "cascade of uncertainties" as one moves through the chain towards final conclusions. Figures V-7 and V-8 show the "uncertainty explosion" as these ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic, social, and political impacts and policy responses.[228] Each set of uncertainties through the IAM process gets magnified at each step until, by the end, it is unclear what reality is.

**Figure V-7**
**Range of Major Uncertainties Typical in Impact Assessments**




The authors of the IPCC Second Assessment report state "A single aggregated damage function or a 'best guess' climate sensitivity estimate is a very restricted representation of the wide range of beliefs available in the literature or among lead authors about climate sensitivity or climate damages. . . . The cascade of uncertainty implied by coupling the separate probability distributions for emissions and biogeochemical cycle calculations to arrive at concentrations needed to calculate radiative forcing, climate sensitivity, climate impacts, and valuation of such impacts into climate damage functions has yet to be produced in the literature."[229]

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[228]See IPCC, *Third Assessment Report: Climate Change 2001* (TAR), Chapter 2: "Method and Tools," p. 130. http://www.ipcc.ch/ipccreports/tar/wg2/pdf/wg2TARchap2.pdf.
[229]Ibid. p. 130.

In addition, the level of uncertainty does not remain constant over time. As Kelly and Kolstad note in their review of IAMs, there are two kinds of uncertainty, which they label stochastic uncertainty and parametric uncertainty. [230] The latter can be expected to decline over time as scientists learn more about the operation of the global climate system and the value for parameters such as "climate sensitivity" become more accurate. Stochastic uncertainty refers to those phenomena that impact economic or geophysical processes but are not included in the model, processes such as earthquakes, volcanic eruptions, or abrupt economic downturns such as the Global Financial Crisis. A major element of stochastic uncertainty is the fact that we cannot know the future trend of technology or the economy and are, therefore, always susceptible to "surprises".

**Figure V-7**
**Cascade of Uncertainties: With Each Additional Box the Uncertainties Increase**

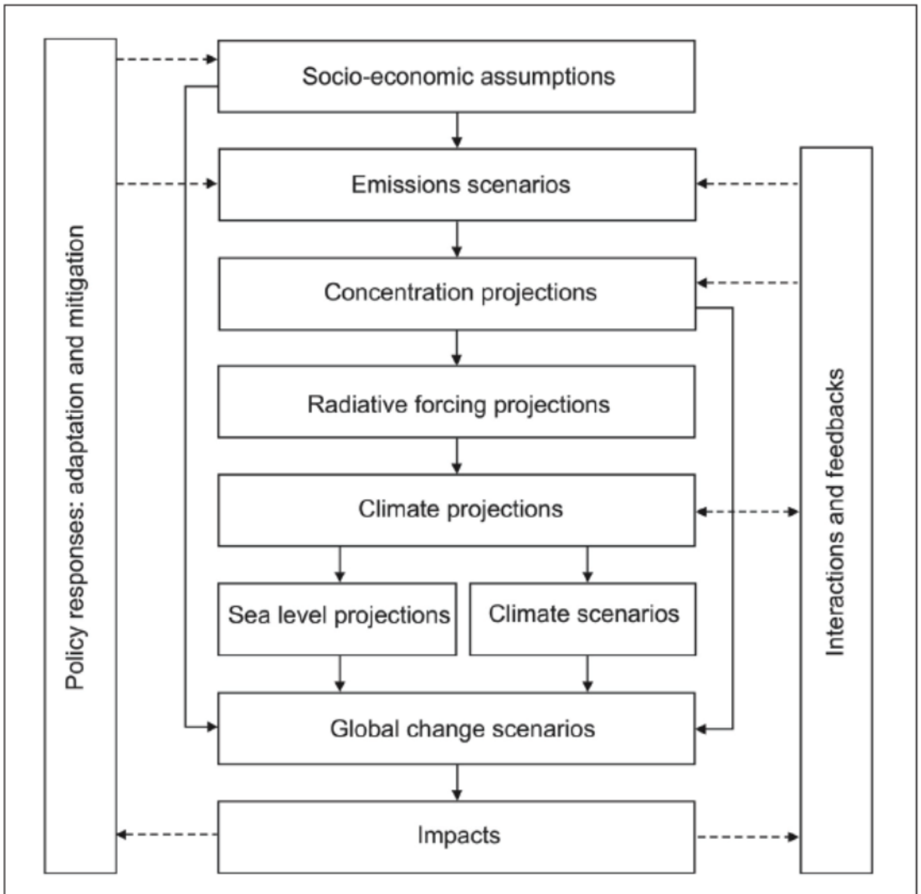


Figure 1.Cascade of Uncertainties. With each additional box the uncertainty increases. Source: Intergovernmental Panel on Climate Change (IPCC), Working Group I Third Assessment Report. 2001.

[230]See David L. Kelly and Charles D. Kolstad, "Integrated Assessment Models for Climate Change Control", US Department of Energy grant number DE-FG03-96ER62277, Current Version: November 1998. Pp. 8-9. http://www.econ.ucsb.edu/papers/wp31-98.pdf.

Some of the uncertainty currently present in IAMs may gradually lesson over time, and IAM model builders are including modeling techniques such as Monte Carlo analysis and stochastic simulation within their models to address the uncertainties. Nevertheless, for the foreseeable future IAM analysis will be saddled with the fact that the degree of uncertainty within the process is immense and renders any IAM results highly questionable.

### V.D. IWG SCC Estimates: "Close to Useless"

IAMs have been in use for over two decades and progress has been made in their sophistication and in the insights they provide about the interaction between human activities and the biosphere. In a background note for the Overseas Development Institute, Nicola Cantore summarized some of the positive results that arise from using IAMs to help design climate policies.[231] He noted that compared to other less sophisticated complex scientific tools, IAMs offer a number of benefits when designing policy:

- They allow the setting up of simulations based on scenarios for the future.
- They incorporate mechanisms governing the complex link between economy and environment.
- They can deal with uncertainty about the future evolution of economic and environmental parameters (e.g. technology, degree of absorption of pollution from the atmosphere).
- They can be used to isolate the effects of a particular parameter on other mechanisms governing economic and environmental processes (e.g. the effect of China's population growth on the rest of the world economy).
- They provide a large amount of information about the path of significant policy variables over time.

Nevertheless, despite the progress that has been made in the building and use of IAMs, perhaps most importantly in bringing together scholars and scientist in a joint effort to assess global climate change, the IAM process remains a very questionable tool for establishing explicit policy goals. In a recent assessment of the limitations of IAMs for use in policy, Granados and Carpintero conclude:[232]

> The lack of robustness of results of different IAMs indicates the limitations of the neoclassical approach, which constitutes the theoretical base of most IAMs; the

[231]See Nicola Cantore, "The Relevance of Climate Change Integrated Assessment Models," in *Policy Design*," Overseas Development Institute (ODI), Background Note, December 2009, p. 3, www.odi.org.uk/sites/odi.org.uk/files/odi-assets/publications-opinion-files/5060.pdf.

[232]Jose A. Tapia Granados and Oscar Carpintero, "Dynamics and Economic Aspects of Climate Change", Chapter 3 in *Combating Climate Change: An Agricultural Perspective*, edited by Manjit S. Kang & Surinder S. Banga, CRC Press, 2013. Pp. 37-38.

variety of so-called ad hoc assumptions (often qualified as "heroic" by their own authors), and the controversial nature of the methods to estimate the monetary value of non-market costs and benefits (mortality, morbidity, damage to ecosystems, etc.). These features explain why many contributions of this type of macroeconomics-oriented IAMs have been criticized for their dubious political usefulness and limited scientific soundness.

They then list several important shortcomings of IAMs, most of which have been discussed above:

- Lack of transparency to explain and justify the assumptions behind the estimates,
- Questionable treatment of uncertainty and discounting of the future,
- Assumption of perfect substitutability between manufactured capital and "natural" capital in the production of goods and services, and
- The way IAMs estimate monetary costs of non-market effects, which can lead to skepticism about policies based on the results of the models.

In an overview of questions of ethics and uncertainty that are endemic in the construction and application of IAMs to questions of global climate change, Frank Ackerman and his colleagues make the following points regarding the appropriateness of IAMs for policy choices:[233]

> There are two take-home messages here. The first is that policy makers and scientists should be skeptical of efforts by economists to specify optimal policy paths using the current generation of IAMs. These models do not embody the state of the art in the economic theory of uncertainty, and the foundations of the IAMs are much shakier than the general circulation models that represent our best current understanding of physical climate processes. ***Not only do the IAMs entail an implicit philosophical stance that is highly contestable, they suffer from technical deficiencies that are widely recognized within economics.*** Second, economists do have useful insights for climate policy. While economics itself is insufficient to determine the urgency for precautionary action in the face of low-probability climate catastrophes, or make judgments about inter-generational and intragenerational justice, it does point the way towards achieving climate stabilization in a cost-effective manner**. *IAMs cannot, however, be looked to as the ultimate arbiter of climate policy choices.*** *(Emphasis added by authors.)*

Thus, there is a limited amount of research linking climate impacts to economic damages, and much of this is speculative, at best. Even the IWG admits that the exercise is subject to "simplifying assumptions and judgments reflecting the various

[233]Frank Ackerman, et al, "Limitations of Integrated Assessment Models of Climate Change," *Climatic Change*, 2009, 95:297–315, p. 312.

modelers' best attempts to synthesize the available scientific and economic research characterizing these relationships."[234] Further, the IWG also admits that each model uses a different approach to translate global warming into damages, and that transforming the stream of economic damages over time into a single value requires "judgments" about how to discount them.[235]

This chapter began with a quote from Nicholas Stern, and it is appropriate to conclude with a quote from him. Here he summarizes the many of the weaknesses of integrated assessment modeling discussed here.[236]

> As I have argued, it is very hard to believe that models where radically different paths have to be compared, where time periods of hundreds of years must be considered, where risk and uncertainty are of the essence, and where many crucial economic, social, and scientific features are poorly understood, can be used as the main quantitative plank in a policy argument. Thus, IAMs, while imposing some discipline on some aspects of the argument, risk either confusing the issues or throwing out crucial features of the problem.

In conclusion, we find that, to paraphrase Robert Pindyck,[237] the IWG SCC estimates are based on IAMs containing fatal flaws and that the IWG estimates are thus "close to useless" as tools for policy analysis.

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[234] Interagency Working Group, 2010, op. cit.
[235] Ibid.
[236] Stern, op cit., "The Economics of Climate Change", p. 17.
[237] Pindyck, op. cit.

# VI. CAVEATS AND IMPLICATIONS

The B-C ratio is simply the ratio of benefits to costs, and its validity depends on the veracity of the benefit estimates and of the cost estimates. How viable are these estimates? The benefit estimates are, if anything, more understandable, believable, and robust than the cost estimates.

## VI.A. The Cost Estimates

With respect to the SSC estimates, as discussed in Chapter V, these are questionable because they are based on highly speculative assumptions, forecasts, integrated assessment model (IAM) simulations, damage functions, discount rates, etc. Numerous IAMs have been developed and used to estimate the SCC and evaluate alternative abatement policies. Indeed, the IWG relied critically on IAMs to develop its SCC estimates. However, as Robert Pindyck notes, these models have crucial flaws that make them "close to useless" as tools for policy analysis; for example:[238]

- Certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce.
- The models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation.
- The models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome.
- IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading.
- The damage functions used in most IAMs are completely made up, with no theoretical or empirical foundation — and yet those damage functions are taken seriously when IAMs are used to analyze climate policy.

Pindyck concludes that IAMs are of little or no value for evaluating alternative climate change policies and estimating the SCC. On the contrary, an IAM-based analysis suggests a level of knowledge and precision that is nonexistent, and allows the modeler to obtain almost any desired result because key inputs can be chosen arbitrarily.[239]

A study by the National Academies of Science (NAS) found that an SCC assessment suffers from uncertainty, speculation, and lack of information about:[240]

- Future emissions of greenhouse gases,

[238] Robert S. Pindyck, "Climate Change Policy: What Do The Models Tell Us?" op. cit.
[239] Ibid.
[240] National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Washington, D.C.: National Academies Press, 2009.

- The effects of past and future emissions on the climate system,
- The impact of changes in climate on the physical and biological environment, and
- The translation of these environmental impacts into economic damages.

NAS thus concludes that "As a result, any effort to quantify and monetize the harms associated with climate change will raise serious questions of science, economics, and ethics and should be viewed as provisional."[241]

Further, the differences in the 2010 and 2013 SCC estimates are so large and of such immense potential significance as to raise serious questions as to their validity – especially since, prior to February 2010 there was no "official" Federal government estimate of the value of SCC.[242] If any valid government economic estimates, such as GDP or unemployment, were revised by 30 - 50 percent within a three year period it would represent a scandal and a farce. For example, in 2010, U.S. GDP was estimated to be about $14.6 trillion.[243] While BEA always makes slight revisions to its GDP estimates in subsequent years, it is inconceivable that in 2013 it would have published a revised estimate of 2010 U.S. GDP in the range of $22 trillion.

Nevertheless, despite these overwhelming theoretical and empirical difficulties, the IWG proceeded to develop precise SCC estimates (the 2010 IWG report published SCC estimates in tenths of dollars)[244] that it contends are useful in estimating the social benefits of reducing carbon dioxide emissions. The IWG even admitted that "The limited amount of research linking climate impacts to economic damages makes this modeling exercise even more difficult" and that the exercise is subject to "simplifying assumptions and judgments reflecting the various modelers' best attempts to synthesize the available scientific and economic research characterizing these relationships."[245]

In short, the SCC estimates developed and utilized by the IWG have little or no validity and are, as Pindyck concluded, "close to useless."[246]

[241]Ibid.
[242]"Official" government estimates vary widely. For example, in 1996 the Minnesota PUC established a range of $0.28 to $2.92 per ton (1993 dollars) as the environmental cost of carbon dioxide. Translated into 2007 dollars to be consistent with the IWG estimates, this is a range of $0.38 to $3.97 per ton. See State Of Minnesota, Office of Administrative Hearings For the Minnesota Public Utilities Commission, "In the Matter of the Quantification of Environmental Costs Pursuant to Laws of Minnesota 1993, Chapter 356, Section 3 Findings of Fact, Conclusions, Recommendation," March 22, 1996.
[243]Obtained from the U.S. Bureau of Economic Analysis web site www.bea.gov.
[244]See Table V-2.
[245]U.S. Interagency Working Group, 2010 and 2013, op. cit.
[246]Pindyck, op. cit.

## VI.B. The Benefit Estimates

The benefit estimates developed here are simple, straightforward, logical, transparent, understandable, and based on two centuries of historical fact. The $CO_2$ benefits used in the cost-benefit comparison herein are almost entirely indirect: they derive from the use of fossil fuels which produce $CO_2$. There is extensive literature verifying the critical and essential role of fossil fuels in creating current technology, wealth, and high standards of living. Further, as discussed here and in Chapter II, this relationship will remain well into the foreseeable future. At present, about 81 percent of world energy is derived from fossil fuels and in 2040 between 75 and 80 percent of world energy will still be derived from fossil fuels.[247]

The benefit estimates derived here are extremely large compared even to the questionable IWG SCC estimates, and thus the B-C ratios are very high. The benefit estimates can be modified: They can be scaled, adjusted, forecast, expressed as average or marginal values, be converted to different base year dollars, estimated for past, current, or future years, etc. Nevertheless, they will remain orders of magnitude larger than any reasonable SCC estimates and, therefore, the B-C ratios will remain very high.

[247] This is true in both the EIA and the IEA forecasts.

## APPENDIX I: THE 2008 AND 2009 ENERGY COST SURVEYS

### The 2008 Energy Cost Survey

In 2008, the Energy Programs Consortium and the National Energy Assistance Directors conducted a comprehensive survey to develop an understanding of the sacrifices and tradeoffs that low, moderate, and middle income households have made in response to rising energy costs.[248] The purpose of the study was to examine how increasing home energy and gasoline prices have impacted low- and moderate-income households in the U.S. The study examined the extent to which households have been impacted by the higher prices and how they have coped with these increased prices. Households were asked about beneficial behaviors such as energy conservation and investment in more efficient appliances, and about dangerous sacrifices such as going without food and medicine and keeping the home at an unsafe temperature.[249]

Respondents were asked whether they had taken various actions related to their basic needs as a result of increased home energy or gasoline costs. Table A.I-1 shows that many households reported major sacrifices due to these increased costs:

- 43 percent reported that they reduced purchases of basic household necessities.
- 43 percent reported that they reduced purchases of food.
- 18 percent reported that they reduced purchases of medicine.
- 11 percent said that they changed plans for their education or their children's education.

Respondents with children were more likely to report that they had taken all of these actions.

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[248]"2008 Energy Costs Survey, op. cit.

[249]The sample, purchased from Genesys Sampling Systems, was developed from an unduplicated list of over 97 million households in the U.S. with listed telephone numbers. The list was developed from multiple sources to increase coverage rates, including telephone directories, automobile and motorcycle registrations, real estate listings, and driver's license data. The database is updated bimonthly to provide current data on active households. This survey attempted to collect data from lower and middle lower income households. To accomplish that goal, the requested sample targeted households with estimated annual income at or below $60,000. The sample income data were developed by the sample vendor from self-reports to a panel survey within the past two years and through multiple regression analysis using home value, occupation, and automobile data, as well as other variables as predictors. The listed sample does not include households without telephones or with unlisted telephone numbers.

**Table A.I-1**
**Actions Taken as a Result of Increased Home Energy or Gasoline Costs — Actions Related to Basic Needs**

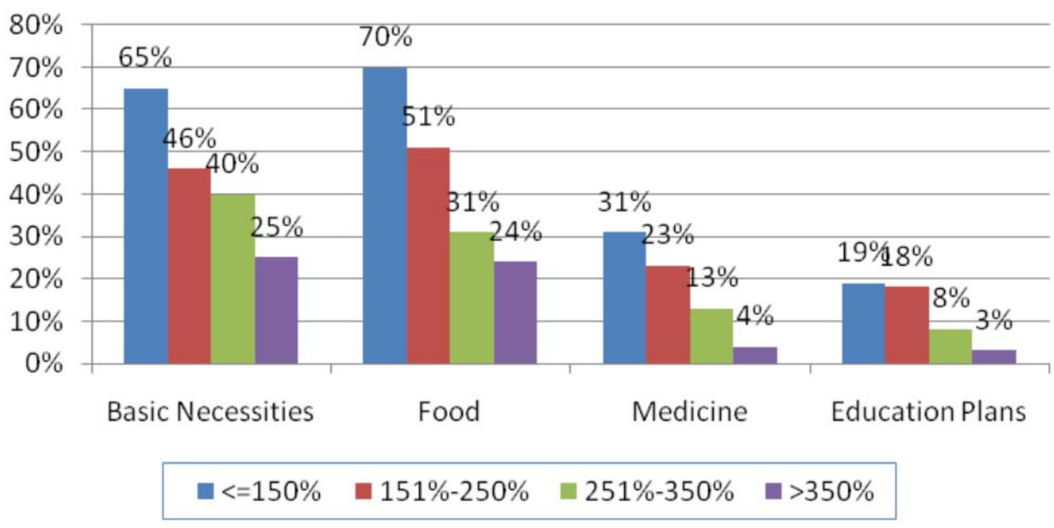
| | All Respondents | Households With Members ≥ 60 | Households With Children ≤ 18 |
|---|---|---|---|
| **Reduced purchases of basic household necessities** | 43% | 43% | 52% |
| **Reduced purchases of food** | 43% | 42% | 56% |
| **Reduced purchases of medicine** | 18% | 17% | 24% |
| **Changed plans for your education or your children's education** | 11% | 5% | 25% |

Source: 2008 Energy Costs Survey (NEADA).

Figure A.I-1 shows that lower income households were more likely to report that increased home energy and gasoline costs impacted their purchases of basic necessities, food, medicine, and education plans:

- 70 percent of low-income respondents stated that that they reduced purchases of food due to these increased costs.
- 31 percent said that they reduced purchases of medication.
- Nine percent said that they had changed plans for their education or their children's education.

**Figure A.I-1**
**Percent of Respondents Who Stated That Increased Energy and Gas Costs Impacted Purchases and Plans**




Source: 2008 Energy Costs Survey (NEADA).

Even high-income households said that these increased costs impacted their behavior. One quarter of households with income above 350 percent of poverty said that they reduced purchases of basic necessities.

Table A.I-2 provides additional detail on actions households have taken by income and poverty level.

**Table A.I-2**
**Actions Taken as a Result of Increased Home Energy or Gasoline Costs – Actions Related to Basic Needs by Income and Poverty Level**

| | Annual Income | | | Poverty Level | | | | No Income Provided |
|---|---|---|---|---|---|---|---|---|
| | <$25,000 | $25,000-$50,000 | >$50,000 | <=150% | 151%-250% | 251%-350% | >350% | |
| **Reduced purchases of basic household necessities** | 61% | 43% | 28% | 65% | 46% | 40% | 25% | 32% |
| **Reduced purchases of food** | 64% | 39% | 30% | 70% | 51% | 31% | 24% | 26% |
| **Reduced purchases of medicine** | 29% | 16% | 7% | 31% | 23% | 13% | 4% | 14% |
| **Changed plans for your education or your children's education** | 15% | 15% | 6% | 19% | 18% | 8% | 3% | 4% |

Source: 2008 Energy Costs Survey (NEADA).

Respondents were also asked about the impact of increased home energy and gasoline costs on their energy usage. Table A.1-3 shows that large percentages of households made sacrifices due to increased energy costs:

- 28 percent said they had closed off part of their home because they could not afford to heat or cool it.
- 19 percent said that they kept their home at a temperature they felt was unsafe or unhealthy.
- 11 percent said that they left the home for part of the day because it was too hot or too cold.

**Table A.1-3**
**Actions Taken as a Result of Increased Home Energy or**

**Gasoline Costs — Actions Related to Energy Usage**

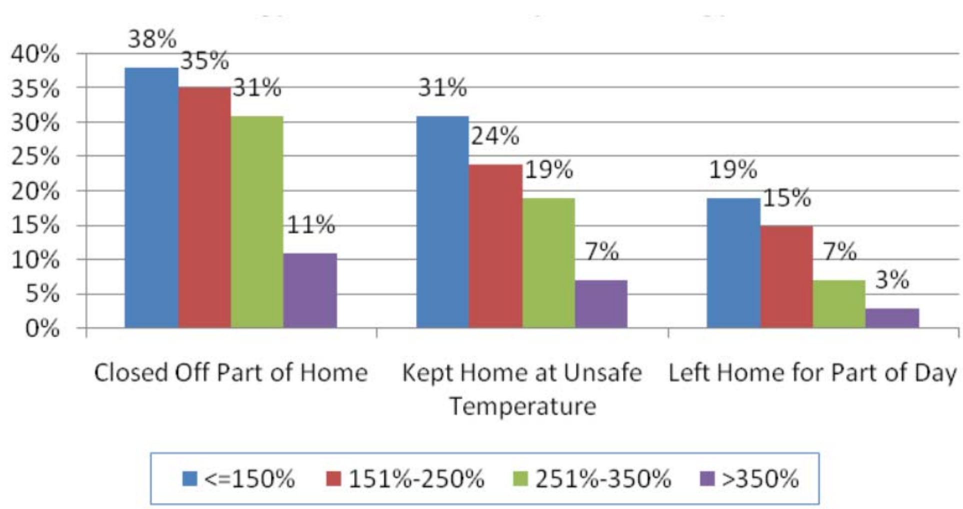
| | All Respondents | Households with Members 60 or Older | Households with Children 18 or Younger |
|---|---|---|---|
| Close off part of your home because you could not afford to heat or cool it | 28% | 28% | 26% |
| Keep your home at a temperature you thought was unsafe or unhealthy at any time of the year | 19% | 19% | 20% |
| Leave your home for part of the day because it was too hot or too cold | 11% | 8% | 15% |

Source: 2008 Energy Costs Survey (NEADA).

Figure A.I-2 shows that lower income households were more likely to report that they had changed their behavior related to energy use due to increased home energy and gas costs:

- 38 percent of low income households said that they closed off part of their home.
- 31 percent said they kept their home at an unsafe temperature.
- 19 percent said that they left their home for part of the day.

**Figure A.I-2**
**Percent of Respondents Who Stated That Increased Energy and Gas Costs Impacted Energy Behavior**




Source: 2008 Energy Costs Survey (NEADA).

Table A.1-4 provides additional detail on energy-related actions households have taken due to increased home energy and gasoline costs by income and poverty level.

**Table A.1-4**
**Actions Taken as a Result of Increased Home Energy or Gasoline Costs — Actions Related to Energy Usage by Income and Poverty Level**

| | Annual Income | | | Poverty Level | | | | No Income Provided |
|---|---|---|---|---|---|---|---|---|
| | <$25,000 | $25,000-$50,000 | >$50,000 | <=150% | 151%-250% | 251%-350% | >350% | |
| Close off part of your home because you could not afford to heat or cool it | 37% | 33% | 13% | 38% | 35% | 31% | 11% | 22% |
| Keep your home at a temperature you thought was unsafe or unhealthy at any time of the year | 30% | 22% | 6% | 31% | 24% | 19% | 7% | 12% |
| Leave your home for part of the day because it was too hot or too cold | 17% | 12% | 5% | 19% | 15% | 7% | 3% | 4% |

Source: 2008 Energy Costs Survey (NEADA).

Respondents were also asked about the impact of increased home energy and gasoline costs on their energy bill payments. Table A.1-5 shows that many households were unable to pay energy bills and had their service terminated due to increased costs:

- 15 percent stated that they skipped paying or paid less than a full home energy bill.
- Four percent stated that they had their electricity shut off.
- Five percent stated that they had their natural gas shut off.
- Households with children were more likely to experience all of these.

**Table A.1-5**
**Actions Taken as a Result of Increased Home Energy or Gasoline Costs — Actions Related to Energy Bill Payment**

| | All Respondents | Households with Members 60 or Older | Households with Children 18 or Younger |
|---|---|---|---|
| Skip paying your home energy bill or pay less than your full home energy bill | 15% | 9% | 29% |
| Have your electricity shut off because you were unable to pay your bill | 4% | 2% | 10% |
| Have your natural gas shut off because you were unable to pay your bill | 5% | 2% | 11% |

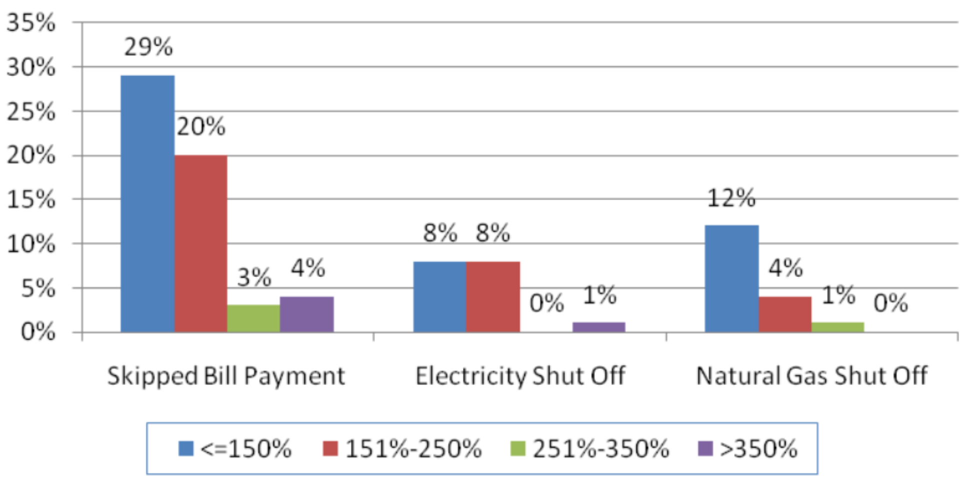
Source: 2008 Energy Costs Survey (NEADA).

Figure A.I-3 shows that for the most part it is low- and moderate-income households who sacrifice their energy bill payments when home energy and gasoline costs increase:

- 29 percent of low-income and 20 percent of moderate-income households skipped paying or paid less than a full energy bill.
- Eight percent of low-income and eight percent of moderate-income households had their electricity shut off.
- 12 percent of low-income and four percent of moderate-income households had their natural gas shut off.

Table A.I-6 provides additional detail on energy bill payment actions households have experienced due to increased home energy and gasoline costs by income and poverty level.

**Figure A.I-3**
**Percent of Respondents Who Stated that Increased Energy and Gas Costs Impacted Energy Payments**




Source: 2008 Energy Costs Survey (NEADA).

**Table A.1-6**
**Actions Taken as a Result of Increased Home Energy or Gasoline Costs — Actions Related to Energy Bill Payment By Income and Poverty Level**

| | Annual Income | | | Poverty Level | | | | No Income Provided |
|---|---|---|---|---|---|---|---|---|
| | <$25,000 | $25,000-$50,000 | >$50,000 | <=150% | 151%-250% | 251%-350% | >350% | |
| Skip paying your home energy bill or pay less than your full home energy bill | 25% | 14% | 6% | 29% | 20% | 3% | 4% | 8% |
| Have your electricity shut off because you were unable to pay your bill | 6% | 4% | 2% | 8% | 8% | 0% | 1% | 3% |
| Have your natural gas shut off because you were unable to pay your bill | 10% | 3% | 2% | 12% | 4% | 1% | 0% | 0% |

Source: 2008 Energy Costs Survey (NEADA).

## The 2009 National Energy Assistance Survey

In 2009, the National Energy Assistance Directors Association, representing state Low Income Home Energy Assistance Program (LIHEAP) directors, conducted a survey to update the information about LIHEAP-recipient households that was collected in the 2003, 2005, and 2008 surveys. This national energy assistance survey documented changes in the affordability of energy bills, the need for LIHEAP, and the choices that low-income households make when faced with unaffordable energy bills. The 2009 survey selected a new sample of 2009 LIHEAP recipients to document changes in the need for LIHEAP and changes in the choices that low-income households make when faced with unaffordable energy bills.[250]

### Low Income Home Energy Assistance Program

LIHEAP is administered by the U.S. Department of Health and Human Services (HHS). The purpose of LIHEAP is "to assist low-income households, particularly those with the lowest incomes, that pay a high proportion of household income for home energy, primarily in meeting their immediate home energy needs."[251] Federal funds for LIHEAP are allocated by HHS to the grantees (i.e., the 50 states, District of Columbia, 128 tribes and tribal organizations, and five insular areas) as a block grant. Program funds are distributed by a formula, which is weighted towards relative cold-weather conditions. Program funds are disbursed to LIHEAP income-eligible households under programs designed by the individual grantees.

[250]National Energy Assistance Directors' Association, *2009 National Energy Assistance Survey, Final Report*, Washington, D.C., April 2009.
[251]See "Low Income Home Energy Assistance Program. Report to Congress for Fiscal Year 2001." U.S. Department of Health and Human Services, Administration for Children and Families, Office of Community Services, Division of Energy Assistance.

LIHEAP grantees can use two income-related standards in determining household eligibility for LIHEAP assistance: Categorical eligibility for households with one or more individuals receiving Temporary Assistance for Needy Families, Supplemental Security Income payments, Food Stamps, or certain needs-tested veterans and survivors payments, without regard for household income. Income eligibility is for households with incomes that do not exceed the greater of an amount equal to 150 percent of the federal poverty level, or an amount equal to 60 percent of the state median income. Grantees may target assistance to poorer households by setting lower income eligibility levels, but grantees are prohibited from setting income eligibility levels lower than 110 percent of the poverty level. Eligibility priority may be given to households with high energy burden or need.

The statutory intent of LIHEAP is to reduce home heating and cooling costs for low-income households.[252] However, information on total residential energy costs is more accessible and more apparent to LIHEAP-recipient respondents. Most states use the 150 percent of federal poverty level maximum as the guideline — 150 percent of federal poverty in FY 2008 was $16,245 for a single person and $33,075 for a family of four.

The 2009 survey collected the following information from LIHEAP-recipient households:

- Demographic, energy expenditure, and income information,
- Healthy home behaviors,
- History of LIHEAP participation,
- Constructive actions taken to meet energy expenses,
- Signs of unaffordable energy bills,
- Health and safety consequences of unaffordable energy bills,
- Effects of unaffordable energy bills on housing,
- Changes in financial situation and affordability of home energy bills, and
- Impact and importance of LIHEAP benefits for recipient households.

The 2009 survey included the 12 states that were included in the 2008 survey and a larger sample of Connecticut LIHEAP recipients.

### Detailed Findings

Table A.1-7 shows the percent of respondents who had to go without showers due to lack of hot water, had to go without hot meals due to lack of cooking fuel, or had to use candles or lanterns due to lack of lights. The table shows that seven to ten percent of respondents faced these problems.

[252]Ibid.

**Table A.1-7**
**Had to Go Without Showers, Hot Meals, or Lights During the Past Year**

| | Percent of Respondents |
|---|---|
| **Had to Go Without Showers or Baths Due to Lack of Hot Water** | 10% |
| **Had to Go Without Hot Meals Due to Lack of Cooking Fuel** | 7% |
| **Had to Use Candles or Lanterns Due to Lack of Lights** | 8% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-8 shows the percent of respondents who had to go without showers, hot meals, or lights during the past year by vulnerable group. It shows that households with children and households without vulnerable members were most likely to face these problems.

Table A.1-9 shows the percent of households who had these problems by poverty group, and illustrates that households in the lower poverty groups are most likely to face these problems.

**Table A.1-8**
**Had to Go Without Showers, Hot Meals, or Lights During the Past Year, By Vulnerable Group**

| | Senior | Disabled | Child Under 18 | Non-Vulnerable |
|---|---|---|---|---|
| **Number of Respondents** | 757 | 788 | 778 | 152 |
| **Had to Go Without Showers or Baths Due to Lack of Hot Water** | 5% | 12% | 13% | 14% |
| **Had to Go Without Hot Meals Due to Lack of Cooking Fuel** | 3% | 8% | 10% | 10% |
| **Had to Use Candles or Lanterns Due to Lack of Lights** | 4% | 9% | 12% | 13% |

Source: National Energy Assistance Directors' Association, 2009.

**Table A.1-9**
**Had to Go Without Showers, Hot Meals, or Lights During the Past Year By Poverty Group**

| | Poverty Level | | | |
|---|---|---|---|---|
| | 0-50% | 51-100% | 101-150% | >150% |
| **Number of Respondents** | 286 | 673 | 557 | 312 |
| **Had to Go Without Showers or Baths Due to Lack of Hot Water** | 14% | 11% | 5% | 10% |
| **Had to Go Without Hot Meals Due to Lack of Cooking Fuel** | 12% | 8% | 3% | 6% |
| **Had to Use Candles or Lanterns Due to Lack of Lights** | 14% | 9% | 5% | 5% |

Source: National Energy Assistance Directors' Association, 2009.

Many respondents faced housing problems due to unaffordable energy bills. Table A.1-10 shows that:

- 31 percent skipped a mortgage payment.
- Five percent were evicted.
- Four percent had a mortgage foreclosure.
- Twelve percent moved in with friends or family.
- Three percent moved into a shelter or were homeless.

Table A.1-11 shows the results by vulnerable group, and illustrates that households with children were most likely to face these problems:

- 45 percent of these households skipped a mortgage payment.
- Eight percent were evicted.
- 17 percent moved in with friends or family.

**Table A.1-10**
**Housing Problems Due to Energy Bills in the Past Five Years**

| | Percent of Respondents |
|---|---|
| **Did not Make Full Rent or Mortgage Payment** | 31% |
| **Evicted from Home or Apartment** | 5% |
| **Had Mortgage Foreclosure** | 4% |
| **Moved in With Friends or Family** | 12% |
| **Moved into Shelter or Was Homeless** | 3% |

Source: National Energy Assistance Directors' Association, 2009.

**Table A.1-11**
**Housing Problems Due to Energy Bills in the Past Five Years, by Vulnerable Group**

| | Senior | Disabled | Child Under 18 | Non-Vulnerable |
|---|---|---|---|---|
| **Number of Respondents** | 757 | 788 | 778 | 152 |
| **Did not Make Full Rent or Mortgage Payment** | 16% | 32% | 45% | 39% |
| **Evicted from Home or Apartment** | 3% | 5% | 8% | 3% |
| **Had Mortgage Foreclosure** | 2% | 4% | 6% | 2% |
| **Moved in With Friends or Family** | 6% | 12% | 17% | 15% |
| **Moved into Shelter or Was Homeless** | 1% | 4% | 5% | 3% |

Source: National Energy Assistance Directors' Association, 2009.

**Problems Meeting Energy Needs**

Table A.1-12 presents the results by poverty group, and shows that the lowest poverty group was most likely to face these problems.

**Table A.1-12**
**Housing Problems Due to Energy Bills in the Past Five Years, by Poverty Group**

| | Senior | Disabled | Child Under 18 | Non-Vulnerable |
|---|---|---|---|---|
| **Number of Respondents** | 757 | 788 | 778 | 152 |
| **Did not Make Full Rent or Mortgage Payment** | 16% | 32% | 45% | 39% |
| **Evicted from Home or Apartment** | 3% | 5% | 8% | 3% |
| **Had Mortgage Foreclosure** | 2% | 4% | 6% | 2% |
| **Moved in With Friends or Family** | 6% | 12% | 17% | 15% |
| **Moved into Shelter or Was Homeless** | 1% | 4% | 5% | 3% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-13 shows the percent of respondents with housing problems by whether or not they own their home. The table shows that respondents who do not own their homes were more likely to face these problems.

**Table A.1-13**
**Housing Problems Due to Energy Bills in the Past Five Years, by Home Ownership**

| | Own Home | Does Not Own Home |
|---|---|---|
| **Number of Respondents** | 826 | 990 |
| **Did not Make Full Rent or Mortgage Payment** | 27% | 36% |
| **Evicted from Home or Apartment** | 3% | 7% |
| **Had Mortgage Foreclosure** | 4% | 3% |
| **Moved in With Friends or Family** | 7% | 16% |
| **Moved into Shelter or Was Homeless** | 1% | 6% |

Source: National Energy Assistance Directors' Association, 2009.

### Medical and Health Problems

Table A.1-14 shows that, of the respondents:

- 30 percent went without food for at least one day.
- 41 percent went without medical or dental care.
- 33 percent did not fill a prescription or took less than their full dose of prescribed medication.
- 22 percent were unable to pay their energy bill due to medical expenses.

**Table A.1-14**
**Medical and Health Problems Due to Energy Bills in the Past Five Years**

| | Percent of Respondents |
|---|---|
| **Went Without Food for at Least One Day** | 30% |
| **Went Without Medical or Dental Care** | 41% |
| **Didn't Fill Prescription or Took Less Than Full Dose** | 33% |
| **Unable to Pay Energy Bill Due to Medical Expenses** | 22% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-15 examines medical and health problems by vulnerable group. It illustrates that households without vulnerable members are most likely to go without food and to go without medical or dental care, and almost three quarters of this group said that they went without medical or dental care in the past five years.

**Table A.1-15**
**Medical and Health Problems Due to Energy Bills in the Past Five Years, By Vulnerable Group**

| | Senior | Disabled | Child Under 18 | Non-Vulnerable |
|---|---|---|---|---|
| **Number of Respondents** | 757 | 788 | 778 | 152 |
| **Went Without Food for at Least One Day** | 20% | 36% | 33% | 49% |
| **Went Without Medical or Dental Care** | 29% | 41% | 45% | 72% |
| **Didn't Fill Prescription or Took Less Than Full Dose** | 26% | 40% | 37% | 40% |
| **Unable to Pay Energy Bill Due to Medical Expenses** | 16% | 28% | 26% | 24% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-16 shows responses to questions about medical and health problems by poverty group. It shows that there is not a strong relationship between poverty level and the presence of these problems.

**Table A.1-16**
**Medical and Health Problems Due to Energy Bills in the Past Five Years, By Poverty Group**

| | Poverty Level | | | |
|---|---|---|---|---|
| | **0-50%** | **51-100%** | **101-150%** | **>150%** |
| **Number of Respondents** | 286 | 673 | 557 | 312 |
| **Went Without Food for at Least One Day** | 33% | 33% | 23% | 30% |
| **Went Without Medical or Dental Care** | 43% | 40% | 40% | 42% |
| **Didn't Fill Prescription or Took Less Than Full Dose** | 33% | 33% | 32% | 35% |
| **Unable to Pay Energy Bill Due to Medical Expenses** | 23% | 23% | 20% | 25% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-17 shows the percent of respondents who did not take prescribed medication by the presence of a serious medical condition. The table shows that 37 percent of households with a serious medical condition skipped taking their prescription medication, compared to 16 percent without a serious medical condition.

Table A.1-18 shows the percent of respondents who skipped taking prescription medication by the presence of necessary medical equipment that uses electricity. It shows that 45 percent of those with medical equipment skipped taking their medication, compared to 29 percent without the equipment.

**Table A.1-17**

**Did Not Fill Prescription or Took Less Than the Full Dose of Prescribed Medicine Due to Energy Bills in the Past Five Years, By Presence of Serious Medical Conditions**

| | Didn’t Fill Prescription or Took Less Than the Full Dose of Prescribed Medicine | |
|---|---|---|
| | Household Member with Serious Medical Condition | No Household Member With Serious Medical Condition |
| **Number of Respondents** | 1,509 | 307 |
| **Yes** | 37% | 16% |
| **No** | 63% | 84% |
| **Don’t Know/ No Answer** | <1% | 0% |

Source: National Energy Assistance Directors’ Association, 2009.

**Table A.1-18**
**Did Not Fill Prescription or Took Less Than the Full Dose of Prescribed Medicine due to Energy Bills in the Past Five Years, By Presence of Necessary Medical Equipment the Uses Electricity**

| | Didn’t Fill Prescription or Took Less Than the Full Dose of Prescribed Medicine | |
|---|---|---|
| | Necessary Medical Equipment That Uses Electricity | No Necessary Medical Equipment That Uses Electricity |
| **Number of Respondents** | 448 | 1,364 |
| **Yes** | 45% | 29% |
| **No** | 55% | 70% |
| **Don’t Know/ No Answer** | <1% | <1% |

Source: National Energy Assistance Directors’ Association, 2009.

Table A.1-19 shows the percent of respondents who said that they were unable to pay their energy bill due to medical expenses by the presence of a serious medical condition. It shows that 25 percent of those with a serious medical condition were unable to pay their energy bill and nine percent without a serious medical condition were unable to pay their energy bill due to medical expenses.

**Table A.1-19**
**Unable to Pay Energy Bill Due to Medical Expenses in the Past Five Years, By Presence of Serious Medical Conditions**

| | Unable to Pay Energy Bill Due to Medical Expenses | |
|---|---|---|
| | Household Member with Serious Medical Condition | No Household Member With Serious Medical Condition |
| **Number of Respondents** | 1,509 | 307 |
| **Yes** | 25% | 9% |
| **No** | 74% | 89% |
| **Don't Know/ No Answer** | 1% | 2% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-20 shows the percent of respondents who became sick and needed to go to the doctor or hospital because the home was too cold. The table shows that 17 percent became sick and needed to go to the doctor or hospital because the home was too cold, and three percent became sick and needed to go to the doctor or hospital because the home was too hot.

**Table A.1-20**
**Someone in Household Became Sick Because Home was Too Cold or Too Hot in the Past Five Years**

| | Became Sick | Became Sick and Needed to Go to the Doctor or Hospital |
|---|---|---|
| **Home Was Too Cold** | 25% | 17% |
| **Home Was Too Hot** | 4% | 3% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-21 shows the percent of respondents who became sick and needed to go to the doctor or hospital because the home was too cold by vulnerable group. It shows that households without vulnerable members were most likely to become sick, but that households with disabled members, households with children, and households with no vulnerable members were most likely to become sick and need to go to the doctor or hospital because the home was too cold.

**Table A.1-21**
**Someone in Household Became Sick Because Home was Too Cold in the Past Five Years, by Vulnerable Group**

| | Didn't Fill Prescription or Took Less Than the Full Dose of Prescribed Medicine | |
|---|---|---|
| | **Necessary Medical Equipment That Uses Electricity** | **No Necessary Medical Equipment That Uses Electricity** |
| **Number of Respondents** | 448 | 1,364 |
| **Yes** | 45% | 29% |
| **No** | 55% | 70% |
| **Don't Know/ No Answer** | <1% | <1% |

Source: National Energy Assistance Directors' Association, 2009.

Table A.1-22 shows the percent of respondents with a serious medical condition who became sick because the home was too hot or too cold and needed to go to the doctor or hospital. The table shows that 26 percent of respondents with a serious medical condition became sick because their home was too hot or too cold and 18 percent needed to go to a doctor or to the hospital due to this illness.

**Table A.1-22**
**Household Member With Allergies, Asthma, Emphysema, or COPD, High Blood Pressure, Heart Disease, or Stroke Got Sick Because the Household was Too Hot or Too Cold and Needed to Go to the Doctor or Hospital in the Past Year**

| | Became Sick | Needed to Go to the Doctor or Hospital |
|---|---|---|
| **Number of Respondents** | 1,509 | 1,509 |
| Yes | 26% | 18% |
| No | 74% | 8% |
| Don't Know | <1% | 0% |
| Did no Become Sick | -- | 74% |

Source: National Energy Assistance Directors' Association, 2009.

These tables confirm the extremely regressive nature of rising energy prices, and increased energy costs have further encroached upon the already-strained resources of the lowest-income households. These families have experienced a diminishing quality of life as they become increasingly unable to provide for their most basic needs.

## APPENDIX II: THEORETICAL ANALYSIS OF THE RELATIONSHIP BETWEEN ENERGY COSTS AND THE ECONOMY

Beginning with the oil supply shocks of the 1970's, analyses that have addressed the impact of energy price shocks on economic activity have produced, and continue to produce, a steady stream of reports and studies on the topic.[253] Here we first analyze the issues surrounding attempts to gauge the short-run impacts of energy price changes and then examine some of the issues involved in studies of the long-run impacts.

### Short-Run Effects

Following the disruptive oil shocks of the 1970's, what began as a seemingly straight forward attempt to establish the quantitative relationship between oil price changes and the economy has evolved over the last three decades into an ongoing scholarly debate. While most economists who have examined this issue agree that there is an inverse relationship between energy prices and economic activity, there is little agreement as to the size of the relationship, the channels through which energy price changes alter economic activity, or how stable the relationship might be.

James Hamilton is generally credited with writing the first influential paper to demonstrate that there was causality that ran from oil price increases and U.S. recessions.[254] Hamilton argued that oil price increases had been responsible for all but one of the U.S. recessions since the end of WWII. Other scholars produced studies that supported Hamilton's findings, either with respect to the U.S. economy or to the economies of other countries.

However, researchers began to find anomalies in the published research that raised questions about how solid the economic relationship between oil prices and economic activity actually was. Some of the more contentious issues concerned the mechanisms through which oil price changes impacted economic activity, the reason or reasons why oil price impacts apparently were asymmetric — causing economic recessions when prices increased, but producing no economic boom when prices declined, as they did during much of the 1980's, and whether or not it was oil price shocks or something else (monetary policy) that caused the reaction.

One of the earliest questions raised asked how increases in the price of oil, even as large as those experienced during the 1970's, could cause such disproportionally large decreases in economic output, since the value of oil consumed in the economy

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[253]See, for example, Donald E. Jones, Paul N. Leiby and Inja K. Paik, "Oil Price Shocks and the Macroeconomy: What Has Been Learned since 1996", *The Energy Journal*, Vol. 25, No. 2, 2004. (This paper is an update of an earlier review that Jones and Leiber authored in 1996.); Lutz Kilian, "The Economic Effects of Energy Price Shocks", *Journal of Economic Literature*, Vol. 46, No. 4, 2008, pp. 871-909; Stephen P.A. Brown, et al, "Business Cycles: The Role of Energy Prices", FRB of Dallas Working Paper, Number 0304; Paul Segal, "Why Do Oil Price Shocks No Longer Shock?" WPM 35, Oxford Institute for Energy Studies, New College, Department of Economics, University of Oxford. October 2007.
[254]James D. Hamilton, "Oil and the Macroeconomy since World War II," *Journal of Political Economy*, vol. 91, 1983, pp. 228-248.

was such a small share of total output — around three to five percent. The standard model for assessing the impact of an oil change was a neoclassical production function that related real economic output, Y, to inputs of capital, K, labor, L, and energy, E.

$$Y = F(K,L,E)$$

In a competitive market, firms would buy a resource input, say energy, up to the point where the price of the input was equal to the marginal value product of the input,

$$P_E = pF_E(L,K,E)$$

where $P_E$ is the partial derivative of F with respect to E. Multiplying both sides of this equation by E (Energy) and dividing by pY (the value of total output) results in the equation

$$P_E\ E/pY = pF_E(L,K,E)E/Y$$

The left side of the equation shows the value of energy as a share of total output and the right side is the elasticity of output with respect to energy use. Since the share of energy in total output was relatively small, how could the analysis explain the relatively large changes in output? As a result of the conundrum, research turned to looking for alternative routes by which oil price changes could impact output.

The description above of the anticipated impact of an oil price shock operating through production, as an increase in the price of an input, is an example of a supply shock to a market. The increase in the input price results in a supply-side impact to the market. In a competitive equilibrium, one can then analyze what the expected change in output, prices and other variables, such as the interest rate might be. In a classical macro model, a decrease in aggregate supply caused by an increase in oil prices would be expected to raise prices, lower output (GDP) and raise interest rates. Interest rates would increase as consumers, faced with higher prices, save less or borrow more, increasing real interest rates.

These changes – lower output, higher prices, and higher interest rates – describe the changes in the economy that followed the oil price shocks of the 1970's. Thus, the prediction of the theory seemed to be corroborated by the historical record. To match results of the theory with the historical record and to compare these findings with alternative ideas about how oil shocks impact the economy, Brown, et al.[255] created a table which is reproduced below as Table A.II-1.

[255]Steven Brown, Mine K. Yucel and John Thompson, "Business Cycles: The Role of Energy Prices", in *Encyclopedia of Energy*, C.J. Cleveland, ed., New York, Academic Press, 2004. A review article is available as a FRB of Dallas Working Paper, Number 0304, 2006. The chart is found on page 3 of the working paper.

**Table A.II-1**

**Expected Responses to Rising Oil Price**

| | Real GDP | Price Level | Interest Rate |
|---|---|---|---|
| Historical Record | Down | Up | Up |
| Classic Supply Shock | Down | Up | Up |
| Aggregate Demand Shock | Down | Down | Down |
| Monetary Shock | Down | Down | Up |
| Real Balance Effect | Down | Down | Up |

Source: Steven Brown, Mine K. Yucel, and John Thompson, 2004.

One obvious channel through which energy price impacts might operate is through a decrease in demand, since much oil is imported and the income from the higher prices results in a transfer from domestic consumers to foreign producers who may or may not spend the earnings in the U.S. The loss of real income is comparable to a tax increase and it reduces aggregate demand through four possible channels: [256]

- Higher energy prices reduce discretionary income leading to less spending
- The price shock may create uncertainty and cause consumers to postpone discretionary spending
- Consumers may increase precautionary saving
- Consumers may decrease the consumption of goods that are complementary with the use of energy intensive products.

The result is less aggregate demand, leading to falling prices and output. Also, foreign oil producers tend to save more than U.S. consumers, which results in downward pressure on interest rates. Thus, the anticipated impacts of a reduction of aggregate demand produces results that may not agree with the historical record, except for the reduction in output.

The third item in the table, "Monetary Shocks," has a long and contentious history in the literature on energy price shocks. Some of the early dissenters from the oil-shock theory of post-WWII recessions have argued that it has been monetary policy rather than changes in the price of oil that has caused the downturns in output that seem follow most episodes of oil price hikes. A seminal paper that argues this point is the 1997 paper by Bernanke, et al. which concluded that the recessions that followed the 1973, 1979-80, and 1990 oil price increases could be almost entirely attributable to monetary policy and not oil shocks.[257] Their argument is that it was restrictive

[256]These reactions to higher oil prices are spelled out in Lutz Kilian, "The Economic Effects of Energy Price Shocks," *Journal of Economic Literature*, Vol. 46, 2008, pp. 871–909 – see page 881.

[257]Ben S. Bernanke, Mark Gertler, and Mark Watson, "Systematic Monetary Policy and the Effects of Oil Price Shocks," *Brookings Papers on Economic Activity*, Issue 1, pp. 91–142, 1997.

monetary policy that caused interest rates to increase and aggregate demand to fall leading to the recessions, and that the oil price increases had little influence on the downturn. While two of the three highlighted variables in this theoretical construct of events do move in the same direction as the historical record, a monetary tightening would tend to reduce prices, not increase them.

The final item in the chart, the "Real Balance Effect" is an argument that was offered as a possible explanation as to why seemingly small oil price changes had such large impacts on the economy. It was argued that increasing energy prices led to increased demand for money to restore a desired level of portfolio liquidity. Unless monetary authorities recognized this increased demand for funds and increased the money supply, the increased demand for money would drive up interest rates, reduce aggregate demand, and lead to a decrease in output. Table 1 shows that a "Real Balance Effect" would have the same impact as a tightening of monetary policy. As in the case of a tightening of monetary policy, the resulting impacts parallel the historical record in only two of the three variables – interest rates and output.

The above approaches to accounting for energy price shocks make the standard assumptions regarding market competitiveness. However, there have been other approaches to explaining the outsized impact of energy price shocks that rely on market imperfections. Most of these approaches involve imperfections on the supply side of the economy and, therefore, would create impacts that mirror the historical record.

Rotemberg and Woodford assume collusive pricing powers that allow mark-ups to the original energy-price spike throughout the manufacturing chain.[258] Their theoretical model can duplicate the impact on output found in the data, but their assumption of such widespread collusive power is problematic. Another widely cited paper by Finn accepts perfect competition, but adds to the increasing cost of energy inputs large increases in the cost of capital depreciation as high energy costs render energy-using capital non-productive.[259] Reductions in capital utilization reduce efficiency and decrease output. Models of this type are called "putty-clay" meaning that once decisions are made to install a certain type of capital technology – the "putty" stage, the decisions are not then alterable – the "clay" stage — despite changes in the operating environment (e.g., changing energy prices).

Other research has considered friction in labor markets to account for the size of downturns following energy price spikes. For example, energy price increases have exceptionally large adverse impacts on the transportation industry.[260] Idled workers (and capital) in the industry cannot be shifted easily to other employment owing to structural issues and, perhaps, sticky wages. This increase in unemployed resources

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[258] See J.J. Rotemberg and M. Woodford, "Imperfect Competition and the Effects of Energy Price Increases on Economic Activity," *Journal of Money, Credit and Banking*, Vol. 28, 1996, pp. 549-577.

[259] See Mary G. Finn, "Perfect Competition and the Effects of Energy Price Increases on Economic Activity," *Journal of Money, Credit and Banking*, Vol. 32, 2000, pp. 400-416.

[260] See, for example, Timothy F. Bresnahan and Valerie A. Ramey, "Segment Shifts and Capacity Utilization in the U.S Automobile Industry," *American Economic Review*, 83 (2), 1993, pp. 213–18.

owing to allocative inefficiencies magnifies the direct, aggregate effects of the energy price change. Hamilton estimated that the downturn in the auto industry during the 1980 and 1990-91 recessions was enough to push the economy into recession from what might well have been periods of "sluggish" growth.[261]

### Asymmetric Impact

Various other controversies have also characterized the research on the energy shock-output relationship. One such issue is the apparent asymmetry of energy shocks – they apparently have a greater negative impact when prices increase than positive impacts when prices decline. This issue came to the forefront during the 1980's when a decline in energy prices failed to result in an acceleration in growth similar to the decline in growth after the 1970's energy price increases.

Mork found that when he introduced separate oil price variables for price increases and price declines, the price increases had more of an effect than the price decreases.[262] Other researchers found similar results, although the classic aggregate supply-aggregate demand model predicts that there should be no difference in response whether the oil price shock is positive or negative. Several explanations have been suggested for the anomaly, including an asymmetry of the price pass-through of oil price changes to retail product (e.g., gasoline) price changes – price increases are passed through more rapidly than are decreases.[263] Another possibility suggested was that monetary policy responses to oil price increases were different than the responses to an oil price decreases, and that it was this policy asymmetry that caused the apparent difference in positive versus negative energy price changes.[264]

Another possible explanation hypothesized that the same allocative frictions that were identified as the cause of the size of oil price shock impacts could be responsible for the asymmetrical effects. The reasoning is that although the aggregate impact of a price decrease would shift the supply curve to the right resulting in increased output, the same allocative adjustment problems that accompany price increases would be present during price decreases, operating to slow growth and partially offset any positive aggregate effect. Finally, Lutz Kilian, who generally disputes the argument that energy price shocks are responsible for shifts in economic activity, offers the explanation that the apparent asymmetry was caused by policy changes (e.g., the 1986 Tax Reform Act) and not differences in the way that oil prices changes impact the economy.[265]

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[261] James D. Hamilton, "Causes and Consequences of the Oil Shock of 2007-08", presented at the Brookings Panel on Economic Activity, April 2009; James D. Hamilton, Department of Economics, UC San Diego, Working Paper, 2009, p. 29.
[262] See Knut A. Mork, "Business Cycles and the Oil Market," *Energy Journal*, Vol. 15, No. 4, Special Issue (1994): pp. 15-38.
[263] Nathan S. Balke, et al., "Oil Price Shocks and the U.S. Economy: Where Does the Asymmetry Originate?" Federal Reserve Bank of Dallas, Working Paper No. 9911, 1999.
[264] See John Tatum, "Are the Macroeconomic Effects of Oil-Price Changes Symmetric?" *Carnegie-Rochester Conference Series on Public Policy*, Volume 28, Spring 1988, pp. 325-368.
[265] See Kilian, op. cit., p. 891.

### A Weakening Relationship

Aside from the possible explanation discussed above, some analysts contend that the reason for the weak response of output to energy prices decreases during the 1980's was caused by a general weakening of the relationship, that the structure of the economy had changed. Brown, et al. offers several possible reasons for the diminishing impact of oil price changes. They discuss the role of a fall in the energy-to-GDP ratio, the growing experience with oil price changes (In the 1970's the changes were a "shock," but by the 1980's and 1990's oil price changes were not so novel.), the fact that strong productivity gains in the late 1990's tended to hide the oil price-output relationship and, finally, that the increases in energy prices in the 1990's came from an increase in aggregate demand and not from a decrease in aggregate supply.[266,267]

The last explanation became popular during the run-up of energy prices in the late 2000's, prior to the onset of the financial crisis in 2008. There were numerous articles and commentaries pointing to the fact that despite increasing oil prices, the economy continued to grow. Perhaps most notable among these papers is one by William Norhaus, in which he offered several of the factors discussed above as to why higher oil prices failed to derail the economic expansion.[268] Following the financial crises of the summer and fall of 2008 and the subsequent economic implosion, most economic commentary focused on the role of the financial sector as the primary cause of the sharp downturn. There were those, however, who argued that the run-up in oil prices was a significant factor behind the recession, pointing out that the economy began to slow and that the NBER marked the start of the recession in December 2007 – months before the financial crises caused the bottom to fall out.[269]

### What is the Size of the Relationship?

Not surprisingly, given the dozens of studies that have examined the relationship between oil price shocks and the economy, there are numerous estimates of the size of the response in GDP to a one percent change in the price of oil or energy. One generalization that can be made from the results of these studies is that those estimates that are the result of more simple time-series estimates of the impact of oil and energy prices on the macroeconomy tend to be larger than estimates made using large

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[266]See Brown, et al., op. cit., p. 14.

[267]In addition to possible structural changes as explanations for the reduction of the force of oil price shocks, several analysts considered other, more technical, reasons including the structure of equations used to estimate impacts and the precise definition of what an "oil price shock" really was. See Jones, et al., op. cit. p. 10, for a discussion if these issues.

[268]William D. Nordhaus, "Who's Afraid of a Big Bad Oil Shock?" *Brookings Papers on Economic Activity*, Issue 2 (Fall 2007), p. 219-240.

[269]See James D. Hamilton, "Causes and Consequences of the Oil Shock of 2007-08," presented at the Brookings Panel on Economic Activity, Department of Economics, UC San Diego, April 2009. Also, see Joe Cortright, "Driven to the Brink: How the Gas Price Spike Popped the Housing Bubble and Devalued the Suburbs", White Paper, CEOs for Cities, May 2008.

disaggregated macroeconomic models of the economy. In the former case, estimates tend to range from around 2.5 percent to up to 11 percent in an estimate by Hamilton.[270]

In contrast, disaggregated models, such as the models of the IMF, OECD and Federal Reserve, tend to derive estimates that are much smaller, in the range of 0.2 percent to 1.0 percent. Jones, et al. explains the difference by pointing out that much of the overall impact on GDP that results from an energy price shock comes as a result of the friction in inter-sectoral resource allocation, and the large, disaggregated models are not able to gauge these effects.[271] Nevertheless, the salient point is that all estimates indicate a negative relationship between energy prices and the economy.

**Long-Run Impacts**

In the above discussion of the impact of changes in energy prices in the short run, energy, E, was introduced as an explicit factor – along with labor and capital – in the production function that described the structure of the aggregate supply curve. In the mainstream theories of long-term economic growth, energy plays no such role. Rather, growth is theorized as being a function of labor (population), capital, and technological change.[272]

A seminal article by Robert Solow in 1956 marked the beginning of mainstream neoclassical growth theory.[273] Although his work on the issue of economic growth earned Solow the Nobel Prize, the construct that he used to describe growth Q = f(L,K) had a major flaw in that the two explicit exogenous variables, labor and capital, explained little of the actual growth in the U.S. economy. A large “Solow residual,” introduced as an exogenous unexplained variable accounted for most of the growth in per capita income. Since this residual, that Solow identified as “technological progress” was unexplained, or exogenous, this class of models came to be known as exogenous growth models.

During the 1980s, Pail Romer, Robert Lucas, and others initiated a new phase of growth theory that has come to be known as “modern” or “endogenous” growth theory. Their models were structured to include variables such as R&D and human capital to explain the sources of Solow’s “technological progress.”[274] While these new

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[270]See James D. Hamilton, “What is an Oil Shock?” *Journal of Econometrics*, v.113, April 2003, pp. 363 – 398. Jones, et al, op. cit., p. 12, has a discussion of some of the results of these estimates.
[271]See Jones, et al, op. cit., p. 12. Also see Hilliard G. Huntington, “The Economic Consequences of Higher Oil Prices,” final report for the U.S. Department of Energy, EMF SR 9, October 2005.
[272]This brief introduction and summary of mainstream economic growth theory draws heavily on the review of the subject by Robert Ayres. See Robert U. Ayres, “Lecture 5: Economic Growth (and Cheap Oil)”, presentation made at the Lisbon, Portugal 2005 meeting of the ASPO Fourth International Workshop on Oil and Gas Depletion.
[273]See Robert M. Solow, “A Contribution to the Theory of Economic Growth, *Quarterly Journal of Economics*, vol. 70, 1956, pp. 65-94.
[274]Fairly non-technical reviews of the development of endogenous growth theory can be found in Robert W. Arnold, “Modeling Long-Run Economic Growth”, Technical Paper Series No. 2003-4, Congressional Budget Office, Washington D.C. June 2003; Lars Weber, “Understanding Recent Developments in Growth Theory”, Brandenburg University of Technology Cottbus, 2007; and Joseph Cortright, “New

approaches have advanced growth theory, they have not served to answer some of the fundamental questions about growth, such as why different economies grow at different rates. Robert Ayres notes that while the neoclassical endogenous growth models have "interesting features," he also states "……all of the so-called endogenous growth models share a fundamental drawback: They are and are likely to remain essentially theoretical because none of the proposed choices of core variables (knowledge, human capital, etc.) is readily quantified, and the obvious proxies (like education expenditure, years of schooling, and R&D spending) do not explain growth."[275]

### Growth Theory and Energy

In a 2002 paper Ayres and Benjamin Warr asked "Why should capital services be treated as a "factor of production" while the role of energy services is widely ignored or minimized?"[276] They then discussed what they see as the two primary reasons behind the fact that mainstream neoclassical economics ignores energy (and other resource) inputs when creating models of economic growth. First, neoclassical theory assumes that the productivity of a factor of production must be proportional to that factor's share of national income. Labor and capital receive, by far, the largest shares of national income, with payments to energy receiving very little. Theory thus concludes that energy must be a negligible factor of production and can be ignored.

A second reason that neoclassical economists ignore energy is because of the problem of causation. Correlation between energy use and growth may be the result of growth leading to more energy use and not because energy use results in growth.[277] The standard mainstream model, such as the EIA NEMS model, makes just this assumption in its forecasts. That is, NEMS assumes that growth in the macroeconomy is determined by exogenous factors such as population growth, technology growth, and monetary, and fiscal policies. Demand for energy products is the result.[278]

As an alternative approach, Ayres and others recommend that growth models include an energy variable as an explicit input. They contend that energy is an example of an "engine of growth" that provides positive feedback cycles in the growth process as depicted in the so-called Salter cycle – see Figure A.II-1.[279] Increases in low-cost energy translate into lower prices for products and services, and this leads to greater demand. The lower energy prices result from new discoveries, economies of scale, and

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Growth Theory, Technology and Learning: A Practitioners' Guide," *Reviews of Economic Development Literature and Practice*, No. 4, report done under contract (99-07-13801) for the U.S. Economic Development Administration by Impresa, Inc. 1424 NE Knott St, Portland, Oregon.

[275] See Ayres, op. cit., p. 8.

[276] See Robert U. Ayres and Benjamin Warr, "The Economic Growth Models and the Role of Physical Resources,", INSEAD Working Paper, No. 2002/53/EPS/CMER, 2002, p. 4.

[277] Ayres and Warr, op. cit., pp. 4-6.

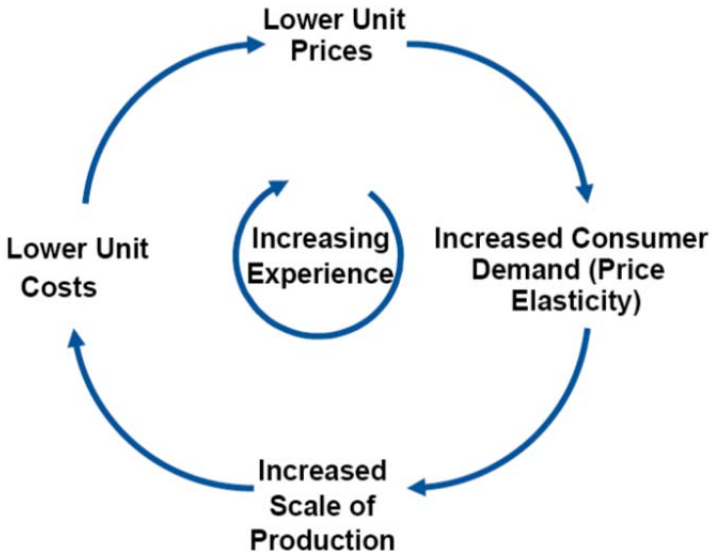
[278] See U.S. Energy Information Administration, "The National Energy Modeling System: An Overview 2003", report No. DOE/EIA-0581 (2003).

[279] Ayres, op. cit., p. 26.

technical progress in the efficiency of energy use. In other words, as in the case of capital, energy is a factor of production and should be treated as such.[280]

Models that have included energy variables in the standard neoclassical production function explain most of the growth left unexplained in the standard two-variable Solow model.[281]

**Figure A.II-1**
**Representation of the Slater Cycle**




Source: Robert U. Ayres, "Lecture 5: Economic Growth (And Cheap Oil)," INSEAD, Boulevard de Constance, F-77305 Fontainebleau Cedex, France

[280]Ayres, ibid, p. 4.

[281]Ayres, ibid. p.4. notes the work of Bruce Hannon and John Joyce, "Energy and Technical Progress", *Energy*, vol. 6, pp. 187-195, 1981; Reiner Kummel, "Energy, Environment and Industrial Growth," in *The Economic Theory of Natural Resources*, Physica-Verlag, Wuerzberg, Germany, 1982; Cutler J. Cleveland, et al., "Energy and the U.S. Economy: A Biophysical Perspective," *Science*, v. 255, pp. 890-97, 1984; and others.

# APPENDIX III: ELECTRICITY-GDP ELASTICITY ESTIMATES

A number of studies have developed estimates of the elasticity of GDP with respect to energy and electricity prices. Examples of these are summarized in Table A.III-1, and include the following:

- In 2010, Lee and Lee analyzed the demand for energy and electricity in OECD countries. They estimated that the elasticities range between -0.01 and -0.19.[282]
- In 2010, Baumeister, Peersman, and Van Robays examined the economic consequences of oil shocks across a set of industrialized countries over time. They estimated that the elasticity was approximately -0.35.[283]
- In 2010, Brown and Hunnington employ a welfare-analytic approach to quantify the security externalities associated with increased oil use, which derive from the expected economic losses associated with potential disruptions in world oil supply. They estimated that the elasticity ranged between -0.01 and -0.08.[284]
- In 2009, Blumel, Espinoza, and Domper used Chilean data to estimate the long run impact of increased electricity and energy prices on the nation's economy.[285] They estimated that the elasticity ranged between -0.085 and -0.16.
- In 2008, in a study of the potential economic effects of peak oil, Kerschner and Hubacek reported elasticities in the range of -0.17 to -0.03 – although they noted that sectoral impacts are more significant.[286]

[282]Chien-Chaing Lee and Jun-De Lee, "A Panel Data Analysis of the Demand for Total Energy and Electricity in OECD Countries," *The Energy Journal*, Vol. 31, No 1 (2010), pp. 1-23.
[283]Christiane Baumeister, Gert Peersman and Ine Van Robays, "The Economic Consequences of Oil Shocks: Differences Across Countries and Time," Ghent University, Belgium, 2010.
[284]Stephen P.A. Brown and Hillard G. Huntington, "Estimating U.S. Oil Security Premiums," Resources for the Future, Washington, D.C., June 2010.
[285]Gonzalo Blumel, Ricardo A. Espinoza, and G. M. de la Luz Domper, "Does Energy Cost Affect Long Run Economic Growth? Time Series Evidence Using Chilean Data," Instituto Libertad y Desarrollo Facultad de Ingenier´ıa, Universidad de los Andes, March 22, 2009.
[286]Christian Kerschnera and Klaus Hubacek, "Assessing the Suitability of Input-Output Analysis For Enhancing Our Understanding of Potential Economic Effects of Peak-Oil," Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK, 2008.

**Table III-1**
**Summary of Energy- and Electricity-GDP Elasticity Estimates**

| Year Analysis Published | Author | Elasticity Estimate |
|---|---|---|
| 2010 | Lee and Lee (energy and electricity) | -0.01 and -0.19 |
| 2010 | Brown and Huntington (oil) | -0.01 to -0.08 |
| 2010 | Baumeister, Peersman, and Robays (oil) | -0.35 |
| 2009 | Blumel, Espinoza, and Domper (energy and electricity) | -0.085 to -0.16 |
| 2008 | Kerschner and Hubacek (oil) | -0.03 to -0.17 |
| 2008 | Sparrow (electricity) | -0.3 |
| 2007 | Maeda (energy) | -0.03 to -0.075 |
| 2007 | Citigroup (energy) | -0.3 to -0.37 |
| 2007 | Lescaroux (oil) | -0.1 to -0.6 |
| 2006 | Rose and Wei (electricity) | -0.1 |
| 2006 | Oxford Economic Forecasting (energy) | -0.03 to -0.07 |
| 2006 | Considine (electricity) | -0.3 |
| 2006 | Global Insight (energy) | -0.04 |
| 2004 | IEA (oil) | -0.08 to -0.13 |
| 2002 | Rose and Young (electricity) | -0.14 |
| 2002 | Klein and Kenny (electricity) | -0.06 to -0.13 |
| 2001 | Rose and Ranjan (electricity) | -0.14 |
| 2001 | Rose and Ranjan (energy) | -0.05 to -0.25 |
| 1999 | Brown and Yucel (oil) | -0.05 |
| 1996 | Hewson and Stamberg (electricity) | -0.14 |
| 1996 | Rotemberg and Woodford (energy) | -0.25 |
| 1996 | Gardner and Joutz (energy) | -0.072 |
| 1996 | Hooker (energy) | -0.07 to -0.29 |
| 1995 | Lee and Ratti (oil) | -0.14 |
| 1995 | Hewson and Stamberg (electricity) | -0.5 and -0.7 |
| 1982 | Anderson (electricity) | -0.14 |
| 1981 | Rasche and Tatom (energy) | -0.05 to -0.11 |

Source: Management Information Services, Inc.

- In 2008, Sparrow analyzed the impacts of coal utilization in Indiana, and estimated electricity elasticities in the range of about -0.3 for the state.[287]
- In 2007, in a study of energy price GDP relationships, Maeda reported a range of elasticity estimates between -0.03 to -0.075.[288]
- In 2007, in a study of the relationship between energy prices and the U.S. economy, Citigroup found that in the long run, protracted high energy prices can have an economic impact and reported elasticities in the range of -0.3 to -0.37 between 1995 and 2005.[289]
- In 2007, in a study of oil-price GDP elasticities, Lescaroux reported a range of elasticities between -0.1 and -0.6.[290]
- In 2006, in an analysis of the likely impacts of coal utilization for electricity generation on the economies of the 48 contiguous states in the year 2015, Rose and Wei estimated the electricity elasticity to be -0.1[291] They also reported that more recent studies for the state of Georgia and the UK yield similar results.
- In 2006, in a study of energy price impacts in the UK, Oxford Economic Forecasting found elasticities to range between about -0.11 and -0.21.[292]
- In 2006, in a study that analyzed the economic impacts from coal Btu energy conversion, Considine estimated an electricity elasticity of -0.3.[293]
- In 2006, in a study of the impact of energy price increases in the UK, Global Insight estimated the elasticity to be -0.04.[294]
- In 2004, IEA employed energy-economic model simulation to calculate how much the increase in oil prices reduces GDPs in several countries. It found that the elasticity estimates ranged between -0.08 to -0.13.[295]

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[287]F.T. Sparrow, Measuring the Contribution of Coal to Indiana's Economy," CCTR Briefing: Coal, Steel and the Industrial Economy, Hammond, IN, December 12, 2008.

[288]Akira Maeda, On the World Energy Price-GDP Relationship, presented at the 27th USAEE/IAEE North American Conference, Houston, Texas, September 16-19, 2007.

[289]PV Krishna Rao, "Surviving in a World with High Energy Prices, Citigroup Energy Inc., September 19, 2007.

[290]F. Lescaroux, "An Interpretative Survey of Oil Price-GDP Elasticities," *Oil & Gas Science and Technology*, Vol. 62 (2007), No. 5, pp. 663-671.

[291]Adam Rose and Dan Wei, *The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015*. Report prepared for the Center for Energy and Economic Development, Inc., Alexandria, Virginia, the Pennsylvania State University, July 2006.

[292]Oxford Economic Forecasting, DTI Energy Price Scenarios in the Oxford Models, London, May 2006.

[293]Tim Considine, *Coal: America's Energy Future*, Volume II, "Appendix: Economic Benefits of Coal Conversion Investments." Prepared for the National Coal Council, March 2006.

[294]Global Insight, "The Impact of Energy Price Shocks on the UK Economy: A Report to the Department of Trade and Industry," London, May 18, 2006.

[295]International Energy Agency, "Analysis of the Impact of High Oil Prices on the Global Economy," Paris, May 2004.

- In 2002, in a study of the economic impact of coal utilization in the continental U.S. Rose and Yang estimated the GDP electricity price elasticity of at -0.14.[296]
- In 2002, Klein and Kenny analyzed the results of six studies of the impacts of energy prices on the U.S. economy conducted between 1997 and 2002 and reported electricity elasticity estimates that ranged between -0.6 and -1.3.[297]
- In 2001, Rose and Ramjan analyzed the impact of coal utilization in Wisconsin. They calculated a price differential between coal and natural gas in electricity production, and then estimated how much economic activity is attributable to this cost saving. They used an economy-wide elasticity of output with respect to energy prices, which they estimated to be -0.14.[298]
- In 2001, Rose and Ranjan surveyed recent studies of the impacts of energy prices on GDP and reported elasticities in the range of -0.5 to -0.25.[299]
- In 1999, Brown and Yucel surveyed a number of studies and reported an average elasticity of about -0.05.[300]
- In 1996, Rotemberg and Woodford analyzed the effects of energy price increases on economic activity and reported an elasticity of -0.25.[301]
- In 1996, Gardner and Joutz analyzed the relationship between economic growth, energy prices, and technological innovation, found that the real price of energy is negatively related to output in the U.S., and estimated that the elasticity is -0.72.[302]
- In 1996, in a study of the impact of electricity prices on manufacturing, Hewson and Stamberg estimated an electricity elasticity of -0.14.[303]
- In 1996, in studying postwar energy-GDP relationships, Hooker estimated that the elasticity ranges between -0.07 and -0.29.[304]

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[296]A Rose and B. Yang, "The Economic Impact of Coal Utilization in the Continental United States," Center for Energy and Economic Development; 2002.
[297]Daniel Klein and Ralph Kenny, "Mortality reductions from use of Low-cost coal-fueled power: An analytical framework," 21st strategies, Mclean, VA, and Duke University, December 2002.
[298]Adam Rose and Ram Ranjan, "The Economic Impact of Coal Utilization in Wisconsin," Department of Energy, Environmental, and Mineral Economics, Pennsylvania State University, August 2001.
[299]Ibid.
[300]S.A. Brown and M.K. Yucel, "Oil Prices and U.S. Aggregate Economic Activity: A Question of Neutrality," *Economic and Financial Review*, second quarter, Federal Reserve Bank of Dallas, 1999.
[301]Rotemberg, Julio J., and Michael Woodford. 1996. "Imperfect Competition and the Effects of Energy Price Increases on the Economy." *Journal of Money, Credit, and Banking*, 28(4): 550–77.
[302]Fred Joutz and Thomas Gardner, "Economic Growth, Energy Prices, and Technological Innovation," *Southern Economic Journal*, vol. 62, 3, January, 1996, pp. 653-666.
[303]T. Hewson and J. Stamberg, *At What Cost? Manufacturing Employment Impacts from Higher Electricity Prices,* Energy Ventures Analysis, Arlington, VA, 1996.
[304] See Mark A. Hooker, "What Happened to the Oil Price-Macroeconomy Relationship?," *Journal of Monetary Economics*, 38, 1996, pp. 195-213, and James D. Hamilton, "Oil and the Macroeconomy," Prepared for the *Palgrave Dictionary of Economics,* August 24, 2005.

- In 1995, in a study of macroeconomic oil shocks, Lee and Ratti estimated the elasticity to be -0.1.4.[305]
- In 1995, in a study of the impact of $NO_x$ control programs in 37 states, Hewson and Stamberg estimated electricity elasticities ranging between -0.5 and -0.7.[306]
- In 1982, in a study of industrial location and electricity prices, Anderson estimated the elasticity to be -0.14.[307]
- In 1981, Rasche and Tatom found that an energy price shock modifies the optimal usage of the existing stock of capital, modifying the optimal capital-labor ratio and generating an upward shift on the aggregate supply curve and a decline in potential output. They estimated that the elasticity of output with respect to the real price of energy ranges between -0.05 and -0.11.[308]

In addition, numerous studies have examined the relationship between energy prices and GDP and found strong causality; for example:

- In 2008, Chontanawat found that the causality relationship is stronger in developed countries rather than developing countries.[309]
- In 2008, Bekhet and Yusop examined the long run relationship between oil prices, energy consumption, and macroeconomic performance in Malaysia over the period 1980-2005. Their findings indicated that there is a stable long-run relationship between oil prices, employment, economic growth, and the growth rate of energy consumption and also substantial short run interactions among them. The linkages and causal effects among prices, energy consumption and macroeconomic performance have important policy implications, and they found that the growth of energy consumption has significant impacts on employment growth.[310]

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[305]Lee, Kiseok, and Shawn Ni Ronald A. Ratti (1995), "Oil Shocks and the Macroeconomy: The Role of Price Variability," Energy Journal, 16, pp. 39-56.

[306]T. Hewson and J. Stamberg, *At What Cost? An Evaluation of the Proposed 37-State Seasonal $NO_x$ Control Program – Compliance Costs and Issues,* Energy Ventures Analysis, Arlington, VA, 1995.

[307]K.P. Anderson, "Industrial Location and Electric Utility Price Competition," National Economic Research Associates, Inc., New York, NY, 1982.

[308]R.H. Rasche and J. A. Tatom, "Energy Price Shocks, Aggregate Supply, and Monetary Policy: The Theory and International Evidence," in K. Brunner and A. H. Meltzer, eds., *Supply Shocks, Incentives, and National Wealth*, Carnegie-Rochester Conference Series on Public Policy, vol. 14, Amsterdam: North-Holland, 1981.

[309]J. Chontanawat, "Modeling Causality Between Electricity Consumption and Economic Growth in Asian Developing Countries", *Conference Paper*, presented at the 2nd IAEE Asian Conference, Perth, Australia, 5-7 November 2008.

[310]A. Hussain Bekhet, Nora Yusma, and Mohamed Yusop, "Assessing the Relationship Between Oil Prices, Energy Consumption and Macroeconomic Performance in Malaysia: Co-integration and Vector Error Correction Model (VECM) Approach," Finance and Economics Department, College of Business Management and Accounting, University Tenaga Nasional, Pahang, Malaysia, 2008.

- In 2006, Soytas and Sari analyzed the causal relationship between energy consumption and GDP in G-7 countries and found that causality runs from energy consumption to GDP in these countries. They argued that energy conservation in some countries could negatively impact economic growth.[311]
- In 2006, Chontanawat, Hunt, and Pierse tested for causality between energy and GDP using a consistent data set and methodology for 30 OECD and 78 non-OECD countries.[312] They found that causality from aggregate energy consumption to GDP and GDP to energy consumption is found to be more prevalent in the developed OECD countries compared to the developing non-OECD countries. This implies that a policy to reduce energy consumption aimed at reducing GHG emissions is likely to have greater impact on the GDP of the developed rather than the developing world.
- In 1995, Finn found that in the U.S. the Solow residual tends to fall when energy price rises, implying a direct link between energy and production.[313]
- In 1987, Erol and You found a causal relationship running from energy consumption to output in a large set of industrialized countries.[314]

Other studies that came to similar conclusions include Al-Faris,[315] Al-Iriani,[316] Apergis, and Payne,[317] Burniaux and Jean Chateau,[318] Chien-Chiang and Jun-De

[311]U. Soytas and R. Sari, "Energy Consumption and GDP: Causality Relationship in G-7 Countries and Emerging Markets", *Energy Economics*, Vol. 25, 2006, pp. 33-37.

[312]Jaruwan Chontanawat, Lester C Hunt, and Richard Pierse, "Causality Between Energy Consumption and GDP: Evidence from 30 OECD and 78 Non-OECD Countries," Surrey Energy Economics Centre, Department of Economics, University of Surrey, UK, June 2006.

[313]Mary G. Finn, "Variance properties of Solow's productivity residual and their cyclical implications," *Journal of Economic Dynamics and Control*, vol. 19, 1995, pp. 1249-1281, and Mary G. Finn, "Perfect Competition and the Effects of Energy Price Increases on Economic Activity," *Journal of Money, Credit, and Banking*, 32, 2000, pp. 400-416.

[314]Umit Erol and Eden H. S. Yu, "On the Causal Relationship between Energy and Income for Industrialized Countries", *Journal of Energy and Development*, Vol. 13, 1987, pp. 113-122; and Umit Erol and Eden H. S. Yu, H., 1987. "Time Series Analysis of the Causal Relationships Between U.S. Energy and Employment," *Resources and Energy*, vol. 9, 1987, pp. 75-89.

[315]A.R. Al-Faris, "The Demand for Electricity in the GCC Countries," *Energy Policy*, Vol. 30, 2002, pp. 117-124.

[316]Mahmoud A. Al-Iriani, "Energy-GDP relationship revisited: An example from GCC countries using panel causality," *Energy Policy*, vol. 34, November 2006, pp. 3342-3350.

[317]Nicholas Apergis and James E. Payne, Energy Consumption and Economic Growth: Evidence from the Commonwealth of Independent States, *Energy Economics*,
Vol. 31, September 2009, pp. 641-647.

[318]Jean-Marc Burniaux and Jean Chateau, "An Overview of the OECD ENV-Linkages Model," Background report to the joint report by IEA, OPEC, OECD, and World Bank *Analysis of the Scope of Energy Subsidies and Suggestions for the G-20 Initiative*, OECD, May 2010.

Lee,[319] Coffman,[320] Cournède,[321] Davis and Haltiwanger,[322] Gausden,[323] Gronwald,[324] Harris,[325] Lee,[326] Manjulika and Koshal,[327] Narayan and Smyth,[328] Oligney,[329] Soytas and Sari,[330] Stern,[331] Stern and Cleveland,[332] and Wolde-Rufael.[333]

Dahl has conducted extensive studies of NEMS elasticities and provided summaries of the elasticities within NEMS.[334] She noted that, since elasticities are a convenient way to summarize the responsiveness of demand to such things as own prices, cross prices, income, or other relevant variables, a substantial amount of resources have been devoted to estimating demand elasticities, at various levels of aggregation using a variety of models. Nevertheless, she found that considerable variation in the estimates at the aggregate and disaggregate levels remains.

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[319]Chien-Chiang Lee and Jun-De Lee, "A Panel Data Analysis of the Demand for Total Energy and Electricity in OECD Countries" The Energy Journal; 2010; Vol. 31, No. 1.
[320]Makena Coffman, "Oil Price Shocks in an Island Economy: An Analysis of the Oil Price-Macroeconomy Relationship." *Annals of Regional Science*, 44(3): 599-620.
[321]Boris Cournède, "Gauging the Impact of Higher Capital and Oil Costs on Potential Output," OECD, Economics Department Working Papers No. 789, July 1, 2010.
[322]Steven J. Davis, and John Haltiwanger, "Sectoral Job Creation and Destruction Responses to Oil Price Changes," *Journal of Monetary Economics*, vol. 48, 1999, pp. 465–512, 2001.
[323]Gausden, Robert. 2010. "The Relationship between the Price of Oil and Macroeconomic Performance: Empirical Evidence for the UK." *Applied Economics Letters*, 17(1-3): 273-78.
[324]Marc Gronwald, "Large Oil Shocks and the US Economy: Infrequent Incidents with Large Effects," *The Energy Journal*; Vol. 29, 2008, pp. 151-171.
[325]Ethan S. Harris, et al., "Oil and the Macroeconomy: Lessons for Monetary Policy", Working Paper for the National Science Foundation, February 2009.
C.C. Lee, "The Causality Relationship between Energy Consumption and GDP in G-11 Countries Revisited," *Energy Policy*, Vol. 34, 2006, pp. 1086-1093.
[327]Manjulika Koshal, and Rajindar K. Koshal, "Production and High Energy Price: A Case of Japan and the United States", Decision Line, December/January 2001.
[328]Paresh Kumar Narayan and Russell Smyth, Russell, 2008. "Energy Consumption and Real GDP in G7 Countries: New Evidence From Panel Cointegration With Structural Breaks," *Energy Economics*, vol. 30, September 2008, pp. 2331-2341.
[329]Ron Oligney, "Energy and GDP are Closely Tied in US Economy, *Drilling Contractor*, November/ December 2003.
[330]R. Sari and U. Soytas, "Disaggregate Energy Consumption, Employment and Income in Turkey", *Energy Economics*, vol. 26, 2004, pp. 335-344.
[331]D.I. Stern, A Multivariate Cointegration Analysis of the Role of Energy in the U.S. Economy, Energy Economics, v. 22, 2000, pp. 267-283.
[332]David I. Stern and Cutler J. Cleveland, "Energy and Economic Growth," Rensselaer Working Papers in Economics, Number 0410, March 2004.
[333]Y.W. Rufael, Y. W. (2006), "Electricity Consumption and Economic Growth: A Time Series Experience of 17 African Countries", *Energy Policy*, Vol. 34, 2006, pp. 1106-1114; also see Paresh Kumar Narayan and Arti Prasad, Arti, 2008, "Electricity Consumption-Real GDP Causality Nexus: Evidence From A Bootstrapped Causality Test For 30 OECD Countries," *Energy Policy*, vol. 36, 2008, pp. 910-918.
[334]Carol Dahl, "A survey of energy demand elasticities in support of the development of the NEMS," Colorado School of Mines, October 1993; Carol Dahl and Carlos Roman, *Energy Elasticity Survey, presented at the* 24th Annual North American Colorado School of Mines Conference, Washington, D.C., July 8-10, 2004.

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The lead author of this report is Dr. Roger H. Bezdek, founder and president of MISI. He has over 30 years' experience in research and management in the energy, utility, environmental, and regulatory areas, serving in private industry, academia, and the federal government. He has served as Senior Adviser in the U.S. Treasury Department, as U.S. energy delegate to the EU and NATO, and as a consultant to the White House, federal and state government agencies, and various corporations and research organizations. He has served on numerous National Academies of Science committees, and during 2008 he presented energy briefings to the staffs of Senators Barack Obama, John McCain, and Hillary Clinton.

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BEFORE THE OFFICE OF ADMINISTRATIVE HEARINGS

FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION

STATE OF MINNESOTA

In the Matter of the Further Investigation in to

Environmental and Socioeconomic Costs

Under Minnesota Statute 216B.2422, Subdivision 3

OAH Docket No. 80-2500-31888

MPUC Docket No. E-999-CI-14-643

Exhibit 3

to

Direct Testimony of

**Dr. Roger H. Bezdek**

June 1, 2015

**BEZDEK EXHIBIT 3: COMPENDIUM OF SCIENTIFIC LITERATURE ON CLIMATE CHANGE**

## **I. Climate Trends Demonstrate That Natural Swings In Temperature Are Common, That There Has Been A “Hiatus” In Warming, That Extreme Weather Is Not Increasing, and That Natural Carbon Sinks Will Mitigate Impacts**

### ***A. Warming Has Been On “Hiatus,” and Natural Swings Are Common In Any Event***

| | |
|---|---|
| Judith Curry, Presentation to the American Physical Society, “Causes and Implications of the Growing Divergence between Model Simulations and Observations” (Mar. 4, 2014), available at https://curryja.files.wordpress.com/2014/03/aps-curry.pdf. | The presentation summarizes theories about the hiatus and examines implications in light of overconfident IPCC recommendations. |
| Ross R. McKitrick, “HAC-Robust Measurement of the Duration of a Trendless Subsample in Global Climate Time Series,” 4 Open J. Statistics 527 (2014). | There has been a trendless hiatus of 19 years in surface temperature measurements. |
| White, J.W.C., Alley, R.B., Brigham-Grette, J., Fitzpatrick, J.J., Jennings, A.E., Johnsen, S.J., Miller, G.H., Nerem, R.S. and Polyak, L. 2010. Past rates of climate change in the Arctic. Quaternary Science Reviews 29: 1716-1727. | The nine researchers begin by describing how “processes linked with continental drift have affected atmospheric circulation, ocean currents, and the composition of the atmosphere over tens of millions of years,” and that “a global cooling trend over the last 60 million years has altered conditions near sea level in the Arctic from ice-free year-round to completely ice covered.” They also report that “variations in arctic insolation over tens of thousands of years in response to orbital forcing have caused regular cycles of warming and cooling that were roughly half the size of the continental-drift-linked changes,” and that, in turn, this glacial-interglacial cycling “was punctuated by abrupt millennial oscillations, which near the North Atlantic were roughly half as large as the glacial-interglacial cycles.” Last of all, they note that “the current interglacial, the Holocene, has been influenced by brief cooling events from single volcanic eruptions, slower but longer lasting changes from random fluctuations in the frequency of volcanic eruptions, from weak solar variability, and perhaps by other classes of events.” White *et al.* conclude that “thus far, human influence does not stand out relative to other, natural causes of climate change.” |
| de Freitas, C.R., Dedekind, M.O. and Brill, B.E. 2014. A reanalysis of long-term surface air temperature trends in New Zealand. Environmental Modeling and Assessment: 10.1007/s10666-014-9429-z. | When a revised, improved measurement technique was applied to New Zealand historical temperature data, warming was significantly lower than previous estimates (which had been used by policymakers). |
| Bahuguna, I.M., Rathore, B.P., Brahmbhatt, R., Sharma, M., Dhar, S., Randhawa, S.S., Kumar, K., Romshoo, S., Shah, R.D., Ganjoo, R.K. and Ajai. 2014. Are the Himalayan glaciers | Study of Himalayan glaciers shows “steady state” corresponding to hiatus in global warming. |

| | |
|---|---|
| retreating? *Current Science* **106**: 1008-1013. | |
| Fyfe, J.C., Gillett, N.P. and Zwiers, F.W. 2013. Overestimated global warming over the past 20 years. Nature Climate Change 3: 767-769. | Noting that models have consistently overestimated climate change and that the inconsistency between observed and simulated global warming is particularly striking for temperature trends computed over the past fifteen years (1998-2012), during which time the data suggest a "hiatus" in warming. |
| Wang, X.L., Feng, Y. and Vincent, L.A. 2014. Observed changes in one-in-20 year extremes of Canadian surface air temperatures. Atmosphere-Ocean 52: 222-231. | Study of Canadian weather stations shows that Canadian warming is specific: less cold, but not more hot. |
| Esper, J., Frank, D.C., Timonen, M., Zorita, E., Wilson, R.J.S., Luterbacher, J., Holzkamper, S., Fischer, N., Wagner, S., Nievergelt, D., Verstege, A. and Buntgen, U. 2012. Orbital forcing of tree-ring data. Nature Climate Change 2: 862-866. | Tree-ring data from Sweden using more advanced techniques suggest that temperatures during Roman and Medieval periods are widely underestimated. Indeed, records show overall cooling between 138 B.C.E. and 2006 C.E. |
| Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tinner, W. and Hu, F.S. 2010. Six millennia of summer temperature variation based on midge analysis of lake sediments from Alaska. Quaternary Science Reviews29: 3308-3316. | Impact of rising $CO_2$ has been negligible on July temperature based on a study of midge assemblages found in Alaska. |
| Lo, T.-T. and Hsu, H.-H. 2010. Change in the dominant decadal patterns and the late 1980s abrupt warming in the extratropical Northern Hemisphere. Atmospheric Science Letters 11: 210-215. | Any warming in the Northern Hemisphere is the result of the emergence of an Artic Oscillation-like pattern and concurrent weakening of the previously prevailing Pacific Decadal Oscillation-like pattern; not anthropogenic greenhouse gas effect. |
| Tokairin, T., Sofyan, A. and Kitada, T. 2010. Effect of land use changes on local meteorological conditions in Jakarta, Indonesia: toward the evaluation of the thermal environment of megacities in Asia. International Journal of Climatology30: 1931-1941. | For Asian megacities, expanding and intensifying urban heat islands will likely prove to be of more immediate significance than will any additional global warming that may develop concurrently. |
| Fujibe, F. 2011. Urban warming in Japanese cities and its relation to climate change monitoring. International Journal of Climatology 31: 162-173. | Urban warming can be a biasing factor that may contaminate data used for monitoring the background temperature change. |
| Galloway, J.M., Lenny, A.M. and Cumming, B.F. 2011. Hydrological change in the central interior of British Columbia, Canada: diatom and pollen evidence of millennial-to-centennial scale change over the Holocene. Journal of Paleolimnology 45: 183-197. | Historical increase in the atmosphere's $CO_2$ content likely had little to do with the development of the milder warmth and dryness of the central interior of British Columbia's current climatic state, with potentially similar implications for the rest of the world. |
| Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X.-W., Xu, T. and Murray, D. 2011. Was there a basis for anticipating the 2010 Russian heat wave? Geophysical Research Letters 38: 10.1029/2010GL046582. | Analysis of July temperatures in western Russia between 1880 and 2009 revealed no clear connection to anthropogenic climate change. |
| Hanggi, P. and Weingartner, R. 2011. Inter-annual variability of runoff and climate within | The Upper Rhine River basin has experienced no significant variance in runoff or climate in |

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| the Upper Rhine River basin, 1808-2007. Hydrological Sciences Journal 56: 34-50. | the past 200 years. |
| Stewart, M.M., Larocque-Tobler, I. and Grosjean, M. 2011. Quantitative inter-annual and decadal June-July-August temperature variability ca. 570 BC to AD 120 (Iron Age-Roman Period) reconstructed from the varved sediments of Lake Silvaplana, Switzerland. Journal of Quaternary Science 26: 491-501. | For Lake Silvaplana and the eastern Swiss Alps, there is nothing unusual, unnatural or unprecedented about late-20th-century/early-21st-century warmth. |
| Box, J.E., Yang, L., Bromwich, D.H. and Bai, L.-S. 2009. Greenland ice sheet surface air temperature variability: 1840-2007. Journal of Climate 22: 4029-4049. | The four researchers determined that "the annual whole ice sheet 1919-32 warming trend is 33% greater in magnitude than the 1994-2007 warming," and that "in contrast to the 1920s warming, the 1994-2007 warming has not surpassed the Northern Hemisphere anomaly." Indeed, they note that "an additional 1.0°-1.5°C of annual mean warming would be needed for Greenland to be in phase with the Northern Hemisphere pattern." |
| Perlwitz, J., Hoerling, M., Eischeid, J., Xu, T. and Kumar, A. 2009. A strong bout of natural cooling in 2008. Geophysical Research Letters 36: 10.1029/2009GL041188. | Perlwitz *et al.* begin their narrative by noting that there has been "a decade-long decline (1998-2007) in globally averaged temperatures from the record heat of 1998," citing Easterling and Wehner (2009). And in further describing this phenomenon, they say that U.S. temperatures in 2008 "not only declined from near-record warmth of prior years, but were in fact colder than the official 30-year reference climatology (-0.2°C versus the 1971-2000 mean) and further were the coldest since at least 1996." With respect to the geographical origin of this "natural cooling," as they describe it, the five researchers point to "a widespread coolness of the tropical-wide oceans and the northeastern Pacific," focusing on the Niño 4 region, where they report that "anomalies of about -1.1°C suggest a condition colder than any in the instrumental record since 1871." |
| Chen, F.-H., Chen, J.-H., Holmes, J., Boomer, I., Austin, P., Gates, J.B., Wang, N.-L., Brooks, S.J. and Zhang, J.-W. 2010. Moisture changes over the last millennium in arid central Asia: A review, synthesis and comparison with monsoon region. Quaternary Science Reviews 29: 1055-1068. | The nine researchers report that the effective moisture (precipitation) in central Asia (ACA) has a generally inverse relationship with the temperature of the Northern Hemisphere, as portrayed by Moberg *et al.* (2005), China, as portrayed by Yang *et al.* (2002), and Central Asia, as portrayed by Esper *et al.* (2007). The "wet (dry) climate in the ACA correlates with low (high) temperature." The ACA "has been characterized by a relatively dry Medieval Warm Period (MWP; the period from ~1000 to 1350 AD), a wet little Ice Age (LIA; from ~1500-1850 AD)," and "a return to arid conditions after 1850 AD," which has been slightly muted -- but only "in some records" -- over the past 20 years by an increase in humidity. |

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| Wood, K.R. and Overland, J.E. 2010. Early 20th century Arctic warming in retrospect. International Journal of Climatology 30: 1269-1279. | The U.S. researchers say about a climatic fluctuation that showed warming almost a hundred years ago that “there is evidence that the magnitude of the impacts on glaciers and tundra landscapes around the North Atlantic was larger during this period than at any other time in the historical period.” In addition, they report that “the ultimate cause of the early climatic fluctuation was not discovered by early authors and remains an open question,” noting that “all of the leading possibilities recognized today were raised by the 1950s, including internal atmospheric variability, anthropogenic greenhouse gas ($CO_2$) forcing, solar variability, volcanism, and regional dynamic feedbacks (e.g. Manley, 1961),” although they add that “greenhouse gas forcing is not now considered to have played a major role (Hegerl *et al.*, 2007).” Thus, they suggest that “the early climatic fluctuation was a singular event resulting from intrinsic variability in the large-scale atmosphere/ocean/land system and that it was likely initiated by atmospheric forcing.” |
| Keigwin, L.D. 1996. The Little Ice Age and Medieval Warm Period in the Sargasso Sea. Science 274: 1504-1508. | Keigwin states that the northern Sargasso Sea SST “was ~1°C cooler than today ~400 years ago (the Little Ice Age) and 1700 years ago [the Dark Ages Cold Period], and ~1°C warmer than today 1000 years ago (the Medieval Warm Period).” In terms of his reason for conducting the study, which was to document natural climate variability in order to understand the effects of anthropogenic forcing, Keigwin states that “over the course of three millennia, the range of SST variability in the Sargasso Sea is on the order of twice that measured over recent decades,” and, therefore, he concludes that “at least some of the warming since the Little Ice Age appears to be part of a natural oscillation.” |
| Bekker, M.F., DeRose, R.J., Buckley, B.M., Kjelgren, R.K. and Gill, N.S. 2014. A 576-year Weber River streamflow reconstruction from tree rings for water resource risk assessment in the Wasatch Front, Utah. *Journal of the American Water Resources Association* **50**: 1338-1348. | A 576-year (AD 1429-2004) tree-ring-based reconstruction of streamflow for northern Utah’s Weber River, revealed that droughts were more severe in duration, magnitude, and intensity “prior to the instrumental record, including the most protracted drought of the record, which spanned 16 years from 1703 to 1718.”<br><br>Extreme wet years and periods were highest during a strong early 17th Century pluvial that dwarfs “the 1980s wet period that caused significant flooding along the Wasatch Front.” In fact “droughts in previous centuries have often exceeded those of the past 100 years in duration and magnitude.” |

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| Johnstone, J.A. and Mantua, N.J. 2014. Atmospheric controls on northeast Pacific temperature variability and change, 1900-2012. *Proceedings of the National Academy of Sciences USA* **111**: 14,360-14,365. | The researchers report that Northeast Pacific coastal warming since 1900 is often ascribed to anthropogenic greenhouse forcing, but interpret "several independent data sources to demonstrate that century-long warming around the northeast Pacific margins, like multi-decadal variability, can be primarily attributed to changes in atmospheric circulation," not anthropogenesis. The researchers explain that "natural internally generated changes in atmospheric circulation were the primary cause of coastal Northeast Pacific warming from 1900 to 2012 and demonstrate more generally that regional mechanisms of inter-annual and multi-decadal temperature variability can also extend to century time scales." |
| "Global warming 'pause' expands to 'new record length': No warming for 18 years 5 months," *Climate Depot*, May 5, 2015. | There is no empirical scientific evidence for significant climate effects of rising $CO_2$ levels, and there is no convincing evidence that anthropogenic global warming (AGW) will produce catastrophic climate changes. Average temperatures in the U.S. and globally have not been increasing in recent decades, and even show a slight cooling trend. According to the Remote Sensing System satellite record there has been no global temperature increase for 18 years 5 months (October 1996 to April 2015) – despite significant recorded increases in $CO_2$ emissions over this period. |
| **"**Satellite measurements of warming in the troposphere," https://www.skepticalscience.com/satellite-measurements-warming-troposphere.htm | Global temperatures are not increasing despite increases in $CO_2$ concentrations. Models predicting increased temperatures on the basis of $CO_2$ concentrations are increasingly inaccurate. |
| ***B. There is No Evidence That Extreme Weather Is Increasing, and In Any Event Warming Would Moderate It Further*** | |
| Spinoni, J., Naumann, G., Carrao, H., Barbosa, P. and Vogt, J. 2014. World drought frequency, duration, and severity for 1951-2010. *International Journal of Climatology* **34**: 2792-2804. | Data show no clear increase in global droughts. |
| Seo, S.N. 2014. Estimating tropical cyclone damages under climate change in the Southern Hemisphere using reported damages. *Environmental and Resource Economics* **58**: 473-490. | Historical records of tropical cyclones in Southern Hemisphere shows no increase over period of increased temperature and $CO_2$ concentration (1970-2006). Both frequency and damage fell over the period. |
| Hodgson, J.Y.S., Ward, A.K. and Dahm, C.N. 2013. An independently corroborated, diatom-inferred record of long-term drought cycles occurring over the last two millennia in New Mexico, USA. *Inland Waters* **3**: 459-472. | A study of three signals for drought (solar intensity, diatoms, and tree rings) showed that droughts correlated strongly with periods of lower solar intensity, and higher solar intensity correlated with increased precipitation. |
| Ballinger, T.J., Allen, M.J. and Rohli, R.V. 2014. Spatiotemporal analysis of the January | The January 2014 "polar vortex" was neither unusual nor extreme in terms of temperature, |

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| Northern Hemisphere circumpolar vortex over the contiguous United States. *Geophysical Research Letters* **41**: 3602-3608. | area, or location/displacement. |
| Foulds, S.A., Macklin, M.G. and Brewer, P.A. 2014. The chronology and the hydrometeorology of catastrophic floods on Dartmoor, South West England. *Hydrological Processes* **28**: 3067-3087. | Trends in floods in southwest England show decreased frequency. |
| Millet, L., Massa, C., Bichet, V., Frossard, V., Belle, S. and Gauthier, E. 2014. Anthropogenic versus climatic control in a high-resolution 1500-year chironomid stratigraphy from a southwestern Greenland lake. Quaternary Research 81: 193-202. | Analysis of sediment cores from Greenland lake gives climate history for 1,500 years. Validates millennial-level fluctuations, and also that warm periods tend to have *more stable* climate. |
| Safeeq, M., Mair, A. and Fares, A. 2013. Temporal and spatial trends in air temperature on the Island of Oahu, Hawaii. *International Journal of Climatology* **33**: 2816-2835. | Safeeq *et al.* report that over the longer 39-year period, island-wide minimum temperature increased by 0.17°C/decade, while there was no detectable trend in the corresponding maximum temperature. And during the more recent 25-year period, they found that annual maximum temperature actually showed a decline, while minimum temperature continued to increase. And they thus calculated that the trend in the diurnal temperature range (DTR) "shows a decline during the past 39 years with a stronger decreasing trend during the recent 25 years." |
| Kumar, A., Chen, M., Hoerling, M. and Eischeid, J. 2013. Do extreme climate events require extreme forcings? Geophysical Research Letters 40: 3440-3445. | Kumar *et al.* write that "based on the diagnosis of a spectrum of possible outcomes for precipitation over the Great Plains from this system, it is concluded that the extreme Great Plains drought did not require extreme external forcings and could plausibly have arisen from atmospheric noise alone." Kumar *et al.* also write that "processes inherent to the atmosphere alone, with no intervention of external forcing, may cause extreme events." |
| Haig, J., Nott, J. and Reichart, G.-J. 2014. Australian tropical cyclone activity lower than at any time over the past 550-1,500 years. Nature 505: 667-671. | Haig *et al.* concluded that the Australian region is experiencing a highly pronounced phase of tropical cyclone *inactivity*. |
| Allen, E.B., Rittenour, T.M., DeRose, R.J., Bekker, M.F., Kjelgren, R. and Buckley, B.M. 2013. A tree-ring based reconstruction of Logan River streamflow, northern Utah. Water Resources Research 49: 8579-8588. | The six scientists say their work reveals that "the Logan River has experienced highly variable streamflow over the last four centuries," "it is likely that past droughts and wet periods [were] more extreme than the models indicate, thereby implying the possibility that water supplies may have been more volatile in the past." |
| Pangle, L.A., Gregg, J.W. and McDonnell, J.J. 2014. Rainfall seasonality and an ecohydrological feedback offset the potential impact of climate warming on evapotranspiration and groundwater recharge. *Water Resources Research* **50**: 1308-1321. | Complex study of water budget showed no net change in water balance under warmer temperatures. Complex system interactions and feedbacks dictate the response to warming. |

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| Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K. and Sherstyukov, B. 2014. Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal* **59**: 1-28. | Contrary to popular perceptions, there is no increase in flood frequency, and there is unlikely to be an increase in either magnitude or frequency. Moreover, reports of increased damage are due to humans putting more expensive assets in the way of floods rather than anthropogenic climate change. |
| Chenoweth, M. and Divine, D. 2012. Tropical cyclones in the Lesser Antilles: descriptive statistics and historical variability in cyclone energy, 1638-2009. *Climatic Change* **113**: 583-598. | Lesser Antilles--which should be right along the path of most Atlantic cyclone formation--show no statistically significant increase over 318-year records, either over entire length or sampled in shorter periods. |
| Barredo, J.I., Sauri, D. and Llasat, M.C. 2012. Assessing trends in insured losses from floods in Spain 1971-2008. *Natural Hazards and Earth System Sciences* **12**: 1723-1729. | Once adjusted for exposure and value of assets to destruction, there is no indication at all of worse or more frequent floods in Spain. "[T]he increasing trend in the original losses is explained by socio-economic factors, such as the increases in exposed insured properties, value of exposed assets and insurance penetration." Indeed, "the analysis *rules out* a discernible influence of anthropogenic climate change on insured losses …" (emphasis added). |
| Deng, H., Zhao, F. and Zhao, X. 2012. Changes of extreme temperature events in Three Gorges area, China. *Environmental and Earth Sciences* **66**: 1783-1790. | Even though the mean temperature near the Three Gorges Dam has increased since 1958, the prevalence of heat waves has decreased, and short heat waves are replacing longer ones. |
| Chen, G., Tian, H., Zhang, C., Liu, M., Ren, W., Zhu, W., Chappelka, A.H., Prior, S.A. and Lockaby, G.B. 2012. Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage. *Climatic Change* **114**: 379-397. | Examining the standard precipitation index for the southern United States, researchers found a (not statistically significant) decrease in drought intensity and no increase in drought duration. Researchers directly suggest that IPCC's AR4 (2007) report is simply incorrect in predicting increased droughts or rapidly increased air temperature. |
| Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H. and Novello, V.F. 2012. A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past* **8**: 1309-1321. | South American Summer Monsoon system significantly weakened during past warmer periods and strengthened during cooler stretches. |
| Zhang, Q., Zhang, W., Lu, X. and Chen, Y.D. 2011. Landfalling tropical cyclones activities in the south China: intensifying or weakening? *International Journal of Climatology* **32**: 1815-1924. | "[D]espite the long-term warming trend in SST in the Western North Pacific, no long-term trend is observed in either the frequency or intensities of" tropical cyclones making landfall in China's Guangdong Province. |
| Hoarau, K., Bernard, J. and Chalonge, L. 2012. Intense tropical cyclone activities in the northern Indian Ocean. *International Journal of Climatology* **32**: 1935-1945. | The supposed upward trend in cyclone activity in the Indian Ocean is based on faulty data. Satellite data show there has been no such rise. |
| Munier, S., Palanisamy, H., Maisongrande, P., Cazenave, A. and Wood, E.F. 2012. Global runoff anomalies over 1993-2009 estimated | Global runoff measures should be an indicator of the effects of anthropogenic global warming, but "[researchers] show that an intensification |

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| from coupled Land-Ocean-Atmosphere water budgets and its relation with climate variability. *Hydrology and Earth system Sciences* **16**: 3647-3658. | of the global water cycle due to global warming is not obvious over the last two decades ….” |
| Li, D., Knudsen, M.F., Jiang, H., Olsen, J., Zhao, M., Li, T., Knudsen, K.L., Seidenkrantz, M.-S. and Sha, L. 2012. A diatom-based reconstruction of summer sea-surface salinity in the Southern Okinawa Trough, East China Sea, over the last millennium. *Journal of Quaternary Science* **27**: 771-779. | Paleoclimate reconstructions in the Southern Okinawa Trough show high salinity during the Medieval Warm Period, but lower salinity during Little Ice Age, mostly due to runoff from increased flooding. This research both validates the widespread nature of the two climatic periods, but also demonstrates increased flooding during cooler periods. |
| Fan, L., Lu, C., Yang, B. and Chen, Z. 2012. Long-term trends of precipitation in the North China Plain. *Journal of Geographic Sciences* **22**: 989-1001. | Localized warming trend in North China Plain has resulted in less variation in precipitation and a decreasing trend in the number of consecutive no-rain days (and important indicator of drought). |
| Cusack, S. 2013. A 101 year record of windstorms in the Netherlands. *Climatic Change* **116**: 693-704. | Contrary to predictions or worse windstorms, the Netherlands is experiencing “the minimum aggregate storm damage of the past 100 years” due to lower rates of occurrence of damaging storms. |
| Sorrel, P., Debret, M., Billeaud, I., Jaccard, S.L., McManus, J.F. and Tessier, B. 2012. Persistent non-solar forcing of Holocene storm dynamics in coastal sedimentary archives. *Nature Geoscience* **5**: 892-896. | Contrary to theory that increased $CO_2$ brings more storm and drought, analysis of actual (non-model) meteorological trends from 1940 to 2009 show dry regions becoming wetter and wet regions becoming drier. Moreover, the data show a slight decline in drought over the last 70 years. |
| Sorrel, P., Debret, M., Billeaud, I., Jaccard, S.L., McManus, J.F. and Tessier, B. 2012. Persistent non-solar forcing of Holocene storm dynamics in coastal sedimentary archives. *Nature Geoscience* **5**: 892-896. | Analysis of sedimentation near Mont-Saint-Michel in English Channel shows storms over last 6,500 years peaked during cold and windy periods, and waned during warmer periods. |
| Peng, S., Piao, S., Ciais, P., Fang, J. and Wang, X. 2010. Change in winter snow depth and its impacts on vegetation in China. *Global Change Biology* **16**: 3004-3013 | Warming has resulted in increased snow depth and increased vegetation coverage in northern China which has decreased dust and sand-dust storms. |
| Gascon, G., Stewart, R.E. and Henson, W. 2010. Major cold-season precipitation events at Iqaluit, Nunavut. *Arctic* **63**: 327-337. | Contradicting anecdotal reports of hazardous weather, the study found a significant decrease in autumn and winter storm activity in the eastern Canadian arctic. |
| Goebbert, K.H. and Leslie, L.M. 2010. Interannual variability of Northwest Australian tropical cyclones. *Journal of Climate* **23**: 4538-4555. | Researchers found no significant increase in tropical cyclones in Northwest Australia. |
| Stambaugh, M.C., Guyette, R.P., McMurry, E.R., Cook, E.R., Meko, D.M. and Lupo, A.R. 2011. Drought duration and frequency in the U.S. corn belt during the last millennium (AD 992-2004). *Agricultural and Forest Meteorology* **151**: 154-162. | Droughts have and will continue to happen in the Corn Belt irrespective of warming. |
| Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R. and Brauer, A. 2010. A 450 year record of spring-summer | Historical analysis of flooding in Southern Germany reveals that they are unrelated to warming. |

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| flood layers in annually laminated sediments from Lake Ammersee (southern Germany). *Water Resources Research* **46**: 10.1029/2009WR008360. | |
| Wise, E.K. 2010. Tree ring record of streamflow and drought in the upper Snake River. *Water Resources Research* **46**: 10.1029/2009WR009282. | Droughts of recent past are eclipsed by the sustained low-flow period lasting for over 30 years in the early to mid-1600s. There has been nothing unusual, unnatural or unprecedented about the early 21st-century drought experienced throughout the Snake River Basin. |
| Kumar, M.R.R. and Sankar, S. 2010. Impact of global warming on cyclonic storms over north Indian Ocean. *Indian Journal of Geo-Marine Science* **39**: 516-520. | "The frequency of storms and severe storms do not show a dramatic rise in spite of a substantial increase in the sea surface temperature in the Bay of Bengal from 1951-2007 compared to 1901-1951." |
| Douglas, E.M. and Fairbank, C.A. 2011. Is precipitation in northern New England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. *Journal of Hydrologic Engineering* **16**: 203-217. | Despite short term trends which give the appearance of increasing frequency of extreme rainfall events in Northern New England, the frequency is relatively stable when compared to longer periods of time. |
| Yeh, S.-W., Kirtman, B.P., Kug, J.-S., Park, W. and Latif, M. 2011. Natural variability of the central Pacific El Niño event on multi-centennial timescales. *Geophysical Research Letters* **38**: 10.1029/2010GL045886. | Increasing frequency of Central Pacific El Niño events could be part of natural variability in the tropical climate system. |
| Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P. and Von Grafenstein, U. 2011. Intense storm activity during the Little Ice Age on the French Mediterranean coast. *Palaeogeography, Palaeoclimatology, Palaeoecology* **299**: 289-297. | Extreme storm events are associated with a large cooling of Europe. |
| Klotzbach, P.J. 2011. The influence of El Niño-Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean tropical cyclone activity. *Journal of Climate* **24**: 721-731. | No warming impact on tropical cyclone activity in the Caribbean Sea. |
| Klotzbach, P.J. 2011. El Niño-Southern Oscillation's impact on Atlantic basin hurricanes and U.S. landfalls. *Journal of Climate* **24**: 1252-1263. | No warming impact on tropical cyclone activity in the North Atlantic Ocean. |
| Kumar, V., Jain, S.K. and Singh, Y. 2010. Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal***55**: 484-496. | India has not experienced an increase in rainfall. |
| Mazvimavi, D. 2010. Investigating changes over time of annual rainfall in Zimbabwe. *Hydrology and Earth System Sciences* **14**: 2671-2679. | Climate change predictions with respect to increased rainfall in Zimbabwe are not yet statistically significant. |
| Mass, C., Skalenakis, A. and Warner, M. 2011. Extreme precipitation over the west coast of North America: Is there a trend? *Journal of* | "Considering the large variability in precipitation trends among the various general circulation models in the above studies and their |

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| *Hydrometeorology* **12**: 310-318. | associated regional climate models, and the differences between the simulated trend distributions and the observed trend patterns found in this study and others, it is unclear whether anthropogenic global warming is the source of past spatial patterns of extreme precipitation trends along the west coast of North America." |
| Vecchi, G.A. and Knutson, T.R. 2011. Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878-1965) using ship track density. *Journal of Climate* **24**: 1736-1746. | Study found that a lack of support for the hypothesis that any warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase. |
| Arrigoni, A.S., Greenwood, M.C. and Moore, J.N. 2010. Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of rivers in the Northern Rocky Mountains, United States. *Water Resources Research* **46**: 10.1029/2010WR009162. | "Changes in climate to date have not been great enough to significantly detect changes in the timing of flows in most natural sub-basins in the Northern Rocky Mountains beyond the natural variability." |
| Bormann, H., Pinter, N. and Elfert, S. 2011. Hydrological signatures of flood trends on German rivers: Flood frequencies, flood heights and specific stages. *Journal of Hydrology* **404**: 50-66. | Warming has not led to any increase in flooding in German rivers. |
| Wallenius, T., Larjavaara, M., Heikkinen, J. and Shibistova, O. 2011. Declining fires in Larix-dominated forests in northern Irkutsk district. *International Journal of Wildland Fire* **20**: 248-254. | Wildfires in Central Siberia have decreased since the Little Ice Age. |
| Alexander. L.V., Wang, X.L., Wan, H. and Trewin, B. 2011. Significant decline in storminess over southeast Australia since the late 19th century. *Australian Meteorological and Oceanographic Journal* **61**: 23-30. | Over the past century, there has been a significant reduction in intense wind events across SE Australia. |
| Villarini, G., Smith, J.A., Baeck, M.L. and Krajewski, W.F. 2011. Examining flood frequency distributions in the Midwest U.S. *Journal of the American Water Resources Association* **47**: 447-463. | There is little indication that any anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S. |
| Wolter, K. and Timlin, M.S. 2011. El Niño/Southern Oscillation behavior since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *International Journal of Climatology* **31**: 1074-1087. | None of the behavior of recent El Niño Southern Oscillation events appears unprecedented, including duration, onset timing, and spacing in the last few decades compared to a full century before then. |
| Sun, L.-h., Ai, W.-x., Song, W.-l. and Wang, Y.-m. 2011. Study on climatic characteristics of China-influencing tropical cyclones. *Journal of Tropical Meteorology* **17**: 181-186. | From 1951-2005, tropical cyclones and super typhoons impacting China have become less frequent and less ferocious. |
| Esteves, L.S., Williams, J.J. and Brown, J.M. 2011. Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Sciences* **11**: 1641-1656. | There has been no evidence of enhanced storminess or increases in surge heights in the eastern Irish sea. |
| Maue, R.N. 2011. Recent historically low global | There is no significant linear trend in the |

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| tropical cyclone activity. *Geophysical Research Letters* **38**: 10.1029/2011GL047711. | frequency of global tropical cyclone activity. |
| Villarini, G., Vecchi, G.A., Knutson, T.R., Zhao, M. and Smith, J.A. 2011. North Atlantic tropical storm frequency response to anthropogenic forcing: Projections and sources of uncertainty. *Journal of Climate* **24**: 3224-3238. | Study does not support the notion of large increases in tropical storm frequency in the North Atlantic basin in response to greenhouse gases. |
| Wang, A., Lettenmaier, D.P. and Sheffield, J. 2011. Soil moisture drought in China, 1950-2006. *Journal of Climate* **24**: 3257-3271. | While trends in droughts in China have worsened, models project that a warmer and moister atmosphere in the future will actually lead to an enhancement of the circulation strength and precipitation of the summer monsoon over most of China that will offset enhanced drying due to increased atmospheric evaporative demand in a warmer world. |
| Li, F., Roncevich, L., Bicknell, C., Lowry, R. and Ilich, K. 2011. Interannual variability and trends of storminess, Perth, 1994-2008. *Journal of Coastal Research* **27**: 738-745. | Despite warming, Perth, Australia has not experienced an increase in storm trends. |
| Gray, S.T., Lukas, J.J. and Woodhouse, C.A. 2011. Millennial-length records of streamflow from three major Upper Colorado River tributaries. *Journal of the American Water Resources Association* **47**: 702-712. | Drought in the Upper Colorado River Basin is not unprecedented or unusual. |
| Nott, J. 2011. Tropical cyclones, global climate change and the role of Quaternary studies. *Journal of Quaternary Science* **26**: 468-473. | Recent analyses of corrected historical tropical cyclones records suggest that there are no definitive trends towards an increase in the frequency of high-intensity tropical cyclones for the Atlantic Ocean region, the northwest Pacific, and the Australian region, South Pacific and south Indian oceans. |
| Callaghan, J. and Power, S.B. 2011. Variability and decline in the number of severe tropical cyclones making land-fall over eastern Australia since the late nineteenth century. *Climate Dynamics* **37**: 647-662. | Despite global climate change, the number of tropical cyclone landfalls in eastern Australia has declined. |
| Ying, M., Yang, Y-H., Chen, B-D. and Zhang, W. 2011. Climatic variation of tropical cyclones affecting China during the past 50 years. *Science China Earth Sciences* **54**: 10.1007/s11430-011-4213-2. | For the whole of China and essentially all of its component parts, major measures of tropical cyclones impact have either remained constant or slightly decreased. |
| Xiao, F., Yin, Y., Luo, Y., Song, L. and Ye, D. 2011. Tropical cyclone hazards analysis based on tropical cyclone potential impact index. *Journal of Geographical Sciences* **21**: 791-800. | Tropical cyclones impacting China have *not* been increasing in either frequency or ferocity over the past half-century or more. |
| Grossmann, I. and Morgan, M.G. 2011. Tropical cyclones, climate change, and scientific uncertainty: what do we know, what does it mean, and what should be done? *Climatic Change* **108**: 543-579. | While Atlantic tropical cyclones have recently become more intense, evidence for changes in other basins is not persuasive, and changes in the Atlantic cannot be clearly attributed to either natural variability or climate change. |
| Marengo, J.A. 2009. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. Hydrological Processes 23: 3236-3244. | Morengo worked with hydrometeorological indices for the Amazon basin and its several sub-basins in an effort designed “to explore long-term variability of climate since the late 1920s and the presence of trends and/or |

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| | cycles in rainfall and river indices in the basin." The Brazilian researcher reports that "no systematic unidirectional long-term trends towards drier or wetter conditions have been identified since the 1920s." Instead, he found that "the rainfall and river series show variability at inter-annual scales." |
| Kunkel, K.E., Palecki, M.A., Ensor, L., Easterling, D., Hubbard, K.G., Robinson, D. and Redmond, K. 2009b. Trends in twentieth-century U.S. extreme snowfall seasons. Journal of Climate 22: 6204-6216. | The seven scientists found there were "large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States," but that they were "balanced by large increases in the frequency of low-extreme snowfall years in the Northeast, Southeast and Northwest." All in all, therefore, they determined that "the area-weighted conterminous United States results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-year period." |
| Schmocker-Fackel, P. and Naef, F. 2010. More frequent flooding? Changes in flood frequency in Switzerland since 1850. Journal of Hydrology 381: 1-8. | The two researchers report that "in Switzerland, periods with frequent floods have alternated with quieter periods during the last 150 years," and that "since 1900, flood-rich periods in northern Switzerland corresponded to quiet periods in southern Switzerland and vice versa." As for the fact that over the same period of time "three of the four largest large-scale flood events in northern Switzerland have all occurred within the last ten years," they report that "a similar accumulation of large floods has already been observed in the second half of the 19th century." |
| Barredo, J.I. 2010. No upward trend in normalized windstorm losses in Europe: 1970-2008. Natural Hazards and Earth System Sciences 10: 97-104. | In the words of Barredo, "the analyses reveal no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure," stating, in fact, that "increasing disaster losses are overwhelmingly a consequence of changing societal factors." |
| Wallace, D.J. and Anderson, J.B. 2010. Evidence of similar probability of intense hurricane strikes for the Gulf of Mexico over the late Holocene. Geology 38: 511-514. | Based on their analyses, Wallace and Anderson report "there has been no notable variation in intense storm impacts across the northwestern Gulf of Mexico coast during this time interval," i.e., 5300-900 yr BP, "implying no direct link between changing climate conditions and annual hurricane impact probability." In addition, they say "there have been no significant differences in the landfall probabilities of storms between the eastern and western Gulf of Mexico during the late Holocene, suggesting that storm steering mechanisms have not varied during this time." |
| Villarini, G. and Smith, J.A. 2010. Flood peak distributions for the eastern United States. Water Resources Research 46: 10.1029/2009WR008395. | Villarini and Smith found that, for flooding reported by stations in the eastern United States during the past century, (1) "only a small fraction of stations exhibited significant linear |

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| | trends," that (2) "for those stations with trends, there was a split between increasing and decreasing trends," and that (3) "no spatial structure was found for stations exhibiting trends." Thus, they concluded that "there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States." |
| Song, J.-J., Wang, Y. and Wu, L. 2010. Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. Journal of Geophysical Research 115: 10.1029/2009JD013058. | Weather pattern data showing increased cyclone activity are confounded by changes in metrics. In the words of the Chinese researchers, "though the differences in TC tracks among these data sets are negligibly small, the JTWC data set tends to classify TCs of category 2-3 as category 4-5, leading to an upward trend in the annual frequency of category 4-5 TCs and the annual accumulated power dissipation index, as reported by Webster *et al.* (2005) and Emanuel (2005)." And they add that "this trend and potential destructiveness over the period 1977-2007 are found only with the JTWC data set," while noting that actual downward trends "are apparent in the RSMC and STI data sets." |
| Eckert, N., Parent, E., Kies, R. and Baya, H. 2010. A spatio-temporal modelling framework for assessing the fluctuations of avalanche occurrence resulting from climate change: application to 60 years of data in the northern French Alps. Climatic Change 101: 515-553. | Eckert *et al.* compared a number of different ways of analyzing snow avalanche data contained in the Enquete Permanente sur les Avalanches -- EPA, which they say "is a chronicle describing the avalanche events on approximately 5,000 determined paths in the French Alps and the Pyrenees." The four researchers report that they could find "no strong modifications in mean avalanche activity or in the number of winters of low or high activity over the last 60 years." After considering all they had learned from their many analyses and the works of the other scientists they cited, Eckert *et al.* concluded that "climate change has recently had little impact on the avalanching rhythm in this region." |
| Fengjin, X. and Ziniu, X. 2010. Characteristics of tropical cyclones in China and their impacts analysis. Natural Hazards 54: 827-837. | The two researchers say the data indicate "a decreasing trend in the generation of TCs [tropical cyclones] in the WNP since the 1980s," and they say that "the number of TCs making landfall has remained constant or shown only a slight decreasing trend." Likewise, they report that "the number of casualties caused by TCs in China appears to show a slight decreasing trend," as would be expected under these less dangerous circumstances. |
| Bollschweiler, M. and Stoffel, M. 2010. Changes and trends in debris-flow frequency since AD 1850: Results from the Swiss Alps. The Holocene 20: 907-916. | The two Swiss scientists found there were peaks in debris-flow activity "toward the end of the Little Ice Age and in the early twentieth century when warm-wet conditions prevailed |

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| | during summers in the Swiss Alps," but also observed "a considerable decrease in frequency over the past decades which results from a decrease in the frequency of triggering precipitation events." Most importantly, they report that when longer-term changes were sought, they could not identify "any significant trends in the debris-flow series between 1850 and 2009." These results "contradict the widely accepted assumption that climatic changes will univocally lead to an increase in event frequency." |
| Hanson, C.T. and Odion, D.C. 2014. Is fire severity increasing in the Sierra Nevada, California, USA?*International Journal of Wildland Fire* **23**: 1-8. | Historical studies of fire rates in Sierra Nevada mountains overestimate number of fires and severity compared to remote sensing (i.e., observational) data. |
| Matthews, J.A., Dahl, S.O., Dresser, P.Q., Berrisford, M.S., Lie, O., Nesje, A. and Owen, G. 2009. Radiocarbon chronology of Holocene colluvial (debris-flow) events at Sletthamn, Jotunheimen, southern Norway: a window on the changing frequency of extreme climatic events and their landscape impact. The Holocene 19: 1107-1129. | There is "no obvious correlation between debris-flow frequency and a relative warm climate." In fact, they say that "debris-flow frequency was lowest post-8000 cal. BP during the Holocene Thermal Maximum," and that most of the "century- to millennial-scale phases of enhanced debris-flow activity appear to correlate with Neoglacial events," one of which was the "Little Ice Age," concluding there is little support in observational data "for the association of higher debris-flow frequencies with an increasingly warm climate." In fact, they say that "the evidence suggests the opposite." |
| Wilcox, B.P. and Huang, Y. 2010. Woody plant encroachment paradox: Rivers rebound as degraded grasslands convert to woodlands. Geophysical Research Letters 37: 10.1029/2009GL041929. | "Contrary to widespread perceptions," streamflows in the study region "have not been declining." In fact, their findings "run counter to current thinking in both lay and scientific circles," and the researchers speculate that "baseflows are higher now than in pre-settlement times, because rooting by trees has facilitated groundwater recharge." In addition, the transpiration-reducing effect of atmospheric $CO_2$ enrichment may also have played a role in this regard, as has been suggested by several prior studies of river basin hydrology |
| Nott, J. and Forsyth, A. 2012. Punctuated global tropical cyclone activity over the past 5,000 years.*Geophysical Research Letters* **39**: 10.1029/2012GL052236. | Global tropical cyclone activity appears to be cyclical over the span of millennia, and not connected to $CO_2$ levels. |
| Lloyd, P. 2010. Historical trends in the flows of the Breede River. Water SA 36: 329-333. | "Examination of river flows over the past 43 years in the Breede River basin," demonstrate that "changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows." Unaccounted-for land use changes, rather than warming resulted in decreased flow rates, and sites that had not experienced the same develpments experienced a "14% increase in flow over the study period," which was "contrary to the |

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| | climate change predictions" and indicative of the fact that "climate change models cannot yet account for local climate change effects." Predictions of possible adverse local impacts from global climate change should therefore be treated with "the greatest caution," and, "above all, they must not form the basis for any policy decisions until such time as they can reproduce known climatic effects satisfactorily." |
| Fritz, S.C., Baker, P.A., Ekdahl, E., Seltzer, G.O. and Stevens, L.R. 2010. Millennial-scale climate variability during the Last Glacial period in the tropical Andes. Quaternary Science Reviews 29: 1017-1024. | The five researchers report that their work "shows clear evidence of millennial-scale climate variation between ~60 and 20 ka BP," which was driven by variations in the degree of regional wetness; and they say that this climatic oscillation is well correlated with the stadial/interstadial oscillation of the North Atlantic region. |
| Billeaud, I., Tessier, B. and Lesueur, P. 2009. Impacts of late Holocene rapid climate changes as recorded in a macrotidal coastal setting (Mont-Saint-Michel Bay, France). Geology 37: 1031-1034. | "Rapid climate changes, with ~1500-year periodicity, are recorded in the sedimentary successions that constitute the late Holocene infill of the bay," and that "the various changes reflect an increase in wave dynamics in association with Bond cold events" as well as "storm impacts, which occur with a millennial time-scale periodicity" |
| Rani, B.A., Manikandan, N. and Maragatham, N. 2014. Trend analysis of rainfall and frequency of rainy days over Coimbatore. *Mausam* **65**: 379-384. | The three researchers say their results showed there was "no change in long-term monthly, seasonal and annual rainfall and frequency of rain days" and that "there is no significant trend in the annual and seasonal rainfall totals." This being the case, they also say "it can be concluded that there is no climate change observed over Coimbatore." |
| Brooks, H.E., Carbin,G.W. and Marsh, P.T. 2014. Increased variability of tornado occurrence in the United States. *Science* **346**: 349-352. | "Changes in how tornadoes are reported have made it difficult to answer" the question of whether climate change has increased the number of US tornadoes. Nevertheless, the mean occurrence of *well*-reported aspects of U.S. tornadoes, such as "the mean annual number of all but the weakest tornadoes…has appeared to show little or no consistent trend."<br><br>The stronger tornadoes from 1954 to 2013 exhibited "much inter-annual variability but no long-term linear trend", leading the researchers to conclude that "how such a change would relate to the increase in global temperature, if it relates at all, is unknown at this time." |
| Clemmensen, L.B., Hansen, K.W.T and Kroon, A. 2014. Storminess variation at Skagen, northern Denmark since AD 1860: Relations to climate change and implications for coastal dunes. *Aeolian Research* **15**: 101-112. | Using wind data from a lighthouse station in northern Denmark where data had been collected consistently since 1860, researchers determined storminess (wind events exceeding Beaufort 8) was far higher between 1860-75 and the annual drift potential (DP) of coastal dunes was "also extremely high during that |

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| | period, but "since 1980 DP levels are…[lower] and decreasing." |
| Dowdy, A.J. 2014. Long-term changes in Australian tropical cyclone numbers. *Atmospheric Science Letters* **15**: 292-298. | Researchers studied the occurrence of tropical cyclones in the Australia region of the Indian Ocean between 1982 and 2013. The data "revealed a decreasing trend in the yearly number of TCs experienced in *this* region over *this* time period." |
| Fitchett, J.M. and Grab, S.W. 2014. A 66-year tropical cyclone record for south-east Africa: temporal trends in a global context. *International Journal of Climatology* **34**: 3604-3615. | Despite increased sea surface temperatures over the past sixty years, the study did not find "statistically significant trends in the frequency of tropical cyclone landfalls over Madagascar and Mozambique over the past six decades" which would be consistent with projected decreases across the Indian Ocean area. |
| Benitez, J.B. and Domecq, R.M. 2014. Analysis of meteorological drought episodes in Paraguay. *Climatic Change* **127**: 15-25 | No clear drought trend can be found between 1964 and 2011 in data from Paraguay. |
| Wetter, O., Pfister, C., Werner, J.P., Zorita, E., Wagner, S., Seneviratne, S.I., Herget, J., Grunewald, U., Luterbacher, J., Alcoforado, M.-J., Barriendos, M., Bieber, U., Brazdil, R., Burmeister, K.H., Camenisch, C., Contino, A., Dobrovolny, P., Glaser, R., Himmelsbach, I., Kiss, A., Kotyza, O., Labbe, T., Limanowka, D., Litzenburger, L., Nordl, O., Pribyl, K., Retso, D., Riemann, D., Rohr, C., Siegfried, W., Soderberg, J. and Spring, J.-L. 2014. The year-long unprecedented European heat and drought of 1540 - a worst case. *Climatic Change* **125**: 349-363. | A long series of grape harvest dates (AD 1444-2011) demonstrate that April-July temperatures in 1540 both in France and Switzerland were likely significantly warmer than in 2003" and "confirm these findings in a larger, European context."<br><br>Furthermore, the 1540 drought was significantly more persistent and extreme than any droughts since 1860, thus resulting in a severe annual number of days with precipitation deficit. |
| Damberg, L. and AghaKouchak, A. 2014. Global trends and patterns of drought from space. *Theoretical and Applied Climatology* **117**: 441-448 | The study analyzed changes in areas under droughts over the past three decades "based on satellite gauge-adjusted precipitation observations," and found that while several areas are showing significant drying trends over the past three decades that other regions in the globe show a wetting trend during the same time span," and "the area of global land under drought conditions does not show a significant trend over the past three decades." These results "disagree with several model-based studies (e.g., Dai, 2012) that indicate droughts have been increasing over land." |
| Partasenok, I.S., Groisman, P.Y., Chekan, G.S. and Melnik, V.I. 2014. Winter cyclone frequency and following freshet streamflow formation on the rivers in Belarus. Environmental Research Letters **9**: 10.1088/1748-9326/9/095005. | Moderate warming over the past half-century has resulted in reduced inundations and flooding events in Belarus. |
| Axelson, J.N., Smith, D.J., Daniels, L.D. and Alfaro, R.I. 2015. Multicentury reconstruction of western spruce budworm outbreaks in central British Columbia, Canada. *Forest Ecology and Management* **335**: 235-248. | Outbreaks of western spruce budwork in Douglas firs occur on fairly routine intervals. Outbreaks over the last 40 years are not unprecedented. |

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| Xia, F., Liu, X., Xu, J., Wang, Z., Huang, J. and Brookes, P.C. 2015. Trends in the daily and extreme temperatures in the Qiantang River basin, China. *International Journal of Climatology* **35**: 57-68. | Qiantang River Basin experienced warming but not for daily maximum tempteratures: the region is becoming less cold, but not hotter. |
| Judith A. Curry, "Statement to the Committee on Environment and Public Works of the United States Senate in the Hearing on Review of the President's Climate Action Plan," January 16, 2014 | In the U.S., most types of weather extremes were worse in the 1930's and even in the 1950's than in the current climate, while the weather was overall more benign in the 1970's. This sense that extreme weather events are now more frequent and intense is symptomatic of 'weather amnesia' prior to 1970. The extremes of the 1930's and 1950's are not attributable to greenhouse warming and are associated with natural climate variability (and in the case of the dustbowl drought and heat waves, also to land use practices)." |
| Hisayuki Kubota1 and Johnny C. L. Chan, "Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005, *Geophysical Research Letters*, Vol. 36, 2009. | Numerous specious claims were made following the disastrous landfall of typhoon Haiyan in the Philippines in November 2013 that $CO_2$ was somehow responsible. However, there are no reliable scientific data that link the burning of fossil fuels to more powerful typhoons, whether they have hit the Philippines or not. In fact, definitive research has concluded that "No long-term trend is found" and that natural variability appears to prevail. |
| Jessica Weinkle, Ryan Maue, and Roger Pielke Jr., "Historical Global Tropical Cyclone Landfalls," *Journal of Climate*, Volume 25, July 2012, pp. 4729 - 4735. | The authors examined all landfalls in the western North Pacific, the region which includes the Philippines. They found a declining trend of tropical cyclone landfalls over the past six decades. |
| Thomas R. Knutson, John L. McBride, Johnny Chan, Kerry Emanuel, Greg Holland, Chris Landsea, Isaac Held, James P. Kossin, A. K. Srivastava, and Masato Sugi, "Tropical Cyclones and Climate Change**,"** *Nature Geoscience*, vol. 3, 2010, pp. 157 – 163 | This paper, by ten top hurricane scientists, concluded that the U.S. has not seen any long-term increase in land-falling tropical storms and hurricanes, and that "it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes." |
| Dai, Aiguo et al. "A Global Dataset of Palmer Drought Severity Index for 1870-2002: Relationship with Soil Moisture and Effects of Surface Warming," *Journal of Hydrometeorology*, Vol. 5, No. 6, pp. 1117–1130, December 2004; Cook, E.R. et al. "Long-Term Aridity Changes in the Western United States, *Science*, Vol. 306, No. 5698, pp. 1015-1018, 5 November 2004 | The Palmer Drought Index, also known as the Palmer Drought Severity Index (PDSI), which is a measurement of dryness based on recent precipitation and temperature. The index It was developed by meteorologist Wayne Palmer for the Office of Climatology of the U.S. Weather Bureau, and has proven effective in determining long-term drought over several months. It is also used by climatologists to standardize global long-term drought analysis. Global Palmer data sets have been developed based on instrumental records beginning in the 19th century. These researchers found no increase in drought severity in the U.S. over |

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| | the past two centuries. |
| R. Justin DeRose, Shih-Yu Wang, Brendan M. Buckley, and Matthew F. Bekker, 'A 576-Year Weber River Streamflow Reconstruction from Tree Rings for Water Resource Risk Assessment in the Wasatch Front, Utah," *Journal of the American Water Resources Association*, April 2014. | This study foun that over the longer term, the Dust Bowl, the worst drought of the 20th century, barely makes the top 10 in a study that extended Utah's climate record back to the year 1429. The authors developed a 576-year tree-ring-based reconstruction of streamflow for northern Utah's Weber River and found that, while the 20th Century instrumental period includes several extreme individual dry years, it was the century with the fewest such years of the entire reconstruction. Extended droughts were more severe in duration, magnitude, and intensity prior to the instrumental record, including the most protracted drought of the record, which spanned 16 years from 1703 to 1718. Extreme wet years and periods are also a regular feature of the reconstruction. The study revealed a history of nightmare droughts in the West and worse wet periods. |
| https://theclimatefix.wordpress.com/2015/02/05/the-precipitous-decline-in-us-flood-damage-as-a-percentage-of-gdp/. | The U.S. is prone to very large flood events, resulting in tens of billions of dollars in losses. However, the trend since 1940 is striking. As the nation has seen its economic activity expand by a factor of almost 13, flood losses as a proportion of that activity have actually decreased by about 75 percent There is very little evidence of increasing flood frequency or magnitude either in the U.S. or globally, and the diminishing economic impact of floods in the U.S. is undeniable. Similarly, over the past five decades, despite rapid growth in population U.S. deaths from floods have not increased. |
| Roger Pielke, Jr., "Statement of Dr. Roger Pielke, Jr. to the Committee on Environment and Public Works of the United States Senate Hearing on Climate Change: It's Happening Now," 18 July 2013 | Pielke noted that what matters is not the incidence of extreme weather events per se but the impact of such events -- especially the human impact. He: It is misleading, and just plain incorrect, to claim that disasters associated with hurricanes, tornadoes, floods or droughts have increased on climate timescales either in the United States or globally. It is further incorrect to associate the increasing costs of disasters with the emission of greenhouse gases; Globally, weather-related losses ($) have not increased since 1990 as a proportion of GDP (they have actually decreased by about 25 percent) , and insured catastrophe losses have not increased as a proportion of GDP since 1960; hurricanes have not increased in the US in frequency, intensity or normalized damage since at least 1900. The same holds for tropical cyclones globally since at least 1970 (when data allows for a global perspective); floods have not increased in the US in frequency or intensity since at least |

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| | 1950. Flood losses as a percentage of US GDP have dropped by about 75 percent since 1940; tornadoes have not increased in frequency, intensity or normalized damage since 1950, and there is some evidence to suggest that they have actually declined; drought has for the most part, become shorter, less frequent, and cover a smaller portion of the U. S. over the last century. Globally, there has been little change in drought over the past 60 years; the absolute costs of disasters will increase significantly in coming years due to greater wealth and populations in locations exposed to extremes. Consequent, disasters will continue to be an important focus of policy, irrespective of the exact future course of climate change. |
| Indur M. Goklany and Julian Morris, The Decline in Deaths from Extreme Weather, 1900–2010, Reason foundation, Policy Study 393, September 2011; Indur M. Goklany, “Deaths and Death Rates from Extreme Weather Events: 1900-2008,” 2009, *Journal of American Physicians and Surgeons*, vol. 14 (4), 2009, pp. 102–09 | The authros examined trends in global mortality (i.e. the number of people killed) and mortality rates (i.e. the proportion of people killed) associated with extreme weather events for the 111-year period from 1900 to 2010. They foud that aggregate mortality attributed to all extreme weather events globally has declined by more than 90 percent since the 1920s, in spite of a four-fold rise in population and much more complete reporting of such events. The aggregate mortality rate declined by 98 percent., largely due to decreased mortality in three main areas: Deaths and death rates from droughts, which were responsible for approximately 60 percent of cumulative deaths due to extreme weather events from 1900–2010, are more than 99.9 percent lower than in the 1920s; deaths and death rates for floods, responsible for over 30 percent of cumulative extreme weather deaths, have declined by over 98 percent since the 1930s; deaths and death rates for storms (i.e. hurricanes, cyclones, tornados, typhoons), responsible for around seven percent of extreme weather deaths from 1900–2008, declined by more than 55 percent since the 1970s. |
| University of California, San Diego, “Introduction to Natural Disasters,” October 2014. | This report finds that since 1940, the U.S. population has increased by 180 million but deaths from lighting have decreased by more than 90 percent |
| Indur M. Goklany, “The Amazing Decline in Deaths from Extreme Weather in an Era of Global Warming, 1900–2010,” September 2011 | Goklany found that, globally, aggregate mortality attributed to all extreme weather events globally has declined by more than 90 percent since the 1920s, in spite of a four-fold rise in population and much more complete reporting of such events. |
| ***C. Historical Cycles of Warming (e.g., Medieval Warm Period) Have Been More*** | |

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| ***Significant Than Predictions Today, and Historical Warming Periods Had Positive Impacts for Humanity and Culture*** | |
| Judith Curry, "Statement to the Committee on Science, Space, and Technology of the U.S. House of Representatives," Hearings on the President's U.N. Climate Pledge, April 15, 2015, available at http://docs.house.gov/meetings/SY/SY00/20150415/103329/HHRG-114-SY00-Wstate-CurryJ-20150415-U1.pdf. | "Numerous recent research papers have highlighted the importance of natural variability associated with circulations in the Atlantic and Pacific Oceans, which is now believed to be the dominant cause of the hiatus. If the recent warming hiatus is caused by natural variability, then this raises the question as to what extent the warming between 1975 and 1998 can also be explained by natural climate variability." |
| Courtney Mustaphi, C.J. and Gajewski, K. 2013. Holocene sediments from a coastal lake on northern Devon island, Nunavut, Canada. *Canadian Journal of Earth Science* **50**: 564-575. | Sediment analysis of a small lake in Canada shows that warmest recent periods (Holocene Thermal Maximum, Medieval Warm Period) came during a period of low $CO_2$ concentration. |
| Cunningham, L.K., Austin, W.E.N., Knudsen, K.L., Eiriksson, J., Scourse, J.D., Wannamaker Jr., A.D., Butler, P.G., Cage, A.G., Richter, T., Husum, K., Hald, M., Andersson, C., Zorita, E., Linderholm, H.W., Gunnarson, B.E., Sicre, M.-A., Sejrup, H.P., Jiang, H. and Wilson, R.J.S. 2013. Reconstructions of surface ocean conditions from the northeast Atlantic and Nordic seas during the last millennium. The Holocene 23: 921-935. | Noting that the IPCC had limited data regarding sea surface temperatures, Jansen *et al.* concluded that "the 'Medieval Climate Anomaly' warming was most pronounced before AD 1200, with a long-term cooling trend apparent after AD 1250," and that "in recent decades temperatures have been similar to those inferred for the 'Medieval Climate Anomaly'." |
| Rosenthal, Y., Linsley, B.K. and Oppo, D.W. 2013. Pacific Ocean heat content during the past 10,000 years. Science342: 617-621. | Rosenthal *et al.* concluded that "water masses linked to North Pacific and Antarctic intermediate waters were warmer by 2.1 ± 0.4°C and 1.5 ± 0.4°C, respectively, during the middle Holocene Thermal Maximum [HTM] than over the past century," and that "both water masses were ~0.9°C warmer during the Medieval Warm Period [MWP] than during the Little Ice Age and ~0.65°C warmer than in recent decades." |
| He, Y., Zhao, C., Wang, Z., Wang, H., Song, M., Liu, W. and Liu, Z. 2013. Late Holocene coupled moisture and temperature changes on the northern Tibetan Plateau. Quaternary Science Reviews 80: 47-57. | He *et al.* state that "within chronological uncertainty, potentially corresponding temperature and hydrological changes could be identified for the Oort, Wolf, Sporer, Maunder and Dalton solar minimums, as well as the Medieval and modern solar maximums," implying that "the natural climate variability on the northern Tibetan Plateau during the late Holocene might be linked to solar irradiance changes on multi-decadal and centennial timescales." Last of all, they say that their data also indicate "warmer climatic conditions during the MWP than the current warm period." |
| Hanhijarvi,S., Tingley, M.P. and Korhola, A. 2013. Pairwise comparisons to reconstruct mean temperature in the Arctic Atlantic Region over the last 2,000 years. Climate Dynamics 41: 2039-2060. | "The Arctic Atlantic reconstruction features temperatures during the Roman Warm Period and Medieval Climate Anomaly that are comparable [to] or even warmer than those of the twentieth century, and coldest temperatures in the middle of the nineteenth |

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| | century ….” |
| Glur, L., Wirth, S.B., Buntgen, U., Gilli, A., Haug, G.H., Schar, C., Beer, J. and Anselmetti, F.S. 2013. Frequent floods in the European Alps coincide with cooler periods of the past 2500 years. Scientific Reports 3: 10.1038,srep02770. | Citing other research, Glur *et al.* stated that “[r]egarding the best-characterized climatic periods during the past 2500 years,” “flood activity was generally enhanced during the Little Ice Age (1430-1850 C.E.; LIA) compared to the Medieval Climate Anomaly (950-1250 C.E.; MCA).” And they say that “this result is confirmed by other studies documenting an increased (decreased) flood activity during the LIA (MCA) in the Alps.” |
| Thomas, E.R., Bracegirdle, T.J., Turner, J. and Wolff, E.W. 2013. A 308-year record of climate variability in West Antarctica. Geophysical Research Letters 40: 5492-5496. | The four UK researchers report that observed warming in Western Antarctica “is not unusual, with equally large warming and cooling trends observed several times over the past 308 years,” which they further note is “consistent with a study from continental West Antarctica (Steig *et al.*, 2013) which concluded that this recent warming is not unprecedented in the context of the past 2000 years.” Thomas *et al.* were able to confidently conclude that “the effect of anthropogenic climate drivers at this location has not exceeded the natural range of climate variability in the context of the past ~300 years.” |
| Kress, A., Hangartner, S., Bugmann, H., Buntgen, U., Frank, D.C., Leuenberger, M., Siegwolf, R.T.W. and Saurer, M. 2014. Swiss tree rings reveal warm and wet summers during medieval times. *Geophysical Research Letters* **41**: 1732-1737. | The Medieval Warm Period resulted in “beneficial conditions for agriculture and human well-being.” |
| Olafsdottir, G.A., Westfall, K.M., Edvardsson, R. and Palsson, S. 2014. Historical DNA reveals the demographic history of Atlantic cod (Gadus morhua) in medieval and early modern Iceland. *Proceedings of the Royal Society B* **281**: 10.1098/rspb.2013.2976. | Analysis of Atlantic cod population vertebrae at historical fishing sites show that Medieval Warm Period may have been much warmer than the Current Warm Period. |
| Salzer, M.W., Bunn, A.G., Graham, N.E. and Hughes, M.K. 2014. Five millennia of paleotemperature from tree-rings in the Great Basin, USA. *Climate Dynamics* **42**: 1517-1526. | New source of temperature data going back 5,000 years shows that Current Warm Period is not unusual. Periods prior to Industrial Revolution showed even greater temperature swings. |
| Datsenko, N.M., Ivashchenko, N.N., Qin, C., Liu, J., Sonechkin, D.M. and Yang, B. 2014. A comparison between medieval and current climate warming using the Przewalskii’s juniper tree-ring data. *Russian Meteorology and Hydrology* **39**: 17-21. | Tree-ring data from long-lived trees in Tibet show Medieval Warm Period was warmer than Current Warm Period, and that cooler periods in between correlated with lower solar activity. |
| Niemann, H., Stadnitskaia, A., Wirth, S.B., Gilli, A., Anselmetti, F.S., Damste, J.S.S., Schouten, S., Hopmans, E.C. and Lehmann, M.F. 2012. Bacterial GDGTs in Holocene sediments and catchment soils of a high Alpine lake: application of the MBT/CBT-paleothermometer. *Climate of the Past* **8**: 889-906. | Intensity of Medieval Warm Period validated through analysis of bacterial membrane lipids, which change in reaction to shifts in temperature and pH. |

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| Moros, M., Jansen, E., Oppo, D.W., Giraudeau, J. and Kuijpers, A. 2012. Reconstruction of the late-Holocene changes in the Sub-Arctic Front position at the Reykjanes Ridge, north Atlantic. *The Holocene* **22**: 877-886. | Oxygen isotope data validate Medieval Warm period and other climate shifts as ordinary climate variations over time. |
| Pau, S., MacDonald, G.M. and Gillespie, T.W. 2012. A dynamic history of climate change and human impact on the environment from Kealia Pond, Maui, Hawaiian Islands. *Annals of the Association of American Geographers* **102**: 748-762. | Detailed sedimentary records from Maui show that Medieval Warm Period correlated with population growth and expansion of Polynesian society. |
| Novenko, E.Yu., Volkova, E.M., Glasko, M.P. and Zuganova, I.S. 2012. Palaeoecological evidence for the middle and late Holocene vegetation, climate and land use in the upper Don River basin (Russia). *Vegetation History and Archaeobotany* **21**: 337-352. | Study of vegetation fossil records shows mean July and annual temperatures were 2 C above current in the Don river valley in Russia. |
| Gu, Y., Wang, H., Huang, X., Peng, H. and Huang, J. 2012. Phytolith records of the climate change since the past 15000 years in the middle reach of the Yangtze River in China. *Frontiers of Earth Science* **6**: 10-17. | Sediment cores from China show similar temperature trends as other paleoclimate evidence, which links much more strongly to solar activity than to $CO_2$, on both centennial and millennial scales. |
| Rhodes, R.H., Bertler, N.A.N., Baker, J.A., Steen-Larsen, H.C., Sneed, S.B., Morgenstern, U. and Johnsen, S.J. 2012. Little Ice Age climate and oceanic conditions of the Ross Sea, Antarctica from a coastal ice core record. *Climate of the Past* **8**: 1223-1238. | Evidence from Antarctic core samples shows "Little Ice Ace" of decreased temperatures from about 1500 to about 1850 was a global event, not simply local. |
| Ran, L., Jiang, H., Knudsen, K.L. and Eiriksson, J. 2011. Diatom-based reconstruction of palaeoceanographic changes on the North Icelandic shelf during the last millennium. *Palaeogeography, Palaeoclimatology, Palaeoecology* **302**: 109-119. | The warmth of the distant past in North Iceland exceeded the recent past. "The data suggest that solar radiation may be one of the important forcing mechanisms behind the palaeoceanographic changes." |
| Magny, M., Peyron, O., Gauthier, E., Vanniere, B., Millet, L. and Vermot-Desroches, B. 2011. Quantitative estimates of temperature and precipitation changes over the last millennium from pollen and lake-level data at Lake Joux, Swiss Jura Mountains. *Quaternary Research* **75**: 45-54. | Peak warmth at Lake Joux in the Swiss Jura Mountains in the Medieval Warm Period exceeded that of the Current Warm Period. |
| Martin-Chivelet, J., Munoz-Garcia, M.B., Edwards, R.L., Turrero, M.J. and Ortega, A.I. 2011. Land surface temperature changes in Northern Iberia since 4000 yr BP, based on $\delta^{13}C$ of speleothems. *Global and Planetary Change* **77**: 1-12. | The current level of warmth in northern Iberia is no different than it has been for the last four millennia. |
| Mallinson, D.J., Smith, C.W., Mahan, S., Culver, S.J. and McDowell, K. 2011. Barrier island response to late Holocene climate events, North Carolina, USA. *Quaternary Research* **76**: 46-57. | Relative to climatic conditions of both the Medieval Warm Period and Little Ice Age, there has more recently been a general decrease in storminess in the North Carolina Barrier Islands. |
| Reimann, T., Tsukamoto, S., Harff, J., Osadczuk, K. and Frechen, M. 2011. | Analysis of sediment history along the southern end of the Baltic coast reveals that the Current |

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| Reconstruction of Holocene coastal foredune progradation using luminescence dating -- An example from the Swina barrier (southern Baltic Sea, NW Poland). *Geomorphology* **132**: 1-16. | Warm Period may be a product of natural variability. |
| McInerney, F.A. and Wing, S.L. 2011. The Paleocene-Eocene Thermal Maximum: A perturbation of carbon cycle, climate, and biosphere with implications for the future. *Annual Review of Earth and Planetary Sciences* **39**: 489-516. | Study found that most groups of organisms did not suffer mass extinction during the Paleocene-Eocene Thermal Maximum and many adapted. |
| Kaniewski, D., Van Campo, E., Paulissen, E., Weiss, H., Bakker, J., Rossignol, I. and Van Lerberghe, K. 2011. The medieval climate anomaly and the little Ice Age in coastal Syria inferred from pollen-derived palaeoclimatic patterns.*Global and Planetary Change* **78**: 178-187. | Syrian temperature fluctuations within the Medieval Warm Period are nearly identical to the present fluctuations. |
| Larsen, D.J., Miller, G.H., Geirsdottir, A. and Thordarson, T. 2011. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvitarvatn, Iceland. *Quaternary Science Reviews* **30**: 2715-2731. | Icelandic study showed that there is nothing unusual or unprecedented about the warmth of the Current Warm Period. |
| Bertler, N.A.N., Mayewski, P.A. and Carter, L. 2011. Cold conditions in Antarctica during the Little Ice Age -- Implications for abrupt climate change mechanisms. *Earth and Planetary Science Letters* **308**: 41-51. | In the Ross Sea Region of Antarctica, the temperatures in the Medieval Warm Period were warmer than in the Modern Period. |
| Perner, K., Moros, M., Lloyd, J.M., Kuijpers, A., Telford, R.J. and Harff, J. 2011. Centennial scale benthic forminiferal record of late Holocene oceanographic variability in Disko Bugt, West Greenland. *Quaternary Science Reviews* **30**: 2815-2816. | Historical cycling between relatively warmer and cooler conditions in Disko Bugt, West Greenland is normal. |
| Andrade, A., Rubio, B., Rey, D., Alvarez-Iglesias, P., Bernabeu, A.M. and Vilas, F. 2011. Palaeoclimatic changes in the NW Iberian Peninsula during the last 3000 years inferred from diagenetic proxies in the Ria de Muros sedimentary record. *Climate Research* **48**: 247-259. | Analysis of samples from the northwestern coast of the Iberian Peninsula established a climatic history of the region reflecting oscillation of climate that brought the earth into and out of various periods. |
| Neukom, R., Luterbacher, J., Villalba, R., Kuttel, M., Frank, D., Jones, P.D., Grosjean, M., Wanner, H., Aravena, J.-C., Black, D.E., Christie, D.A., D'Arrigo, R., Lara, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urritia, R. and von Gunten, L. 2011. Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries. *Climate Dynamics* **37**: 35-51. | The Medieval Warm Period was a global phenomenon that was composed of even warmer intervals than the Current Warm Period based on a study of Southern South America. |
| Kelly, M.A. and Lowell, T.V. 2009. Fluctuations of local glaciers in Greenland during latest Pleistocene and Holocene time. Quaternary Science Reviews 28: 2088-2106. | "[S]ubsequent to late-glacial or early Holocene time, most local glaciers were smaller than at present or may have disappeared completely during the Holocene Thermal Maximum." |

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| | Thereafter, however, local glaciers began to grow once again; and for all regions except a few locations in western and southeastern Greenland, the two researchers report that glaciers "grew to their maximum Holocene extents during Historical time," which period they identify as extending all the way up to 1940 in certain cases. |
| Seppa, H., Bjune, A.E., Telford, R.J., Birks, H.J.B. and Veski, S. 2009. Last nine-thousand years of temperature variability in Northern Europe. Climates of the Past 5: 523-535. | Seppa *et al.* report that "the stacked records show that the 'Holocene Thermal Maximum' in the region dates to 8000 to 4800 cal yr BP and that the '8.2 event' and the 'Little Ice Age' at 500-100 cal yr BP are the clearest cold episodes during the Holocene," while the graphical representations of their data indicate the Little Ice Age was the colder of the two major cold episodes |
| Sepulveda, J., Pantoja, S., Hughen, K.A., Bertrand, S., Figueroa, D., Leon, T., Drenzek, N.J. and Lange, C. 2009. Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile (Jacaf Fjord, 44°S). Quaternary Research 72: 400-409. | The researchers observed two different regimes of climate variability in [their] record which they associated with the Medieval Warm Period and Little Ice Age, respectively. The reasonably good correlation between our results (particularly SST) and other continental and marine archives from central-south Chile, Peru, and Antarctica ... confirms the occurrence of globally important climatic anomalies such as the Medieval Warm Period and the Little Ice Age." |
| Siklosy, Z., Demeny, A., Szenthe, I., Leel-Ossy, S., Pilet, S., Lin, Y. and Shen, C.-C. 2009. Reconstruction of climate variation for the last millennium in the Bukk Mountains, northeast Hungary, from a stalagmite record. Quarterly Journal of the Hungarian Meteorological Service 113: 245-263. | Siklosy *et al.* determined that the highest oxygen isotope values occurred around AD 1000-1150, which interval they identified as the Medieval Warm Period, while the coldest years, which they associated with the Little Ice Age, prevailed from about AD 1550 to 1700. Additionally, the 50-year period from approximately AD 1450-1500 was almost as warm as the Medieval Warm Period. This warm interval has also been observed in a number of other paleoclimate studies. |
| Stancikaite, M., Sinkunas, P., Risberg, J., Seiriene, V., Blazauskas, N., Jarockis, R., Karlsson, S. and Miller, U. 2009. Human activity and the environment during the Late Iron Age and Middle Ages at the Impiltis archaeological site, NW Lithuania. Quaternary International 203: 74-90. | Stancikaite *et al.* determined that "the transition from the first to the second millennium AD, also the onset of the 'Medieval Warm Period,' coincided with a period of intensive human activity. . . ." and they say that "the favorable climatic conditions of [this] 'Medieval Warm Period' may have supported human activity during its maximum phase." Thereafter, they suggest "it is possible that the ensuing gradual regression of human activity was caused, in part, by the climatic deterioration known as the 'Little Ice Age'." |
| Black, D.E., Abahazi, M.A., Thunell, R.C., Kaplan, A., Tappa, E.J. and Peterson, L.C. 2007. An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic | Black *et al.* report that there was a rise and fall of the region's SST that occurred between the Medieval Warm Period and the Little Ice Age and write that "on average, twentieth-century temperatures are not the warmest in the entire |

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| hurricane frequency. Paleoceanography 22: 10.1029/2007PA001427. | record." |
| Vinther, B.M., Jones, P.D., Briffa, K.R., Clausen, H.B., Andersen, K.K., Dahl-Jensen, D. and Johnsen, S.J. 2010. Climatic signals in multiple highly resolved stable isotope records from Greenland. Quaternary Science Reviews 29: 522-538. | In the words of the seven scientists, "temperatures during the warmest intervals of the Medieval Warm Period," which they defined as occurring "some 900 to 1300 years ago, "were as warm as or slightly warmer than present day Greenland temperatures." |
| Ge, Q.S., Zheng, J.-Y., Hao, Z.-X., Shao, X.-M., Wang, W.-C. and Luterbacher, J. 2010. Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference. Geophysical Research Letters 37: 10.1029/2009GL041281. | With respect to three sections of China temperatures in the Medieval Warm Period exceeded or were comparable to the late 20th century. |
| Benito, G., Rico, M., Sanchez-Moya, Y., Sopena, A., Thorndycraft, V.R. and Barriendos, M. 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentin River, southeast Spain. Global and Planetary Change 70: 53-63. | Benito *et al.* report that the combined paleoflood and documentary records indicate that past floods were clustered during particular time periods: AD 950-1200 (10), AD 1648-1672 (10), AD 1769-1802 (9), AD 1830-1840 (6), and AD 1877-1900 (10), where only the first time interval coincides with the Medieval Warm Period and the latter four time intervals all fall within the confines of the Little Ice Age. |
| Gasiorowski, M. and Sienkiewicz, E. 2010. The Little Ice Age recorded in sediments of a small dystrophic mountain lake in southern Poland. Journal of Paleolimnology 43: 475-487. | Gasiorowski and Sienkiewicz report the presence of "a diverse ecosystem at the beginning of [the] record, ca. AD 360-570," which period of time has classically been assigned to the Dark Ages Cold Period. Thereafter, however, they found that from AD 570 to 1220 "environmental conditions were better," and that various cold-water taxa were "totally absent." In addition, they write that the younger section of this zone -- approximately its upper third (AD 850-1150), which contained the highest concentration of warm-water Chironomus species -- "can be correlated with the Medieval Warm Period (Moberg *et al.*, 2005)." Next came the Little Ice Age, which was the focal point of their study, extending all the way to the start of the 20th century, after which relative warmth once again returned, persisting to the present. And based on the peak Chironomus concentrations of this portion of their record, which we call the Current Warm Period or CWP, their data suggest that the peak warmth of the CWP and the earlier MWP were about the same. |
| Yang, B., Kang, X., Brauning, A., Liu, J., Qin, C. and Liu, J. 2010. A 622-year regional temperature history of southeast Tibet derived from tree rings. The Holocene 20: 181-190. | Yang *et al.* identified a number of relatively warmer and cooler intervals throughout their 622-year record, among the former of which were several that exceeded late 20th-century warmth. The two most striking of these short-term warm periods were those of 1443-1466 and 1482-1501; and graphical representations of the data indicate that annual temperatures |

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| | during the second of these two warm periods exceeded those of the late 20th century by as much as 0.75°C, while 11-year smoothed temperatures of the first of the two warm periods exceed those of the late 20th century by as much as 0.3°C. |
| Cage, A.G. and Austin, W.E.N. 2010. Marine climate variability during the last millennium: The Loch Sunart record, Scotland, UK. Quaternary Science Reviews: 10.1016/j.quascirev.2010.01.014. | The results of the two researchers' most recent efforts revealed that the most distinctive feature of the Loch Sunart temperature record was an abrupt warming at CE 1540 that led to a temperature anomaly of 1.1°C above the long-term mean from CE 1540-1600, which period was preceded within the interval CE 1445-1495 by some of the coldest temperatures of the past 1000 years. The researchers note that "the rate and magnitude of the inferred warming at AD 1540 ... is similar to the rate of change and magnitude observed during the late twentieth century." Cage and Austin concluded that "changes in twentieth century marine climate cannot yet be resolved from a background of natural variability over the last millennium." |
| Bonnet, S., de Vernal, A., Hillaire-Marcel, C., Radi, T. and Husum, K. 2010. Variability of sea-surface temperature and sea-ice cover in the Fram Strait over the last two millennia. Marine Micropaleontology 74: 59-74. | Bonnet *et al.* report that the sea surface temperature (SST) histories they developed via the two techniques they employed were "nearly identical and show oscillations between -1°C and 5.5°C in winter and between 2.4°C and 10.0°C in summer," and their graphical results indicate that between 2500 and 250 years before present (BP), the mean SSTs of summers were warmer than those of the present about 80% of the time, while the mean SSTs of winters exceeded those of current winters approximately 75% of the time, with the long-term (2250-year) means of both seasonal periods averaging about 2°C more than current means. |
| Ely, L.L. 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. Geomorphology 19: 175-201. | There was a "sharp drop in the frequency of large floods in the southwest from AD 1100-1300," which corresponded "to the widespread Medieval Warm Period, which was first noted in European historical records." With the advent of the Little Ice Age, however, there was another "substantial jump in the number of floods in the southwestern U.S.," which was "associated with a switch to glacial advances, high lake levels, and cooler, wetter conditions." Ely states that "global warm periods, such as the Medieval Warm Period, are times of dramatic decreases in the number of high-magnitude floods in this region." |
| Kobashi, T., Severinghaus, J.P., Barnola, J.-M., Kawamura, K., Carter, T. and Nakaegawa, T. 2010. Persistent multi-decadal Greenland temperature fluctuation through the last | The authors say their data "show clear evidence of the Medieval Warm Period and Little Ice Age in agreement with documentary evidence," and those data show that the |

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| millennium. Climatic Change 100: 733-756. | Medieval Warm Period was at times considerably warmer than the Current Warm Period has been to date, and that even the Little Medieval Warm Period was considerably warmer than it was over the last decades of the twentieth century, as well as the first decade of the 21st century. |
| Rorvik, K.-L., Grosfjeld, K. and Hald, M. 2009. A late Holocene climate history from the Malangen fjord, North Norway, based on dinoflagellate cysts. Norwegian Journal of Geology 89: 135-147. | Rorvik *et al.* discovered four major climatic/hydrologic periods that they describe as follows: "zone 1 from c. AD 500 to 790, representing the Dark Ages Cold Period, represents the coldest time interval during the last 1500 years ... zone 2, from c. AD 790 to 1500, including the Medieval optimum, reflects strong advection of warm saline water ... zone 3, from c. AD 1500 to 1940, representing the Little Ice Age, reflects cool and low saline surface water conditions ... zone 4, from c. AD 1940 to the present (AD 1999)" is described by them as "the Modern Climate Optimum." |
| Fritz, S.C., Ito, E., Yu, Z., Laird, K.R. and Engstrom, D.R. 2000. Hydrologic variation in the Northern Great Plains during the last two millennia. Quaternary Research 53: 175-184. | "From the vantage point of the 20th century," in the words of Fritz *et al.*, "the three North Dakota sites suggest that droughts equal or greater in magnitude to those of the Dust Bowl period were a common occurrence during the last 2000 years and that severe droughts may have been frequent for multiple decades within this period." Interestingly, they also report that "both the Medieval Period and Little Ice Age were hydrologically complex, and there is no clear evidence to suggest that either interval was coherent or unusual in effective moisture relative to long-term patterns." In addition, they report that "studies from the northern Great Plains and western North America (Cook *et al.*, 1997; Dean, 1997; Laird *et al.*, 1996; Yu and Ito, 1999) have shown a correlation between solar forcing and centennial- and decadal-scale drought patterns." Thus, they conclude that "solar variability may influence the duration of dry periods through its impact on convective activity and circulation (Rind and Overpeck, 1993)." |
| Frisia, S., Borsato, A., Spotl, C., Villa, I.M. and Cucchi, F. 2005. Climate variability in the SE Alps of Italy over the past 17,000 years reconstructed from a stalagmite record. Boreas 34: 445-455. | This work describes the occurrence of the Roman Warm Period and a Medieval Warm Period that was broken into two parts by an intervening central cold period. With respect to both parts of the Medieval Warm Period, the five researchers say they were "characterized by temperatures that were similar to the present," while with respect to the Roman Warm Period, they say its "temperatures were similar to those of today or even slightly warmer." |
| Hong, B., Liu, C.-Q., Lin, Q.-H., Yasuyuki, S., Leng, X.-T., Wang, Y., Zhu, Y.-X. and Hong, | The eight researchers report that phenological data from east China (Ge *et al.*, 2006) and |

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| Y.-T. 2009. Temperature evolution from the δ18O record of Hani peat, Northeast China, in the last 14000 years. Science in China Series D: Earth Sciences 52: 952-964. | tree-ring records from west China (Yang *et al.*, 2000) also indicate that "the temperature on the Chinese mainland was distinctly warmer during the MWP." In fact, they say MWP temperatures were as much as "0.9-1.0°C higher than modern temperatures (Zhang, 1994)." |
| Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M. and Kamenik, C. 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. Quaternary Science Reviews 29: 1940-1949. | Larocque-Tobler *et al.* report that "at the beginning of the record, corresponding to the last part of the 'Medieval Climate Anomaly' (here the period between ca. AD 1032 and 1262), the chironomid-inferred mean July air temperatures were 1°C warmer than the climate reference period (1961-1990)," which would also make them warmer than most subsequent temperatures as well. And in looking at their graphs of 20- and 50-year running means, it can be seen that the peak mean warmth of the Medieval Warm Period exceeded that of the Current Warm Period by approximately 0.5°C in the case of 20-year averages and 1.2°C in the case of 50-year averages. The five researchers conclude that "based on the chironomid-inferred temperatures, there is no evidence that mean-July air temperature exceeded the natural variability recorded during the Medieval Climate Anomaly in the 20th century at Lake Silvaplana," while noting that similar results "were also obtained in northern Sweden (Grudd, 2008), in Western Europe (Guiot *et al.*, 2005), in a composite of Northern Hemisphere tree-ring reconstructions (Esper *et al.*, 2002) and a composite of tree rings and other archives (Moberg *et al.*, 2005)." |
| Aono, Y. and Saito, S. 2010. Clarifying springtime temperature reconstructions of the medieval period by gap-filling the cherry blossom phenological data series at Kyoto, Japan. International Journal of Biometeorology 54: 211-219. | Aono and Saito report that their temperature reconstruction "showed two warm temperature peaks of 7.6°C and 7.1°C, in the middle of the tenth century and at the beginning of the fourteenth century, respectively," and they say that "the reconstructed tenth century temperatures [AD 900-1000] are somewhat higher than present temperatures after subtracting urban warming effects." Last of all, they add that "the general pattern of change in the reconstructed temperature series in this study is similar to results reported by previous studies, suggesting a warm period in Asia corresponding to the Medieval Warm Period in Europe." |
| Daimaru, H., Ohtani, Y., Ikeda, S., Okamoto, T. and Kajimoto, T. 2002. Paleoclimatic implication of buried peat layers in a subalpine snowpatch grassland on Mt. Zarumori, northern Japan. Catena 48: 53-65. | The five researchers report that "peaty topsoils were recognized at seven soil pits in the dense grassland, whereas sparse grassland lacked peaty topsoil," and they say that "most of the buried peat layers contained a white pumice layer named 'To-a' that fell in AD 915." This |

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| | observation, plus their 14C dating, led them to conclude that the buried peat layers in the poor vegetation area indicate "warming in the melt season," as well as "a possible weakened winter monsoon in the Medieval Warm Period." |
| Sorrel, P., Tessier, B., Demory, F., Baltzer, A., Bouaouina, F., Proust, J.-N., Menier, D. and Traini, C. 2010. Sedimentary archives of the French Atlantic coast (inner Bay of Vilaine, south Brittany): Depositional history and late Holocene climatic and environmental signals. Continental Shelf Research 30: 1250-1266. | "[T]he late Holocene component (i.e., the last 2000 years) is best recorded in the most internal sedimentary archives," where they find that "an increase in the contribution of riverine inputs occurred during the MWP [Medieval Warm Period]" implying that during that considerably warmer period than most (if not all) of what followed it, "climatic conditions were probably mild enough to prevent coastal erosion in northwestern France." |
| Yamada, K., Kamite, M., Saito-Kato, M., Okuno, M., Shinozuka, Y. and Yasuda, Y. 2010. Late Holocene monsoonal-climate change inferred from Lakes Ni-no-Megata and San-no-Megata, northeastern Japan. Quaternary International 220: 122-132. | The data revealed the presence of a cold/dry interval stretching from AD 1 to 750, a warm/humid interval stretching from AD 750 to 1200, and another cold/dry interval stretching from AD 1200 to the present; and they say that these intervals could represent, respectively, "the Dark Ages Cold Period (DACP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA)." |
| Zhang, D.D., Lee, H.F., Wang, C., Li, B., Zhang, J., Pei, Q. and Chen, J. 2011. Climate change and large-scale human population collapses in the pre-industrial era. *Global Ecology and Biogeography* **20**: 520-531. | Historically, and for the Northern Hemisphere as a whole, warming and warmer times have most often been good times for humanity, as exemplified by the greater numbers of people the earth was able to support under such conditions, while cooling and colder times were typically just the opposite, with many significant population collapses. |
| Field, J.S. and Lape, P.V. 2010. Paleoclimates and the emergence of fortifications in the tropical Pacific islands. Journal of Anthropological Archaeology 29: 113-124. | "[T]he comparison of fortification chronologies with paleoclimatic data indicate that fortification construction was significantly correlated with periods of cooling, which in the tropical Pacific is also associated with drying," noting that "the correlation was most significant in the Indo-Pacific Warm Pool, the Southwestern Pacific and New Zealand," where "people constructed more fortifications during periods that match the chronology for the Little Ice Age (AD 1450-1850)," as opposed to the Medieval Warm Period (AD 800-1300) when they say the Indo-Pacific Warm Pool was both warm and saline "with temperatures approximating current conditions (Newton *et al.*, 2006)." |
| Yan, H., Sun, L., Shao, D., Wang, Y. and Wei, G. 2014. Higher sea surface temperature in the northern South China Sea during the natural warm periods of late Holocene than recent decades. *Chinese Science Bulletin* **59**: 4115-4122. | This undertaking revealed that the mean annual SSTs of the 80-year periods centered on AD 990 (MCA) and AD 50 (RWP) were 0.8°C and 1.4°C *higher* than the mean SST during the AD 1994-2005 portion of the Current Warm Period (CWP). Likewise, they also report that the mean *summer* SSTs of the MCA and RWP were, respectively, 0.2 and 1.0°C higher than that of the CWP, while the mean *winter* |

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| | SSTs of the MCA and RWP were, respectively, 1.3 and 1.8°C higher than that of the CWP. As a result, the "SST records, which suggested a warmer MCA than recent decades, did not agree with the results of the IPCC fourth report, which suggested that the recent decades were the warmest in at least the past 1,300 years." |
| Ouellet-Bernier, M.-M., de Vernal, A., Hillaire-Marcel, C. and Moros, M. 2014. Paleoceanographic changes in the Disko Bugt area, West Greenland, during the Holocene. *The Holocene* **24**: 1573-1583. | Using ice core data in Greenland the researchers found that during the Medieval Warm Period that occurred between approximately 1000 and 800 years BP the region's "summer SSTs increased to about 10°C, … much higher than the present day summer SST of about 4.4°C at the coring site," as recorded in the World Ocean Database of the NODC (2001). This occurred during a period of time when the atmosphere's $CO_2$ concentration was only a mere 285 ppm compared to the 40%-greater 400 ppm of today. |
| McCarroll, D., Loader, N.J., Jalkanen, R., Gagen, M.H., Grudd, H., Gunnarson, B.E., Kirchhefer, A.J., Friedrich, M., Linderholm, H.W., Lindholm, M., Boettger, T., Los, S.O., Remmele, S., Kononov, Y.M., Yamazaki, Y.H., Young, G.H.F. and Zorita, E. 2013. A 1200-year multiproxy record of tree growth and summer temperature at the northern pine forest limit of Europe. *The Holocene* **23**: 471-484. | The data indicated that (1) the 20th century was the warmest of the last 1200 years, but that it was not significantly different from the 11th century; and that (2) the warmest summer in the regression-based reconstruction was AD 1092 (13.47 ± 1.32°C), followed by AD 1937 (13.29 ± 1.32°C). Hence, the MWP and CWP would appear to have experienced essentially *equivalent* degrees of elevated warmth to this point in time, and that the MWP should, at the very least, be assigned to the 11th century (AD 1000 - 1100). |
| Antipina, T.G., Panova, N.K. and Korona, O.M. 2014. The Holocene dynamics of vegetation and environmental conditions on the eastern slope of the Northern Urals. *Russian Journal of Ecology* **45**: 351-358. | "Analysis of the Holocene dynamics of vegetation and natural environment is especially relevant," as it provides "insight into relationships of changes in natural plant ecosystems with climatic changes." The data indicated that the climate of those earlier times "were higher than today by approximately 1°C and 3-4°C, respectively." |
| T.C. Peterson & M. O. Baringer, "2009: State of the Climate in 2008," 90 Bull. Am. Meteor. Soc. S1 (2009). | "The simulations rule out (at the 95% level) zero trends for intervals of 15 yr or more." |
| Marcia G. Wyatt & Judith A. Curry, "Role for Eurasian Arctic Shelf Sea Ice in a Secularly Varying Hemispheric Climate Signal During the 20th Century," 42 Climate Dynamics 2763 (2013), available at http://curryja.files.wordpress.com/2013/10/stadium-wave1.pdf. | Arctic shelf sea ice plays an important role in the extended hiatus in warming. |
| Liew, P.-M., Wu, M.-H., Lee, C.-Y., Chang, C.-L. and Lee, T.-Q. 2014. Recent 4000 years of climatic trends based on pollen records from lakes and a bog in Taiwan. Quaternary International **349**: 105-112. | Study corroborates European studies showing Roman Warm Period, Dark Ages Cold Period, Medieval Warm Period, Little Ice Age, and now the Current Warm Period. |

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| Ahmad, W., Fatima, A., Awan, U.K. and Anwar, A. 2014. Analysis of long term meteorological trends in the middle and lower Indus Basin of Pakistan - A non-parametric statistical approach. Global and Planetary Change **22**: 282-291. | As found in other studies, both high and low temperatures are increasing, but lows are increasing significantly *faster*. |
| Wagner, B. and Bennike, O. 2015. Holocene environmental change in the Skallingen area, eastern North Greenland, based on a lacustrine record. *Boreas* **44**: 45-59. | Researchers examining northern Greenland developed an 8000-year environmental history of the region and determined that the region was warmer during the Holocene thermal maximum, when $CO_2$ concentration was significantly lower than it is currently. |
| Zhang, H., Zhang, Y., Kong, Z., Yang, Z., Li, Y. and Tarasov, P.E. 2015. Late Holocene climate change and anthropogenic activities in north Xinjiang: Evidence from a peatland archive, the Caotanhu wetland. *The Holocene* **25**: 323-332. | Researchers reconstructed a temperature history stretching some four millennia back in time, as indicated by radiocarbon dating of sequential segments of the sediment profile. The six scientists report that one of what they call the "significant climate events during this period" was the Medieval Warm Period, which held sway from approximately AD 700-1200, and which they say "was also revealed at some other sites in Xinjiang." |
| *Cliff Harris and Randy Mann,* "Global Temperature Trends From 2500 B.C. To 2040 A.D.," *April 9, 2014,* www.longrangeweather.com/global_temperatures.htm. | The authors found that the Earth's temperatures and climate have varied significantly over the past five millennia – variations that had nothing to do with fossil fuel consumption. There have been at least 75 major temperature swings over the past 4500 years. The Earth's coldest periods have usually followed excessive warmth. Such was the case when the planet moved from the Medieval Warm Period between 900 and 1300 A.D. to the sudden "Little Ice Age," which peaked in the 17th Century. Since 2,500 B.C., there have been at least 78 major climate changes worldwide, including two major changes in just the past 40 years. Indeed, by the end of this 21st Century, a cooling trend may occur that could ultimately lead to expanding glaciers worldwide, even in the mid-latitudes. Based on long-term climatic data, these major ice ages have recurred about every 11,500 years. |
| "Global Cooling," pp. 121-124 in Roger Bezdek, Robert Hirsch, and Robert Wendling, *The Impending World Energy Mess*, Toronto, Canada: Apogee Prime Press, 2010. | Colder temperatures are much more troublesome and dangerous to humans than are warmer temperatures, and the world has much more to fear from potential global cooling than potential global warming. |
| U.S. Environmental Protection Agency, "Climate Change Indicators in the United States, Drought," May 2014. | With respect to droughts in the U.S., there is no indication of increasing severity of droughts for at least the past 130 years. Average drought conditions in the contiguous U.S. 48 states have not worsened since 1880. |
| ***D. Solar Influences on Climate Have Been Substantially Underestimated*** | |

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| Sejrup, H.P., Lehman, S.J., Haflidason, H., Noone, D., Muscheler, R., Berstad, I.M. and Andrews, J.T. 2010. Response of Norwegian Sea temperature to solar forcing since 1000 A.D. *Journal of Geophysical Research* **115**: 10.1029/2010JC006264. | Near-surface water temperature was found to be "robustly and near-synchronously correlated with various proxies of solar variability spanning the last millennium." In other words, climate change has been driven by the sun. |
| Qian, W.-H. and Lu, B. 2010. Periodic oscillations in millennial global-mean temperature and their causes. *Chinese Science Bulletin* **55**: 4052-4057. | Oscillations in solar radiation variability force oscillations in global-mean temperature. |
| Zhao, C., Yu, Z., Zhao, Y. and Ito, E. 2009. Possible orographic and solar controls of Late Holocene centennial-scale moisture oscillations in the northeastern Tibetan Plateau. Geophysical Research Letters 36: 10.1029/2009GL040951. | Cross-spectral analysis between moisture proxies and a solar activity proxy "shows high coherence at the ~200-year periodicity which is similar to Chinese monsoon intensity records, implying the possible solar forcing of moisture oscillations in the NE Tibetan Plateau." |
| Cai, Q., Liu, Y., Lei, Y., Bao, G. and Sun, B. 2014. Reconstruction of the March-August PDSI since 1703AD based on tree rings of Chinese pine (*Pinus tabulaeformis* Carr.) in the Lingkong Mountain, southeast Chinese loess Plateau. *Climate of the Past* **10**: 509-521, doi:10.5194/cp-10-509-2014. | Tree-ring studies show drought in Chinese Loess Plateau more likely driven by solar effects than by anthropogenic sources. |
| Habibullo Abdussamatov, "Current Long-Term Negative Energy Balance of the Earth Leads to the New Little Ice Age," 2 Journal of Geology and Geophysics 113 (2013), available at http://omicsgroup.org/journals/grand-minimum-of-the-total-solar-irradiance-leads-to-the-little-ice-age-2329-6755.1000113.php. | An upcoming solar minimum will lead to unexpected cooling. |

| **II. Climate Models Are Not Sufficiently Reliable to Form a Basis for Policymaking** | |
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| Judith Curry, "Statement to the Committee on Science, Space, and Technology of the U.S. House of Representatives," Hearings on the President's U.N. Climate Pledge, April 15, 2015, available at http://docs.house.gov/meetings/SY/SY00/20150415/103329/HHRG-114-SY00-Wstate-CurryJ-20150415-U1.pdf. | "The IPCC AR5 (2013) concluded that the transient climate response is likely [17-83%] in the range of 1 to 2.5°C. Last year, Nicholas Lewis and I published a paper that found transient climate response to have a likely range of 1.05-1.80°C. Using an observation-based energy balance approach, our calculations used the same data for the effects on the Earth's energy balance of changes in greenhouse gases, aerosols and other drivers of climate change given by the IPCC AR5. Our range for the transient climate response is much narrower, with far lower upper limits, than reported by the IPCC AR5. Recent research suggests even lower values of the transient climate response. The greatest uncertainty in these estimates is accounting for the effects of small aerosol particles in the atmosphere, which have a cooling effect on the climate (partially counteracting the greenhouse warming). A new paper by Stevens constrains |

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| | the impact of aerosols on climate to be significantly smaller than assumed in the AR5. Nicholas Lewis has re-run the calculations using aerosol impact estimates in line with this paper. The likely range for the transient climate response is 1.05 to 1.45°C. By contrast, most climate model estimates of transient climate response are higher than 1.8°C. Research continues to assess the methods used to estimate climate sensitivity. However, the reduced estimates of aerosol cooling lead inescapably to reductions in the estimated upper bound of climate sensitivity." |
| A. Lupo and Kininmonth, W., "Global Climate Models and Their Limitations." In: *Climate Change Reconsidered II: Physical Science.* C.D. Idso, R.M. Carter and S.F. Singer, (Eds.). Chicago, IL: The Heartland Institute, 2013. | Analyses of state-of-the-art climate models models have consistently revealed multiple problems in their abilities to accurately represent and simulate reality. |
| Roy Spencer, "95% of Climate Models Agree: The Observations Must be Wrong," February 7, 2014, www.drroyspencer.com/2014/02/95-of-climate-models-agree-the-observations-must-be-wrong/. | Spencer emphasized that the level of observed tropical atmospheric warming since 1979 is dramatically below that predicted by climate models. Not only are the global warming models inaccurate, but they have grown increasingly inaccurate over the past two decades. |
| Annan, J.D. and Hargreaves, J.D., "On the Generation and Interpretation of Probabilistic Estimates of Climate Sensitivity." *Climatic Change* 104: 324-436, 2011; R.S. Lindzen and Choi, Y.-S., "On the Observational Determination of Climate Sensitivity and Its Implications." *Asia-Pacific Journal of Atmospheric Science* 47: 377-390, 2011; A. Schmittner et al., "Climate Sensitivity Estimated From Temperature Reconstructions of the Last Glacial Maximum." *Science* 334: 1385-1388, 2011; Holden M. Aldrin et al., "Bayesian Estimation of Climate Sensitivity Based on a Simple Climate Model Fitted To Observations of Hemispheric Temperature and Global Ocean Heat Content," *Environmetrics* 23: 253-271, 2012; J.C. Hargreaves et al., "Can the Last Glacial Maximum Constrain Climate Sensitivity?" *Geophysical Research Letters* 39: L24702, Doi: 10.1029/ 2012GL053872, 2012; M.J. Ring et al., "Causes of the Global Warming Observed Since the 19th Century." *Atmospheric And Climate Sciences* 2: 401-415, 2012; J.H. Van Hateren, "A Fractal Climate Response Function Can Simulate Global Average Temperature Trends of the Modern Era and the Past Millennium." *Climate Dynamics,* Doi: 10.1007/S00382-012-1375-3, | These studies find that the sensitivity of temperature to carbon dioxide, which is the amount of total warming for a nominal doubling of atmospheric carbon dioxide, is the core parameter that ultimately drives climate model temperature projections. The magnitude of this parameter used in the models is likely the reason for their overestimation of recent (and likely future) projections of temperature observations. Although most models incorporate a mean sensitivity of 3.4°C (range of 2.1 to 4.7°C), several recent studies indicate the true sensitivity is much lower. Until such problems are resolved, damage estimates relying on future temperature projections should be considered to be invalid. |
| Steven Koonin, *Climate Science is Not Settled*, Wall St. J., (Sep. 19, 2014), online at http://online.wsj.com/articles/climate-science- | Koonin, a former Obama administration official, documents the many uncertainties in climate models and the multiple gaps where current |

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| is-not-settled-1411143565. | understanding is crucially sparse. |
| B.E. Harlow, and Spencer, R. W., "An Inconvenient Burden of Proof? $CO_2$ Nuisance Plaintiffs Will Face Challenges in Meeting the Daubert Standard." *Energy Law Journal* 32: 459-496, 2011. | The authors state that it is time for scientists to entertain the possibility that there is something wrong with the assumptions built into their climate models. The fact that all of the models have been peer reviewed does not mean that any of them have been deemed to have any skill for predicting future temperatures. In the parlance of the Daubert standard for rules of scientific evidence, the models have not been successfully field tested for predicting climate change, and so far their error rate should preclude their use for predicting future climate change." |
| Lindzen, R.S. 2010. Global warming: The origin and nature of the alleged scientific consensus. Problems of Sustainable Development 5: 13-28. | In statements summing up his evaluation of the pertinent science, Lindzen writes that (1) "the physics of unresolved phenomena such as clouds and other turbulent elements is not understood to the extent needed for incorporation into models," so that (2) models are presently merely "experimental tools whose relation to the real world is questionable," that (3) "current models depend heavily on undemonstrated positive feedback factors to predict high levels of warming," that (4) "there is compelling evidence for all the known feedback factors to actually be negative," that (5) "even supercomputers are inadequate to allow long-term integrations of the relevant equations at adequate spatial resolutions," that (6) "current models all predict that warmer climates will be accompanied by increasing humidity at all levels" but that "such behavior is an artifact of the models since they have neither the physics nor the numerical accuracy to deal with water vapor," and that (7) "the models' predictions for the past century incorrectly describe the pattern of warming and greatly overestimate its magnitude." Lindzen concludes that "with poor and uncertain models in wide use, predictions of ominous situations are virtually inevitable -- regardless of reality," and, therefore, he says that "it goes almost without saying that the dangers and costs of those economic and social consequences [of reducing GHGs] may be far greater than the original environmental danger." |
| Alexander M.R. Bakker, "The Robustness of the Climate Modelling Paradigm," Ph.D. thesis (Jan. 8, 2015), available at http://dare.ubvu.vu.nl/handle/1871/52184. | Climate models upon which the IPCC relies are inaccurate. |
| Paul Ballonoff, "A Fresh Look at Climate Change," 34 Cato Journal 113 (Feb. 24, 2014), available at http://object.cato.org/sites/cato.org/files/serials/files/cato-journal/2014/2/v34n1-6.pdf. | Climate models upon which the IPCC relies have dramatically overestimated warming and do not comport with real-world observational data. |

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| Judith Curry, "The Global Warming Statistical Meltdown," *Wall Street Journal* (Oct. 9, 2014). | "A growing body of evidence suggests that the climate is less sensitive to increases in carbon-dioxide emissions than policy makers generally assume—and that the need for reductions in such emissions is less urgent." |
| H. Douville, *et al.*, "The Recent Global Warming Hiatus: What is the Role of Pacific Variability?," 42 Geophys. Rsch. Letters 880 (Feb. 16, 2015). | Even a model that correctly reproduces the warming hiatus will still overestimate warming compared to observed results, and other models fare worse. |
| John C. Fyfe, *et al.*, "Overestimated Global Warming over the Past 20 Years," 3 *Nature Climate Change* 767, 767 (Sep. 2013). | Models fail to reproduce either the actual global temperatures or slowdown in the increase over the past 20 years. |
| N. Lewis & J.A. Curry, "The Implications for Climate Sensitivity of AR5 Forcing and Heat Uptake Estimates," *Climate Dynamics* (Sep. 25, 2014), available at http://link.springer.com/article/10.1007%2Fs00382-014-2342-y#page-1. | A doubling of $CO_2$ would likely result in an increase in temperature of only 1.64 ºC. |
| Richard Lindzen, "Can Increasing Carbon Dioxide Cause Climate Change?," 94 Proceedings of the Nat'l Acad. of Sciences of the United States 8335 (Aug. 5, 1997), available at http://www.pnas.org/content/94/16/8335.full. | Questioning whether $CO_2$ will even have a significant effect on climate change at all compared to natural varation, especially pole-to-equator differences. |
| Richard Lindzen & Yong-Sang Choi, "On the Determination of Climate Feedbacks from ERBE Data," 36 Geophys. Rsch. Letters L16705 (2009), available at http://www.drroyspencer.com/Lindzen-and-Choi-GRL-2009.pdf. | Models consistently overestimate climate sensitivity compared to observed data. |
| Richard Lindzen, *et al.*, "Does the Earth Have An Adaptive Infrared Iris?," 82 Bull. Am. Meteorological Soc'y 417 (Mar. 2001), available at http://www-eaps.mit.edu/faculty/lindzen/adinfriris.pdf. | This article finds a negative feedback effect from increased sea surface temperature in the tropics, which results in reduced cirrus clouds and thus more infrared radiation leakage from Earth's atmosphere. |
| Thorsten Mauritsen & Bjorn Stevens, "Missing Iris Effect as a Possible Cause of Muted Hydrological Change and High Climate Sensitivity in Models," __ Nature Geosci. __ (Apr. 20, 2015) (advance online publication), available at http://www.nature.com/ngeo/journal/vaop/ncurrent/full/ngeo2414.html. | Including an iris effect moves models closer to matching observations. |
| Patrick J. Michaels & Paul C. Knappenberger, "The Collection of Evidence for a Low Climate Sensitivity Continues to Grow," *Cato Institute* (Sep. 25, 2014), available at http://www.cato.org/blog/collection-evidence-low-climate-sensitivity-continues-grow. | Since 2011, at least 14 peer-reviewed papers, published by 42 authors, many of whom are key contributors to the reports of the IPCC, have concluded that climate sensitivity is low because net feedbacks are modest or even close to zero. |
| Christopher Monckton, *et al.*, "Why Climate Models Run Hot: Results from an Irreducibly Simple Climate Model," 60 Sci. Bull. 122 (2015), available at http://wmbriggs.com/public/Monckton.et.al.pdf. | The author resolves discrepancies in IPCC methodology, demonstrating that IPCC's own data, correctly interpreted and applied, shows a much lower rate of warming. |
| Bjorn Stevens, "Rethinking the Lower Bound | Showing that the cooling effect of aerosols is |

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| on Aerosol Radiative Forcing," __ J. Climate __ (2015) (early online release), available at http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00656.1. | much lower than models assume, meaning that models that have used aerosol effects to "mask" or "cancel" warming – in an attempt to match observational data – are flawed. |
| Nicholas Lewis, "The implications for climate sensitivity of Bjorn Stevens' new aerosol forcing paper," *Climate Audit* (Mar. 15, 2015), available at: http://climateaudit.org/2015/03/19/the-implications-for-climate-sensitivity-of-bjorn-stevens-new-aerosol-forcing-paper/. | This article describes Stevens's paper (above) as a "game-changer" and recalculates ECS and TCR values in an energy budget study using aerosol forcing estimates in line with the analysis in the Stevens paper. Ultimately it finds that IPCC figures for ECS and TCR are substantially too high; Lewis calculates ECS of 1.2-1.8°C and TCR of 1.05-1.8°C (within 17%-83% range), while corresponding IPCC AR5 estimates are ECS of 1.5-4.5°C and TCR of 1-2.5°C). |
| Xianyao Chen & Ka-Kit Tung, "Varying Planetary Heat Sink Led to Global-Warming Slowdown and Acceleration," 345 *Science* 897 (Aug. 2014), available at http://www.sciencemag.org/content/345/6199/897. | "The man-made warming of the past 20 years has been so feeble that a shifting current in one ocean was enough to wipe it out altogether." |
| Paul J. Durack, *et al.*, "Quantifying Underestimates of Long-Term Upper-Ocean Warming," 4 Nature Climate Change 999 (2014). | Warming of the upper ocean in the southern hemisphere has been underestimated. |
| W. Llovel, *et al.*, "Deep-Ocean Contribution to Sea Level and Energy Budget Not Detectable Over the Past Decade," 4 Nature Climate Change 1031 (2014). | The "missing energy" posited by global warming theories not found in deep ocean. |
| Laepple, T. and Huybers, P. 2014b. Ocean surface temperature variability: Large model-data differences at decadal and longer periods. Proceedings of the National Academy of Sciences USA **111**: 16,682-16,687. | Study found that centennial- and millennial-scale sea surface temperature variations were two orders of magnitude larger than decadal variations (which most models work with), suggesting that the variation makes prediction extremely difficult to accomplish accurately with the tools we presently have. |
| Westby, R.M., Lee, Y.-Y. and Black, R.X. 2013. Anomalous temperature regimes during the cool season: Long-term trends, low-frequency mode modulation, and representation in CMIP5 simulations. *Journal of Climate* **26**: 9061-9076. | Advanced paired-model system cannot replicate known recurring temperature anomalies. |
| Endo, H. 2011. Long-term changes of seasonal progress in baiu rainfall using 109 years (1901-2009) daily station data. *Scientific Online Letters on the Atmosphere (SOLA)* **7**: 5-8. | Climate model projections of increased Baiu rainfall in response to global warming induced by increasing concentrations of atmospheric greenhouse gases are simply not correct. |
| Keeley, S.P.E., Sutton, R.T. and Shaffrey, L.C. 2012. The impact of North Atlantic sea surface temperature errors on the simulation of North Atlantic European region climate. *Quarterly Journal of the Royal Meteorological Society* **138**: 1774-1783. | Current climate models cannot accurately model the Gulf Stream or North Atlantic Current correctly. Indeed, the errors in the models can be explained simply by the fact that they underestimate sea surface temperature by 8 C near New Foundland and overestimate it by 6 C near the East Coast of the United States. |
| Chu, J.-E., Ha, K.-J., Lee, J.-Y., Wang, B., Kim, B.-H. and Chung, C.E. 2014. Future change of | Paired-model attempt to reproduce sea surface temperature in the Indian Ocean showed |

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| the Indian Ocean basin-wide and dipole modes in the CMIP5. *Climate Dynamics* **43**: 535-551. | "considerable biases" in the models. The models were generally unable to simulate the dominant variability modes in the Indian Ocean. |
| Lewis, S.C. and Karoly, D.J. 2013. Evaluation of historical diurnal temperature range trends in CMIP5 models. *Journal of Climate* **26**: 9077-9089. | Paired-model simulations cannot reproduce diurnal temperature range, an easily identifiable characteristic of recent climate change. "[U]biquitous model deficiencies." |
| Geil, K.L., Serra, Y.L. and Zeng, X. 2013. Assessment of CMIP5 model simulations of the North American monsoon system. *Journal of Climate* **26**: 8787-8801. | Paired-model simulations show multiple types of error when modeling the North American Monsoon System--a prevalent and well-known phenomenon. Some models "do not have a recognizable monsoon signal at all." |
| Evans, J.P. and McCabe, M.F. 2013. Effect of model resolution on a regional climate model simulation over southeast Australia. *Climate Research* **56**: 131-145. | Global climate models (GCMs) are often downscaled, using regional climate models (RCMs) as guides--but this produces errors at higher resolutions. The GCMs yielded incorrect predictions compared to observed data at finer resolutions, even changing the sign of projected change; RCM correction did not remove errors. |
| Abhik, S., Mukhopadhyay, P. and Goswami, B.N. 2014. Evaluation of mean and intraseasonal variability of Indian summer monsoon simulation in ECHAM5: identification of possible source of bias. *Climate Dynamics***43**: 389-406. | Comparison of sophisticated model (ECHAM5) to observed data for India's summer monsoons shows the model consistently wrong, despite being one of the few that can reproduce even parts of the monsoon systems. |
| Pithan, F., Medeiros, B. and Mauritsen, T. 2014. Mixed-phase clouds cause climate model biases in Arctic wintertime temperature inversions. *Climate Dynamics* **43**: 289-303. | Models, including CMIP5, failed to reproduce crucial cloudy state of Arctic winter boundary layer. |
| Chen, L. and Frauenfeld, O.W. 2014. A comprehensive evaluation of precipitation simulations over China based on CMIP5 multimodel ensemble projections. *Journal of Geophysical Research: Atmospheres* **19**: 5767-5786. | Assessment of model performance shows not only do the models not match observed rainfall over China, but the "improved" model (CMIP5) fared worse than its predecessor (CMIP3), and a multi-model mean like CMIP still does not accurately reflect observed data. |
| Cretat, J., Vizy, E.K. and Cook, K.H. 2014. How well are daily intense rainfall events captured by current climate models over Africa? *Climate Dynamics* **42**: 2691-2711. | Regional climate models failed to simulate rains down in Africa. Coupled atmospheric and atmosphere-ocean general circulation models were wrong because of overly simplified assumptions. |
| Ryu, J.-H. and Hayhoe, K. 2014. Understanding the sources of Caribbean precipitation biases in CMIP3 and CMIP5 simulations. *Climate Dynamics* **42**: 3233-3252. | Climate models generally cannot simulate Caribbean rainfall patterns. Moreover, scientists are not sure what the origins of the biases are. |
| Brown, J.N., Langlais, C. and Maes, C. 2014. Zonal structure and variability of the Western Pacific dynamic warm pool edge in CMIP5. *Climate Dynamics* **42**: 3061-3076. | Models unable to simulate key isotherm in Western Pacific (Western Pacific Warm Pool). Many could not identify it, and many that could do so underestimated temperature by 1-2 C. (The isotherm itself is a difference of 1 C.) |
| Zhang, T. and Sun, D.-Z. 2014. ENSO asymmetry in CMIP5 models. *Journal of Climate* **27**: 4070-4093. | Models, including CMIP5, cannot accurately simulate the asymmetry between El Niño and La Niña, a key driver of climate variability. |
| Kim, S.T., Cai, W., Jin, F.-F. and Yu, J.-Y. | Systematic errors persist in modeling of ENSO |

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| 2014. ENSO stability in coupled climate models and its association with mean state. *Climate Dynamics* **42**: 3313-3321. | (El Niño-Southern Oscillation). CMIP3 consistently underestimates feedbacks, and CMIP5 fares no better. |
| Yan, Y., Luo, Y., Zhou, X. and Chen, J. 2014. Sources of variation in simulated ecosystem carbon storage capacity from the 5th Climate Model Intercomparison Project (CMIP5). *Tellus B* **66**: 10.3402/tellusb.v66.22568. | CMIP5 models failed to simulate ecosystem carbon storage, which is "essential to predict future climate change." |
| Feng, J., Wei, T., Dong, W., Wu, Q. and Wang, Y. 2014. CMIP5/AMIP GCM simulations of East Asian summer monsoon. *Advances in Atmospheric Sciences* **31**: 836-850. | Models, including CMIP5, cannot reproduce the East Asian Summer Monsoon system, a key feature of climate in Asia. Systematic errors persist. |
| Ding, Q., Wallace, J.M., Battisti, D.S., Steig, E.J., Gallant, A.J.E., Kim, H.-J. and Geng, L. 2014. Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland. *Nature* **509**: 10.1038/nature13260. | Recent warming in surface temperatures of NE Canada/Greenland attributable to natural cycles, not anthropogenic. Moreover, it is coupled to North Atlantic Oscillation System, which is not well-reproduced by CMIP5 models. |
| Toreti, A., Naveau, P., Zampieri, M., Schindler, A., Scoccimarro, E., Xoplaki, E., Dijkstra, H.A., Gualdi, S. and Luterbacher, J. 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 Models. Geophysical Research Letters 40: 4887-4892. | Model hindcasts of the past compared with actual historical precipitation records, showed a "lack of reliable and consistent estimations" that "might be connected with model deficiencies in the representation of organized convective systems." |
| Nair, A., Acharya, N., Singh, A., Mohanty, U.C. and Panda, T.C. 2013. On the predictability of northeast monsoon rainfall over south peninsular India in general circulation models. Pure and Applied Geophysics 170: 1945-1967. | General Circulation Models (GCMs) have low predictive ability. |
| Grotjahn, R. 2013. Ability of CCSM4 to simulate California extreme heat conditions from evaluating simulations of the associated large scale upper air pattern. *Climate Dynamics* **41**: 1187-1197. | Community Climate Simulation Model (CCSM4), a regional climate model, failed to simulate extreme temperatures in California's Central Valley, a crucial agricultural location. Models could not accurately predict hot spells. |
| Siam, M.S., Demory, M.-E. and Eltahir, E.A.B. 2013. Hydrological cycles over the Congo and Upper Blue Nile basins: Evaluation of general circulation model simulations and reanalysis products. Journal of Climate 26: 8881-8894. | The study concluded, regarding general circulation models, that "an analysis of their outputs reveals that these models do not accurately reproduce the past and current climates," noting that "this is particularly the case for hydrological variables (e.g., precipitation) that show large inconsistency, especially over Africa." |
| Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T. and Roeckner, E. 2013. Atmospheric component of the MPI-M System Model: ECHAM6. Journal of Advances in Modeling Earth Systems 5: 146-172. | The study discusses the ECHAM6 atmospheric general circulation model and identifies problems with the newest version of the model. |
| Duan, A., Hu, J. and Xiao, Z. 2013. The Tibetan Plateau summer monsoon in the CMIP5 simulations. Journal of Climate 26: 7747-7766. | The study argues that "the large bias associated with precipitation [a] intensity and [b] patterns remains," that "regarding long-term trends, most models overestimated [c] the |

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| | amplitude of the tropospheric warming and [d] the declining trend in the surface heat low between 1979 and 2005," and that "the observed cooling trend in the upper troposphere and [4] the decline of the Tibetan high were not reproduced by most models." As such, "there is still significant scope for improving GCM simulations of regional climate change." |
| Kim, J., Grise, K.M. and Son, S.-W. 2013. Thermal characteristics of the cold-point tropopause region in CMIP5 models.Journal of Geophysical Research: Atmospheres 118: 8827-8841. | The article states that the Coupled Model Intercomparison Project phase 5 (CMIP5) models "have several notable limitations" and "the fine-scale processes that govern stratospheric water vapor and the CPT temperature are unlikely to be well represented in CMIP5 models," and that "the coarse vertical resolution of the models and their non-negligible biases in the climatology, seasonal cycle and variability of the tropical tropopause layer limit their accuracy in the assessment of past, present and future climates." |
| Kullman, L. 2010. A richer, greener and smaller alpine world: Review and projection of warming-induced plant cover change in the Swedish Scandes. *Ambio* **39**: 159-169. | "In contrast to model predictions, no single alpine plant species has become extinct, neither in Scandinavia nor in any other part of the world in response to climate warming over the past century." |
| Fyfe, J.C., Gillett, N.P. and Zwiers, F.W. 2013. Overestimated global warming over the past 20 years. Nature Climate Change 3: 767-769. | Noting that models have consistently overestimated climate change and that change has been "significantly slower than that simulated by the climate models participating in Phase 5 of the Coupled Model Intercomparison Project (CMIP5)." |
| Li, J. and Sharma, A. 2013. Evaluation of volcanic aerosol impacts on atmospheric water vapor using CMIP3 and CMIP5 simulations. Journal of Geophysical Research: Atmospheres 118: 4448-4457. | Li and Sharma conclude that "despite the remarkable improvements of GCMs over the past years, it is still a challenge to simulate volcanic impacts for all GCMs, which has also been confirmed by Driscoll *et al.* (2012), who examined 12 CMIP5 GCMs and found that they all overestimated the cooling in the tropical troposphere following the nine explosive eruptions in the nineteenth and twentieth centuries." |
| Sabeerali, C.T., Dandi, A.R., Dhakate, A., Salunke, K., Mahapatra, S. and Rao, S.A. 2013. Simulation of boreal summer intraseasonal oscillations in the latest CMIP5 coupled GCMs. Journal of Geophysical Research: Atmospheres 118: 4401-4420. | Sabeerali *et al.* evaluated the abilities of 32 CMIP5 models to simulate the boreal summer intraseasonal oscillation by comparing their projections against observations covering the last twenty years, and after noting many flaws with the models concluded that "many models still face difficulties." |
| Purich, A., Cowan, T., Min, S.-K. and Cai, W. 2013. Autumn precipitation trends over Southern hemisphere midlatitudes as simulated by CMIP5 models. Journal of Climate 26: 8341-8356. | Purich *et al.* stated that "in recent decades, Southern Hemisphere mid-latitude regions such as southern Africa, southeastern Australia, and southern Chile have experienced a reduction in austral autumn precipitation, the cause of which is poorly understood." Purich *et al.* analyzed "the ability of global climate |

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| | models that form part of the Coupled Model Intercomparison Project phase 5 [CMIP5] to simulate these trends" but the CMIP5 models "underestimate both the historical autumn poleward expansion of the subtropical dry zone and the positive southern annular mode (SAM) trend." |
| Sperber, K.R., Annamalai, H., Kang, I.-S., Kitoh, A., Moise, A., Turner, A., Wang, B. and Zhou, T. 2013. The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. Climate Dynamics 41: 2711-2744. | Sperber *et al.* note significant problems with the models and state that "there are systematic errors that are consistent between the two vintages of models." |
| Marsh, D.R., Mills, M.J., Kinnison, D.E., Lamarque, J.-F., Calvo, N., and Polvani, L.M. 2013. Climate change from 1850 to 2005 simulated in CESM1(WACCM). Journal of Climate 26: 7372-7391. | Marsh *et al.* identify significant problems with models and conclude that "when quantifying uncertainty in past and future climate change predictions, it will be important to consider the systematic errors introduced by the choices made on how the upper atmosphere is represented in the model." |
| Ault, T.R., Deser, C., Newman, M. and Emile-Gray, J. 2013. Characterizing decadal to centennial variability in the equatorial Pacific during the last millennium. Geophysical Research Letters 40: 3450-3456. | Ault *et al.* write that "these findings imply that the response of the tropical Pacific to future forcings may be even more uncertain than portrayed by state-of-the-art models because there are potentially important sources of century-scale variability that these models do not simulate." |
| Islam, S., Tang, Y. and Jackson P.L. 2013. Asian monsoon simulations by Community Climate Models CAM4 and CCSM4.Climate Dynamics 41: 2617-2642. | Islam *et al.* explored in detail "the strengths and limitations of CAM4, CAM5 and CCSM4 in simulating SAM precipitation with an emphasis on the mean climate, seasonal and inter-annual variability and the relationship between SAM and SST (sea surface temperature, local and remote) in the simulations." The researchers found significant problems with the models. |
| Ho, C.K., Hawkins, E., Shaffrey, L., Brocker, J., Hermanson, L., Murphy, J.M., Smith, D.M. and Eade, R. 2013. Examining reliability of seasonal to decadal sea surface temperature forecasts: The role of ensemble dispersion. Geophysical Research Letters 40: 5770-5775. | Ho *et al.* found that "[f]or lead times of less than two years, the initialized ensembles tend to be under-dispersed and give over-confident and, hence, unreliable forecasts, especially in the tropics, consistent with many previous studies on this timescale." "For longer lead times, up to 9 years, the ensembles become over-dispersed in most regions and thus give under-confident and also unreliable forecasts." These findings "highlight the need to carefully evaluate simulated variability in seasonal and decadal prediction systems." |
| Frankignoul, C., Gastineau, G. and Kwon, Y.-O. 2013. The influence of the AMOC variability on the atmosphere in CCSM3. Journal of Climate 26: 9774-9790. | Frankignoul *et al.* state, in the concluding sentence of their paper's abstract, that "although there is some potential climate predictability in CCSM3, it is not realistic." And as they say in the second to the last sentence in the body of their paper, "although the AMOC influence on the atmosphere that we have documented for CCSM3 raises the hope that |

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| | some low-frequency NAO variations might be predictable, in particular in the red noise regime, the signal will not be realistic." |
| Huang, Y. 2013. On the longwave climate feedbacks. Journal of Climate 26: 7603-7610. | Huang concludes his paper by stating that "more studies are still required to understand how clouds modify global warming, even with regard to the longwave aspect alone." |
| Kavvada, A., Ruiz-Barradas, A. and Nigam, S. 2013. AMO's structure and climate footprint in observations and IPCC AR5 climate simulations. Climate Dynamics 41: 1345-1364. | Kavvada *et al.* compared and evaluated "the representation of AMO-related features both in observations and in historical simulations of the twentieth century climate from [climate] models participating in the IPCC's CMIP5 project," namely, CCSM4, GFDL-CM3, UKMO-HadCM3 and ECHAM6/MPI-ESM-LR. After noting significant problems with the models, Kavvada *et al.* state that "without a proper incorporation of low-frequency natural variability in climate simulations, decadal predictability and the accuracy of climate projections under different climate change scenarios remain compromised." |
| Yin, L., Fu, R., Shevliakova, E. and Dickinson, R.E. 2013. How well can CMIP5 simulate precipitation and its controlling processes over tropical South America? Climate Dynamics 41: 3127-3143. | CMIP5 cannot reliably reproduce rainfall over the Amazon Rain Forest--a problem persisting since CMIP3. |
| Sheffield, J., Barrett, A.P., Colle, B., Fernando, D.N., Fu, R., Giel, K.L., Hu, Q., Kinter, J., Kumar, S., Langenbrunner, B., Lombardo, K., Long, L.N., Maloney, E., Mariotti, A., Meyerson, J.E., Mo, K.C., Neelin, J.D., Nigam, S., Pan, Z., Ren, T., Ruiz-Barradas, A., Serra, Y.L., Seth, A., Thibeault, J.M., Stroeve, J.C., Yang, Z. and Yin, L. 2013. North American climate in CMIP5 experiments. Part I: Evaluation of historical simulations of continental and regional climatology. Journal of Climate 26: 9209-9245. | The researchers conclude that "the performance of the CMIP5 models in representing observed climate features has not improved dramatically compared to CMIP3." They note, for example, that "there are some models that have improved for certain features (e.g., the timing of the North American monsoon)," but they say that others "have become worse" in terms of the more basic "continental seasonal surface climate." And, "furthermore," as they conclude, "the uncertainty in the future projections across models can also be of the same magnitude [as] the model spread for the historic period." |
| Joetzjer, E., Douville, H., Delire, C. and Ciais, P. 2013. Present-day and future Amazonian precipitation in global climate models: CMIP5 versus CMIP3. Climate Dynamics 41: 2921-2936. | Joetzjer *et al.* state in their abstract that "model improvements of present-day climate do not necessarily translate into more reliable projections and further efforts are needed for constraining the pattern of the SST response and the soil moisture feedback in global climate scenarios." |
| Rosenfeld, D., Sherwood, S., Wood, R. and Donner, L. 2014. Climate effects of aerosol-cloud interactions. Science 343: 379-380. | Rosenfeld *et al.* state that "recent advances have revealed a much more complicated picture of aerosol-cloud interactions than considered previously," and they say that "further progress is hampered by limited observational capabilities and coarse-resolution models." Rosenfeld *et al.* conclude that "fully resolved, global, multiyear simulations are not likely to become feasible for |

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| | many decades.” |
| Cattiaux, J., Douville, H. and Peings, Y. 2013. European temperatures in CMIP5: origins of present-day biases and future uncertainties. Climate Dynamics 41: 2889-2907. | The three researchers report that (1) “on average, CMIP5 models exhibit a cold bias in winter, especially in Northern Europe,” that (2) “they over-estimate summer temperatures in Central Europe,” that (3) they predict “a greater diurnal range than observed,” and that (4) “in winter, CMIP5 models simulate a stronger North Atlantic jet stream than observed.” |
| Fu, G., Liu, Z., Charles, S.P., Xu, Z. and Yao, Z. 2013. A score-based method for assessing the performance of GCMs: A case study of southeastern Australia. Journal of Geophysical Research: Atmospheres 118: 4154-4167. | Noting that models have major flaws, Fu *et al.* conclude that “GCMs currently do not provide reliable rainfall information on regional scales as required by many climate change impacts studies.” |
| Jourdain, N.C., Gupta, A.S., Taschetto, A.S., Ummenhofer, C.C., Moise, A.F. and Ashok, K. 2013. The Indo-Australian monsoon and its relationship to ENSO and IOD in reanalysis data and the CMIP3/CMIP5 simulations. Climate Dynamics41: 3073-3102. | Models not accurate for regional simulations; fail to model monsoons on Indian Subcontinent. |
| Ruiz-Barradas, A., Nigam, S. and Kavvada, A. 2013. The Atlantic Multidecadal Oscillation in twentieth century climate simulations: uneven progress from CMIP3 to CMIP5. Climate Dynamics 41: 3301-3315. | Ruiz-Barradas *et al.* conclude that “the spurious increase in high 10-20 year variability from CMIP3 to CMIP5 models may be behind the unsatisfying progress in depicting the spatio-temporal features of the AMO.” And they say that “this problem, coupled with the inability of the models to perturb the regional low-level circulation”--which is the driver of moisture fluxes--”seem to be at the center of the poor representation of the hydroclimate impact of the AMO |
| He, Y., Jia, G., Hu, Y. and Zhou, Z. 2013. Detecting urban warming signals in climate records. Advances in Atmospheric Sciences 30: 1143-1153. | He *et al.* write that “urban expansion may not have major impacts on the regional climate, but it may contribute to strong Urban Heat Island signals in meteorological records at the local scale, likely leading to a misinterpretation of overall warming magnitudes and even trends at the regional and global scales.” |
| Rosa, D. and Collins, W.D. 2013. A case study of subdaily simulated and observed continental convective precipitation: CMIP5 and multiscale global climate models comparison. Geophysical Research Letters 40: 10.1002/2013GL057987. | CMIP5 models failed to model precipitation clearly, even in the abstract. Predictions did not match observed incidence. |
| Zhang, L. and Zhou, T. 2014. An assessment of improvements in global monsoon precipitation simulation in FGOALS-s2.Advances in Atmospheric Sciences 31: 165-178. | The Flexible Global Ocean-Atmosphere-Land System model (FGOALS-s2) failed to predict monsoon weather accurately. |
| Prodhomme, C., Terray, P., Masson, S., Izumo, T., Tozuka, T. and Yamagata, T. 2014. Impacts of Indian Ocean SST biases on the Indian Monsoon: as simulated in a global coupled model. Climate Dynamics 42: 271-290. | Extensive errors found in models attempting to reproduce Indian Summer Monsoon systems and the Indian Ocean Dipole. |
| Richter, I., Xie, S.-P., Behera, S.K., Doi, T. and | The researchers noted many problems with the |

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| Masumoto, Y. 2014. Equatorial Atlantic variability and its relation to mean state biases in CMIP5. Climate Dynamics 42: 171-188. | models, including that "in terms of the mean state, 29 out of 33 models examined continue to suffer from serious biases including an annual mean zonal equatorial SST gradient whose sign is opposite to observations." |
| Purich, A., Cowan, T., Min, S.-K. and Cai, W. 2013. Autumn precipitation trends over Southern Hemisphere midlatitudes as simulated by CMIP5 models. Journal of Climate 26: 8341-8356. | The concluding message of Purich *et al.*'s investigation, as they phrase it, is that "to assist in reducing the uncertainty in future precipitation projections, further work investigating the limited ability of climate models in simulating observed historical trends in precipitation over many Southern Hemisphere regions is required." |
| Camargo, S.J. 2013. Global and regional aspects of tropical cyclone activity in the CMIP5 models. Journal of Climate 26: 9880-9902. | Researcher attempted to model tropical cyclone activity, both to match against observed data and under warming scenarios. She found, first, that the CMIP5 models could not consistently model realistic tropical cyclones, and second, that they came to no consensus that tropical cyclone activity would increase under a warming scenario. |
| Weller, E. and Cai, W. 2013. Asymmetry in the IOD and ENSO teleconnections in a CMIP5 model ensemble and its relevance to regional rainfall. Journal of Climate 26: 5139-5149. | Indian Ocean Dipole (IOD), which plays a major role in Australian dry weather, is not modeled well during the crucial spring season. |
| Brown, J.R., Colman, R.A., Moise, A.F. and Smith, I.N. 2013. The western Pacific monsoon in CMIP5 models: Model evaluation and projections. Journal of Geophysical Research: Atmospheres 118: 12,458-12,475. | "[T]he ability of coupled climate models to simulate the characteristics of the monsoon in present day climate is an important condition for the use of such models to make future climate projections." In the words of Brown *et al.*, "the ability of 35 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to simulate the western Pacific (WP) monsoon [was] evaluated and compared with atmosphere-only model simulations (with observed sea surface temperatures, SSTs) to determine the impact of SST biases on model performance." The researchers found many problems with the models and conclude "further investigation of the mechanisms determining the response of the monsoon in individual models is required to understand the reasons for model disagreement and to determine which aspects of projected monsoon change are most robust." |
| Silva, G.A.M., Dutra, L.M.M., da Rocha, R.P., Ambrizzi, T. and Leiva, E. 2014. Preliminary analysis on the global features of the NCEP CFSv2 seasonal hindcasts. Advances in Meteorology 2014: 10.1155/2014/695067. | After identifying significant problems with the current models, Silva *et al.*'s "overall evaluations" thus lead them to conclude that "further investigations are still needed," and they say that these projected studies "should be carried out to help in understanding in further details the reasons for the CFSv2 deficiencies." |
| Rupp, D.E., Abatzoglou, J.T., Hegewisch, K.C. and Mote, P.W. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific | Rupp *et al.* explain how they compared monthly temperature and precipitation projections from 41 CMIP5 GCMs with real- |

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| Northwest USA. Journal of Geophysical Research: Atmospheres 118: 10,884-10,906. | world observations for the 20th century, focusing on the United States Pacific Northwest (PNW) and surrounding regions, and found significant problems with the models. |
| Kothe, S., Luthi, D. and Ahrens, B. 2014. Analysis of the West African Monsoon system in the regional climate model COSMO-CLM. International Journal of Climatology 34: 481-493. | Kothe *et al.* write that "a lot of work has been done in the last years in the field of convection schemes (Braconnot *et al.*, 2007; Zanis *et al.*, 2009), but the convection schemes are still a major error source," with the result that "even with state-of-the-art climate models the simulation of complex atmospheric systems, such as the West African Monsoon, is still subject to errors (and will probably always be)." |
| Gong, H., Wang, L., Chen, W., Wu, R., Wei, K. and Cui, X. 2014. The climatology and inter-annual variability of the East Asian Winter Monsoon in CMIP5 models. Journal of Climate 27: 1659-1678. | Gong *et al.* studied how "model outputs from the Coupled Model Intercomparison Project (CMIP) phase 5 (CMIP5) are used to examine the climatology and inter-annual variability of the East Asian winter monsoon (EAWM)." They found that the models had significant problems. |
| Song, F. and Zhou, T. 2014. Interannual variability of East Asian Summer Monsoon simulated by CMIP3 and CMIP5 AGCMs: Skill dependence on Indian Ocean-Western Pacific anticyclone teleconnection. Journal of Climate 27: 1679-1697. | Song and Zhou investigated the climatology and inter-annual variability of the EASM "by using 13 atmospheric general circulation models (AGCMs) from phase 3 of the Coupled Model Intercomparison Project (CMIP3) and 19 AGCMs from CMIP5." The researchers found significant problems with the models. |
| Ramesh, K.V. and Goswami, P. 2014. Assessing reliability of regional climate projections: the case of Indian monsoon. Scientific Reports 4: 10.1038/srep04071. | The two researchers found that "both CMIP3 and CMIP5 simulations exhibit large spreads in simulations of average monsoon rainfall and their inter-annual variability." "[O]ur results show that no significant progress has been achieved in our ability to simulate basic quantities like observed seasonal mean and trend, and hence to project the regional climate system, namely CIM, with reasonable certainty." |
| Steinhaeuser, K. and Tsonis, A.A. 2014. A climate model intercomparison at the dynamics level. Climate Dynamics 42: 1665-1670. | Data suggest that (1) "the models are in significant disagreement when it comes to their SLP, SAT, and precipitation community structure," that (2) "none of the models comes close to the community structure of the actual observations," that (3) "not only do the models not agree well with each other, they do not agree with reality," that (4) "the models are not capable to simulate the spatial structure of the temperature, sea level pressure, and precipitation field in a reliable and consistent way," and that (5) "no model or models emerge as superior." |
| Ibrahim, B., Karambiri, H., Polcher, J., Yacouba, H. and Ribstein, P. 2014. Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models. Climate Dynamics 42: 1363-1381. | The five researchers report that (1) "the simulated relationship between changed annual rainfall amounts and the number of rain days or their intensity varies strongly from one model to another," that (2) "the climate models' simulations do not show any consensus in the |

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| | trends of the annual rainfall amount over the West African Sahel during the 21st century, even when they are run under the same climate change scenario at a high spatial resolution," and that (3) "some changes do not correspond to what is observed for the rainfall variability over the last 50 years." |
| Wang, C., Zhang, L., Lee, S.-K., Wu, L. and Mechoso, C.R. 2014. A global perspective on CMIP5 climate model biases. *Nature Climate Change* **4**: 201-205. | Broad study of CMIP5 models--upon which the IPCC AR5 depended--have shown long-term, uncorrected deficiencies that show sea surface temperatures off by several degrees in either direction and mis-model the Atlantic Meridional Overturning Circulation (AMOC). These deficiencies undermine the confidence that can be placed in the models. |
| Neukom, R., Gergis, J., Karoly, D.J., Wanner, H., Curran, M., Elbert, J., Gonzalez-Rouco, F., Linsley, B.K., Moy, A.D., Mundo, I., Raible, C.C., Steig, E.J., van Ommen, T., Vance, T., Villalba, R., Zinke, J. and Frank, D. 2014. Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* **4**: 362-367. | CMIP5 models systematically overestimate inter-hemispheric coupling, which in turn overemphasizes anthropogenic causes compared to "internal climate system variability." |
| Rocheta, E., Sugiyanto, M., Johnson, F., Evans, J. and Sharma, A. 2014. How well do general circulation models represent low-frequency rainfall variability? *Water Resources Research* **59**: 2108-2123. | A novel performance metric for rating GCM performance showed that they remain consistently unreliable in predicting low-frequency rainfall variability and persistence, independent of location. |
| Perez-Sanz, A., Li, G., Gonzalez-Samperiz, P. and Harrison, S.P. 2014. Evaluation of modern and mid-Holocene seasonal precipitation of the Mediterranean and northern Africa in the CMIP5 simulations. *Climate of the Past* **10**: 551-568. | CMIP5 models fail to reproduce known precipitation patterns in Mediterranean and Africa. |
| Shashikanth, K., Salvi, K., Ghosh, S. and Rajendran, K. 2014. Do CMIP5 simulations of Indian summer monsoon rainfall differ from those of CMIP3? *Atmospheric Science Letters* **15**: 79-85. | In modeling the Indian Summer Monsoon Rainfall (ISMR) system, CMIP5 models did not improve over CMIP3 with respect to biases, and have greater uncertainty than the older models. In the end, "the simulations of ISMR with coarse resolution climate models have become worse, with similar bias, but with higher uncertainties." |
| Crook, J.A. and Forster, P.M. 2014. Comparison of surface albedo feedback in climate models and observations. *Geophysical Research Letters* **41**: 1717-1723. | CMIP5 models consistently mis-estimate albedo levels from snow and ice. In Antarctica, models find positive climate change feedback where all observations are negative. |
| Bellenger, H., Guilyardi, E., Leloup, J., Lengaigne, M. and Vialard, J. 2014. ENSO representation in climate models: from CMIP3 to CMIP5. *Climate Dynamics* **42**: 1999-2018. | CMIP5 is not an improvement over CMIP3 in terms of modeling ENSO. CMIP5 consistently fails to models feedback effects and cannot get the fundamental features of ENSO correct. |
| Jha, B., Hu, Z.-Z. and Kumar, A. 2014. SST and ENSO variability and change simulated in historical experiments of CMIP5 models. *Climate Dynamics* **42**: 2113-2124. | CMIP5 cannot reproduce observed, known changes in sea surface temperature. |
| Syed, F.S., Iqbal, W., Syed, A.A.B. and Rasul, | Regional Climate Models (RCMs) have |

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| G. 2014. Uncertainties in the regional climate models simulations of South-Asian summer monsoon and climate change. *Climate Dynamics* **42**: 2079-2097. | "systematic biases" in modeling South-Asian Summer Monsoon systems. |
| Taschetto, A.S., Gupta, A.S., Jourdain, N.C. Santoso, A., Ummenhofer, C.C. and England, M.H. 2014. Cold tongue and warm pool ENSO events in CMIP5 mean state and future projections. *Journal of Climate* **27**: 2861-2885. | CMIP5 modeling of ENSO shows substantial failures in modeling known variations in sea surface temperature, including: systematic bias in westward extent, inability to predict asymmetry between La Niña events, and missing La Niña starts by two seasons and endpoints by six months. |
| Lin, J.-L., Qian, T. and Shinoda, T. 2014. Stratocumulus clouds in Southeaster Pacific simulated by eight CMIP5-CFMIP global climate models. *Journal of Climate* **27**: 3000-3022. | Stratocumulus clouds ("climate refrigerators") over Southeast Pacific could not be predicted or correctly models by CMIP5 or Cloud Feedback Model Intercomparison Project (CFMIP5) models. |
| Martin, G.M. 2014. Quantifying and reducing uncertainty in the large-scale response of the water cycle. *Surveys in Geophysics* **35**: 553-575. | Broad uncertainties in modeling of water systems render current models fundamentally unreliable. |
| Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and Sheffield, J. 2014. Global warming and changes in drought. *Nature Climate Change* **4**: 17-22. | "[I]t is probably not possible to determine reliable decadal and longer-term trends in drought due to climate change without first accounting for the effects of ENSO and the Pacific Decadal Oscillation," which has proved extremely difficult to model correctly. |
| Langford, S., Stevenson, S. and Noone, D. 2014. Analysis of low-frequency precipitation variability in CMIP5 historical simulations for southwestern North America. *Journal of Climate* **27**: 2735-2756. | CMIP5 models unable to reproduce decadal variability in droughts and megadroughts in Southwestern United States. |
| Koenigk, T., Devasthale, A., Karlsson, K.-G. 2014. Summer Arctic sea ice albedo in CMIP5 models. *Atmospheric Chemistry and Physics* **14**: 1987-1998. | Sea-ice albedo effects cannot be correctly modeled if the other "large-scale atmospheric and oceanic" systems are not correctly modeled. The current tuning of Arctic ice simulations "might lead to unrealistic amplification rates in future simulations." |
| Michael, J.-P., Misra, V. and Chassignet, E.P. 2013. The El Niño and Southern Oscillation in the historical centennial integrations of the new generation of climate models. *Regional Environmental Change* **13**: S121-S130. | CMIP5 models still fall dramatically short in validating (reproducing) observed data for ENSO. |
| Maloney, E.D., Camargo, S.J., Chang, E., Colle, B., Fu, R., Geil, K.L., Hu, Q., Jiang, X., Johnson, N., Karnauskas, K.B., Kinter, J., Kirtman, B., Kumar, S., Langenbrunner, B., Lombardo, K., Long, L.N., Mariotti, A., Meyerson, J.E., Mo, K.C., Neelin, J.D., Pan, Z., Seager, R., Serra, Y., Seth, A., Sheffield, J., Stroeve, J., Thibeault, J., Xie, S.-P., Wang, C., Wyman, B. and Zhao, M. 2014. North American climate in CMIP5 experiments: Part III: Assessment of Twenty-First-Century Projections. *Journal of Climate* **27**: 2230-2270. | CMIP5 models consistently flawed, but moreover display common areas--meaning that agreement among models falsely predicts confidence. |
| Kim, J., Waliser, D.E., Mattmann, C.A., | GCM downscaled with RCMs for Africa failed |



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| Goodale, C.E., Hart, A.F., Zimdars, P.A., Crichton, D.J., Jones, C., Nikulin, G., Hewitson, B., Jack, C., Lennard, C. and Favre, A. 2014. Evaluation of the CORDEX-Africa multi-RCM hindcast: systematic model errors. *Climate Dynamics* **42**: 1189-1202. | to hindcast precipitation, temperatures, and cloud levels correctly. |
| Li, J.-L.F., Waliser, D.E., Chen, W.-T., Guan, B., Kubar, T., Stephens, G., Ma, H.-Y., Deng, M., Donner, L., Seman, C. and Horowitz, L. 2012. An observationally based evaluation of cloud ice water in CMIP3 and CMIP5 GCMs and contemporary reanalyses using contemporary satellite data. *Journal of Geophysical Research* **117**: 10.1029/2012JD017640. | Models that make up CMIP5 were off by factors ranging from 2x to 10x in modeling cloud ice water content and path. CMIP5 as a whole did not average out the errors. |
| Driscoll, S., Bozzo, A., Gray, L.J., Robock, A. and Stenchikov, G. 2012. Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions. *Journal of Geophysical Research* **117**: 10.1029/JD017607. | Following up on a study of IPCC models that showed they failed to reproduce volcanic effects (Stenchikov *et al.* 2006), this study concludes that CMIP5 and other models have not improved. |
| Catto, J.L., Nicholls, N. and Jakob, C. 2012b. North Australian sea surface temperatures and the El Niño-Southern Oscillation in the CMIP5 models. *Journal of Climate* **25**: 6375-6382. | ENSO is a crucial driver of sea surface temperatures, but CMIP5 models “are still missing some underlying process or mechanism” and cannot fully reproduce it. Until that underlying lack is remedied, predicting the impact of climate change on Australia will be difficult or impossible to do accurately. |
| Cesana, G. and Chepfer, H. 2012. How well do climate models simulate cloud vertical structure? A comparison between CALIPSO-GOCCP satellite observations and CMIP5 models. *Geophysical Research Letters* **39**: 10.1029/2012GL053153. | CMIP5 cannot accurately model cloud processes, compared to satellite-derived observations. |
| Cesana, G., Kay, J.E., Chepfer, H., English, J.M. and de Boer, G. 2012. Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP. *Geophysical Research Letters* **39**: 10.1029/2012GL053385. | CMIP5 models cannot reproduce Artic clouds, resulting in significant inaccuracies in understanding climate feedbacks. |
| Kataoka, T., Tozuka, T., Masumoto, Y. and Yamagata, T. 2012. The Indian Ocean subtropical dipole mode simulated in the CMIP3 models. *Climate Dynamics* **39**: 1385-1399. | CMIP3 models do not agree over temperature anomalies involved with the Indian Ocean Subtropical Dipole. For that reason, they fail to predict accurately rainfall over Africa. |
| Li, G. and Xie, S.-P. 2012. Origins of tropical-wide SST biases in CMIP multi-model ensembles. *Geophysical Research Letters* **39**: 10.1029/2012GL053777. | Errors in computing sea surface temperature patterns have persisted through CMIP3 and 5--”several generations of models for more than a decade.” |
| Kelley, C., Ting, M., Seager, R. and Kushnir, Y. 2012. Mediterranean precipitation climatology, seasonal cycle, and trend as simulated by CMIP5. *Geophysical Research Letters* **39**: 10.1029/2012GL053416. | CMIP5 at best a modest improvement over CMIP3 in terms of modeling Mediterranean precipitation--and it still is not very good. |
| Nam, C., Bony, S., Dufresne, J.-L. and | Current climate models, including CMIP5 |

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| Chepfer, H. 2012. The 'too few, too bright' tropical low-cloud problem in CMIP5 models. *Geophysical Research Letters* **39**: 10.1029/2012GL053421. | models, cannot correctly predict low-cloud cover and radiative effects. |
| Kovach, R.P., Gharrett, A.J. and Tallmon, D.A. 2012. Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B* **279**: 3870-3878. | CMIP3 models--used for IPCC's AR4 report--failed validation tests against observed weather patterns in China. Indeed, "each AR4 GCM performs differently in different regions of China," rendering them "unsuitable for application in China …." |
| Khoi, D.N. and Suetsugi, T. 2012. Uncertainty in climate change impacts on streamflow in Be River Catchment, Vietnam. *Water and Environment Journal* **26**: 530-539. | GCM models unable to predict changes in stream flow in Vietnam. Moreover, choice of model was main source of uncertainty, which will only increase in multi-modal models that bring together multiple GCMs. |
| Hannaford, J. and Buys, G. 2012. Trends in seasonal river flow regimes in the UK. *Journal of Hydrology* **475**: 158-174. | Observed trends in river flows in the United Kingdom show greater flows in winter as predicted by models. The lower summer flows predicted, however, do not agree with actual summer flows, which saw a decrease in the number of low-flows. The river flows seem to have "some degree of resilience to anthropogenic warming." |
| Zhang, H., Liang, P., Moise, A. and Hanson, L. 2012. Diagnosing potential changes in Asian summer monsoon onset and duration in IPCC AR4 model simulations using moisture and wind indices. *Climate Dynamics* **39**: 2465-2486. | Over the 13 models used for IPCC's AR4, no model could accurately capture the Asian Summer Monsoon system. Indeed, the models split evenly as to whether dates of onset and retreat were advancing or falling back. Researchers also could not explain why ENSO was figuring more prominently in some models than others. |
| Ault, T.R., Cole, J.E. and St. George, S. 2012. The amplitude of decadal to multidecadal variability in precipitation simulated by state-of-the-art climate models. *Geophysical Research Letters* **39**: 10.1929/2012GL053424. | CMIP5 models could not capture fluctuations in precipitation in the decadal-to-multidecadal range. |
| Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K. and Liebert, J. 2012. "Should we apply bias correction to global and regional climate model data?" *Hydrology and Earth System Sciences* **16**: 3391-3404. | Knowing that models have "biases to a degree that precludes … direct use, especially in climate change impact studies," some researchers apply bias correction (BC) methods as a standard procedure, "the correction of model output towards observations in a post-processing step." Even so, BC distorts the output and hides rather than reduces uncertainty." Moreover, the application of BC "is in most cases not transparent to the end user," so distorts decisions made on the basis of the models without warning signs. |
| Ray, S. and Giese, B.S. 2012. Historical changes in El Niño and La Niña characteristics in an ocean reanalysis. *Journal of Geophysical Research* **117**: 10.1029/2012JC008031. | Researchers measuring actual sea surface temperatures rather than models found that "[o]verall, there is no evidence that there are changes in the strength, frequency, duration, location or direction of propagation of El Niño and La Niña anomalies caused by global warming during the period from 1871 to 2008." |

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| Kim, H.-M., Webster, P.J., Curry, J.A. and Toma, V.E. 2012. Asian summer monsoon prediction in ECMWF System 4 and NCEP CFSv2 retrospective seasonal forecasts. *Climate Dynamics* **39**: 2975-2991. | Cutting-edge models failed to reproduce the Asian Monsoon system between 1982 and 2009. |
| Bates, S.C., Fox-Kemper, B., Jayne, S.R., Large, W.G., Stevenson, S. and Yeager, S.G. 2012. Mean biases, variability, and trends in air-sea fluxes and sea surface temperature in the CCSM4. *Journal of Climate* **25**: 7781-7801. | In an attempt to understand mean biases in Community Climate System Model version 4 by comparing it to real-world dataset, researchers found systematic flaws, including a set of flaws taking on different patterns in different time scales. |
| Handorf, D. and Dethloff, K. 2012. How well do state-of-the-art atmosphere-ocean general circulation models reproduce atmospheric teleconnection patterns? *Tellus A* **64**: org/10.3402/tellusa.v64i0.19777. | CMIP3 models could not simulate the atmospheric teleconnection patterns of the mid-tropospheric flows of the Northern Hemisphere when checked against reliable re-analysis data. |
| Po-Chedley, S. and Fu, Q. 2012. Discrepancies in tropical upper tropospheric warming between atmospheric circulation models and satellites. *Environmental Research Letters* **7**: 10.1088/1748-9326/7/4/044018. | Even with inputs of known sea surface temperatures, CMIP3 and CMIP5 both failed to correctly model tropical upper troposphere warming. |
| Zhang, W. and Jin, F.-F. 2012 Improvements in the CMIP5 simulations of ENSO-SSTA Meridional width. *Geophysical Research Letters* **39**: 10.1029/2012GL053588. | Knowing CMIP3 models tended to model ENSO poorly--specifically, confining a sea surface temperature anomaly too closely to the equator--researchers tested CMIP5 models to see if they fared better. While they showed “a modest improvement,” they still were not comparable to observational data. |
| Chen, L., Pryor, S.C. and Li, D. 2012. Assessing the performance of Intergovernmental Panel on Climate Change AR5 climate models in simulating and projecting wind speeds over China. *Journal of Geophysical Research* **117**: 10.1029/2012JD017533. | CMIP5 models--the core of IPCC’s AR5--failed completely to reproduce observed decreases in wind speed over China. *No* models matched the observed decrease. |
| Barkhordarian, A., von Storch, H. and Bhend, J. 2013. The expectation of future precipitation change over the Mediterranean region is different from what we observe. *Climate Dynamics* **40**: 225-244. | Observed trends in Mediterranean precipitation were compared to CMIP3 projections. The result was “an outright sign mismatch”: the models predicted drying, but observed data all showed increased late-summer and autumn precipitation. |
| Stephens, G.L., L’Ecuyer, T., Forbes, R., Gettlemen, A., Golaz, J.-C., Bodas-Salcedo, A., Suzuki, K., Gabriel, P. and Haynes, J. 2010. Dreary state of precipitation in global models. *Journal of Geophysical Research* **115**: 10.1029/2010JD014532. | Current models of precipitation produce too much precipitation over tropical oceans and too little mid-latitude precipitation. These errors reflect a systemic problem of models more generally. |
| Lang, C. and Waugh, D.W. 2011. Impact of climate change on the frequency of Northern Hemisphere summer cyclones. *Journal of Geophysical Research* **116**: 10.1029/2010JD014300. | Researchers found very little consistency between sixteen models as to whether the frequency of hemispheric-averaged summer cyclones will increase or decrease. |
| Waliser, D.E., Li, J.-L.F., L’Ecuyer, T.S. and Chen, W.-T. 2011. The impact of precipitating ice and snow on the radiation balance in global | Because climate models fail to consider the ice in precipitating hydrometeors explicitly, the models will be getting the top of the |



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| climate models. *Geophysical Research Letters* **38**: 10.1029/2010GL046478. | atmosphere balance right, but for the wrong reasons. |
| Shin, S.-I. and Sardeshmukh, P.D. 2011. Critical influence of the pattern of Tropical Ocean warming on remote climate trends. *Climate Dynamics* **36**: 1577-1591. | The tropical oceanic warming pattern is poorly represented in current models. This failure is an error in the model rather than unpredictable climate noise. |
| Crompton, R.P., Pielke, Jr., R.A. and McAneney, K.J. 2011. Emergence timescales for detection of anthropogenic climate change in US tropical cyclone loss data. *Environmental Research Letters* **6**: 10.1088/1748-9326/6/1/014003. | Short term trends are unreliable in evaluating US tropical cyclone losses due to anthropogenic climate change. |
| Zhang, D., Msadek, R., McPhaden, M.J. and Delworth, T. 2011. Multidecadal variability of the North Brazil Current and its connection to the Atlantic meridional overturning circulation. *Journal of Geophysical Research* **116**: 10.1029/2010JC006812. | Climate models' predictions that Atlantic Meridional Overturning Circulation will slow down in response to rising temperatures has not occurred. |
| Sundal, A.V., Shepherd, A., Nienow, P., Hanna, E., Palmer, S. and Huybrechts, P. 2011. Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature* **469**: 521-524. | Current simulations of the Greenland ice-sheet flow fail to account for the dynamic evolution of subglacial drainage. |
| Cerezo-Mota, R., Allen, M. and Jones, R. 2011. Mechanisms controlling precipitation in the northern portion of the North American monsoon. *Journal of Climate* **24**: 2771-2783. | Commonly used climate models do not reproduce correctly the Great Plains low-level jet stream or the moisture of the Gulf of Mexico and are, thus, unrealistic. |
| Helmuth, B., Yamane, L., Lalwani, S., Matzelle, A., Tockstein, A. and Gao, N. 2011. Hidden signals of climate change in intertidal ecosystems: What (not) to expect when you are expecting. *Journal of Experimental Marine Biology and Ecology* **400**: 191-199. | The timing and magnitude of organismal warming will be highly variable at coastal sites and can't easily be measured by any single environmental measure. |
| Furtado, J.C., Di Lorenzo, E., Schneider, N. and Bond, N.A. 2011. North Pacific decadal variability and climate change in the IPCC AR4 models. *Journal of Climate* **24**: 3049-3067. | Current modeling does not consistently account for projected future changes in frequency of either the first or second leading pattern of North Pacific sea surface temperature anomalies. |
| Scherrer, S.C. 2011. Present-day interannual variability of surface climate in CMIP3 models and its relation to future warming. *International Journal of Climatology* **31**: 1518-1529. | CMIP3 models fail to represent interannual variability and are therefore inaccurate. |
| Fu, Q., Manabe, S. and Johanson, C.M. 2011. On the warming in the tropical upper troposphere: Models versus observations. *Geophysical Research Letters* **38**: 10.1029/2011GL048101. | General circulation models greatly overestimate the tropical surface temperature trend and do not accurately capture climate change. |
| Wan, X., Chang, P., Jackson, C.S., Ji, L. and Li, M. 2011. Plausible effect of climate model bias on abrupt climate change simulations in Atlantic sector. *Deep-Sea Research II* **58**: 1904-1913. | In order to accurately simulate past abrupt climate changes and project future changes, the bias in climate models must be reduced. Little to no progress has been made in the tropical Atlantic and there is little hope for future improvements. |
| Latif, M. and Keenlyside, N.S. 2011. A perspective on decadal climate variability and | State-of-the-art climate models suffer from large biases, are incomplete, suffer from |

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| predictability. *Deep-Sea Research II* **58**: 1880-1894. | inconsistencies from model to model and fail to simulate realistic oscillation. |
| Planque, B., Bellier, E. and Loots, C. 2011. Uncertainties in projecting spatial distributions of marine populations. *ICES Journal of Marine Science* **68**: 1045-1050. | With respect to projections of future ranges of marine plant and animal populations "most current projections are expected to be far less reliable than usually assumed." |
| Fu, Q., Manabe, S. and Johanson, C.M. 2011. On the warming in the tropical upper troposphere: Models versus observations. *Geophysical Research Letters* **38**: 10.1029/2011GL048101. | Current climate models do not appropriately factor in enhanced tropical upper tropospheric warming. |
| Crook, J.A. and Forster, P.M. 2011. A balance between radiative forcing and climate feedback in the modeled 20th century temperature response. *Journal of Geophysical Research* **116**: 10.1029/2011JD015924. | Current climate models are inaccurate due to unrealistic forcing distributions and elevated Arctic amplification, among other issues. |
| Fu, C.-B., Qian, C. and Wu, Z.-H. 2011. Projection of global mean surface air temperature changes in next 40 years: Uncertainties of climate models and an alternative approach. *Science China Earth Sciences* **54**: 1400-1406. | Climate projection models fail to reproduce multi-decadal variability, which may have led to the overestimation of the projection of global warming over the next 40 years. |
| Zheng, Y., Shinoda, T., Lin, J.-L. and Kiladis, G.N. 2011. Sea surface temperature biases under the stratus cloud deck in the Southeast Pacific Ocean in 19 IPCC AR4 coupled general circulation models. *Journal of Climate* **24**: 4139-4164. | Climate models suffer from numerous significant biases in the Southeast Pacific Ocean. |
| Richey, J.N., Poore, R.Z., Flower, B.P., Quinn, T.M. and Hollander, D.J. 2009. Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool. Geophysical Research Letters 36: 10.1029/2009GL040445. | Richey *et al.* (2009) report that results for Gulf of Mexico data locations were similar, and that all of them revealed the occurrence of Little Ice Age temperatures in the mid-1700s that were 2-3°C cooler than present-day temperatures. This large body of real-world data gives a vastly different view of things climatic than what is suggested by current state-of-the-art climate models, which consistently simulate a great amplification of 20th-century warming in high northern latitudes. Noting, in this regard, that "models including solar and volcanic forcing during the Little Ice Age have not been able to produce a >1°C cooling in the Gulf of Mexico-Caribbean region," where they and others have found a 2-3°C warming, Richey *et al.* go on to conclude that "more work needs to be done to better understand the regional climate dynamics that could lead to the observed cooling." |
| Lavers, D., Luo, L. and Wood, E.F. 2009. A multiple model assessment of seasonal climate forecast skill for applications. Geophysical Research Letters 36: 10.1029/2009GL041365. | Lavers *et al.* report that even in the virtual world of the climate models, there was a large drop off in predictive skill after the first 15-day period. In the real world, the models were even less accurate and had negligible skill in land forecasts at a 31-day lead time, which is "a relatively short lead time in terms of seasonal |

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| | climate prediction." |
| Bombardi, R.J. and Carvalho, L.M.V. 2009. IPCC global coupled model simulations of the South America monsoon system. Climate Dynamics 33: 893-916. | Over northern South America the annual precipitation cycle "is poorly represented by most models," and, more specifically, "most models tend to underestimate precipitation during the peak of the rainy season." This underestimation "seems to be one of the main reasons for the unrealistic out-of-phase annual cycles simulated near the equator by many GCMs," resulting in the fact that "poor representation of the total monsoonal precipitation over the Amazon and northeast Brazil is observed in a large majority of the models." As a consequence, therefore, they note that "simulations of the total seasonal precipitation, onset and end of the rainy season diverge among models and are notoriously unrealistic over [the] north and northwest Amazon for most models." |
| Solomon, S., Rosenlof, K., Portmann, R., Daniel, J., Davis, S., Sanford, T. and Plattner, G.-K. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. Sciencexpress: 10.1126/science.1182488. | Stratospheric water vapor concentrations decreased by about 10% after the year 2000; this decrease should have slowed the rate of increase in global near-surface air temperature between 2000 and 2009 by about 25% compared to what would have been expected (on the basis of climate model calculations) due to measured increases in $CO_2$ and other greenhouse gases over the same time period. In their concluding paragraph, the researchers state that it is "not clear whether the stratospheric water vapor changes represent a feedback to global average climate change or a source of decadal variability." Models do not "completely represent the Quasi Biennial Oscillation [which has a significant impact on stratospheric water vapor content], deep convective transport [of water vapor] and its linkages to sea surface temperatures." |
| Carslaw, K.S., Boucher, O., Spracklen, D.V., Mann, G.W., Rae, J.G.L., Woodward, S. and Kulmala, M. 2010. A review of natural aerosol interactions and feedbacks within the Earth System. Atmospheric Chemistry and Physics 10: 1701-1737. | "[T]he number of drivers of change is very large and the various systems are strongly coupled," noting that "there have therefore been very few studies that integrate the various effects to estimate climate feedback factors." Carslaw *et al.* arrive at the ultimate conclusion that "the level of scientific understanding of the climate drivers, interactions and impacts is very low." |
| Liu, Z., Zhu, J., Rosenthal, Y., Zhang, X., Otto-Bliesner, B.L., Timmermann, A., Smith, R.S., Lohmann, G., Zheng, W. and Timm, O.E. 2014. The Holocene temperature conundrum. *Proceedings of the National Academy of Sciences USA* **108**: 10.1073/pnas.1407229111. | "In the latest reconstruction of the global surface temperature throughout the Holocene (Marcott *et al.*, 2013), the most striking feature is a pronounced cooling trend of ~0.5°C following the Holocene Thermal Maximum ... with the Neoglacial cooling culminating in the Little Ice Age." "This inferred global annual cooling in the Holocene is puzzling" because, "the Holocene should be dominated by the retreating ice sheets and rising atmospheric |

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| | greenhouse gases, with both favoring a globally averaged warming." The analysis also resulted in "a robust warming trend in current climate models" that they note was "opposite from the cooling" noted elsewhere, leaving us with what the researchers called an unexplained "model-data inconsistency in global annual temperature of ~1°C." This would imply the existence of what they describe as "major biases" across the entire spectrum of what they call the "current generation of climatic models." |
| Tuffen H. 2010. How will melting of ice affect volcanic hazards in the twenty-first century? Philosophical Transactions of the Royal Society A 368: 2535-2558. | "[N]ew data and improved models are required." In the data area, Tuffen states that "existing databases of known volcanic eruptions need to be augmented by numerous detailed case studies of the Quaternary eruptive history of ice-covered volcanoes," while in the area of models, "improved physical models are required to test how magma generation, storage and eruption at stratovolcanoes are affected by stress perturbations related to the waxing and waning of small-volume ice bodies." Finally, the "feedbacks between the mass balance of ice sheets and glaciers and volcanic activity need to be incorporated into future earth-system models." |
| Bunce, J.A. 2014. Limitations to soybean photosynthesis at elevated carbon dioxide in free-air enrichment and open top chamber systems. *Plant Science* **226**: 131-135. | A little over a decade ago in a study of two species of tropical trees, Holtum and Winter (2003) presented evidence suggesting the possibility that free-air $CO_2$ enrichment or FACE systems "may underestimate the potential fertilizing effects of above-ambient $CO_2$ concentrations on plants."<br>Bunce (2014) concludes that "if night-time $CO_2$ elevation has similar effects on the growth of other species" - and there is much evidence to suggest that it does - "FACE systems which only elevate $CO_2$ during the daytime could underestimate crop responses to future $CO_2$ concentrations." |
| Esper, J., Duthorn, E., Krusic, P.J., Timonen, M. and Buntgen, U. 2014. Northern European summer temperature variations over the Common Era from integrated tree-ring density records. *Journal of Quaternary Science* **29**: 487-494. | Tree-ring chronologies of *maximum latewood density* (MXD) "are most suitable to reconstruct annually resolved summer temperature variations of the late Holocene." This history depicts "a long-term cooling trend of -0.30°C per 1,000 years over the Common Era in northern Europe." Most important, their temperature reconstruction "has centennial-scale variations superimposed on this trend," which indicate that "conditions during Medieval and Roman times were probably warmer than in the late 20th century." |
| Park, S., Bretherton, C.S. and Rasch, P.J. 2014. Integrating cloud processes in the | "Satellite observations reveal that the net radiative effect of clouds on the Earth- |

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| Community Atmosphere Model, Version 5. *Journal of Climate* **27**: 6821-6856. | atmosphere system is a cooling of 20-24 $Wm^{-2}$ in the global average," which they note is "about six times larger than the radiative forcing associated with doubled $CO_2$," hence, it can be appreciated that properly modeling cloud processes is an important aspect of ongoing efforts to predict the future course of Earth's climate. However, even with these improvements in modeling for clouds, "several systematic biases were also identified in the simulated cloud fields in CAM5," which they grouped into three different categories: deficient regional tuning, inconsistency between various physics parameterizations, and incomplete modeled physics. |
| Woppelmann, G., Marcos, M., Santamaria-Gomez, A., Martin-Miguez, B., Bouin, M.-N. and Gravelle, M. 2014. Evidence for a differential sea level rise between hemispheres over the twentieth century. *Geophysical Research Letters* **41**: 1639-1643. | "The evidence for sea level rise primarily comes from the information provided by long tide gauge records," which "are mainly located along the coasts of northeast America or western Europe." That overrepresentation is problematic because the data revealed the existence of "a clearly distinct behavior between the Northern and the Southern Hemispheres," with mean sea level rates of rise of 2.0 mm/year and 1.1 mm/year, respectively. And given the coherent spatial patterns a mean global sea level rate-of-rise value of 1.5 ± 0.5 mm/year is inferred from "a weighted average of the hemispheric trends according to the area they represent." |
| Evan, A.T., Flamant, C., Fiedler, S. and Doherty, O. 2014. An analysis of aeolian dust in climate models. *Geophysical Research Letters* **41**: 5996-6001. | "The representation of dust in state-of-the-art climate models has not been systematically evaluated." "All models fail to reproduce basic aspects of dust emission and transport over the second half of the twentieth century," and "systematically underestimate dust emission, transport, and optical depth." As a result "there is no reason to assume that the projections of dust emission and concentration for the 21st century have any validity," casting doubt on the representation of other features of coupled Earth systems that are affected by aeolian dust, including regional land and ocean surface temperatures, precipitation and cloud processes, coupled equatorial processes, and terrestrial and oceanic biogeochemistry. |
| Yang, W., Seager, R., Cane, M.A. and Lyon, B. 2014. The East African long rains in observations and models. *Journal of Climate* **27**: 7185-7202. | "The multi-model mean of the fully-coupled models of the CMIP5 historical experiment underestimates the East African long rains and overestimates the short rains with a considerable range of performance among the individual models." "This lack of coupled model skill casts doubt on projections of future East African precipitation and on the use of these models to understand past variations." "It should not, therefore, be assumed that recent |

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| | drying trends represent an anthropogenically-forced precipitation change and that the trends will continue," nor "should it be assumed that the model projection of wetting in response to rising greenhouse gases is correct." In fact "we are distressingly far from an adequate understanding or a usable ability to model climate variability and change in this socially critical region." |
| Grose, M.R., Brown, J.N., Narsey, S., Brown, J.R., Murphy, B.F., Langlais, C., Gupta, A.S., Moise, A.F. and Irving, D.B. 2014. Assessment of the CMIP5 global climate model simulations of the western tropical Pacific climate system and comparison to CMIP3. *International Journal of Climatology* **34**: 3382-3399. | "An important influence on confidence in model projections is the realism with which the models simulate the current climate mean and variability." "While models are now sufficiently reliable to provide useful insights into many aspects of the climate system in the region, systematic biases in the simulation of some important features in the Pacific region persist." "There is evidence to reject one model as unsuitable for making climate projections in the region, and another two models unsuitable for analysis of the South Pacific Convergence Zone (SPCZ)." "Many of the systematic model biases in the mean climate in CMIP3 are also present in the CMIP5 models," and there are still "several regions in the world where CMIP5 models show significant differences to observed trends in temperature and mean sea level pressure." |
| Tiwari, P.R., Kar, S.C., Mohanty, U.C., Kumari, S., Sinha, P., Nair, A. and Dey, S. 2014. Skill of precipitation prediction with GCMs over north India during winter season. *International Journal of Climatology* **34**: 3440-3455. | The northern part of India "is critically important for the agriculture and economy of the country." The review of current GCM for the area results in finding (1) "skill of predictions is too low," that (2) "most of the GCMs do not respond to sea surface temperature variability over the Pacific in a realistic manner," that (3) "only two of the five GCMs get the observed simultaneous teleconnection correctly," that (4) "only one of these two models has the observed phase lag with the strongest correlation as observed," that (5) "the GCMs in general underestimate the observed climatology and inter-annual variability of precipitation," that (6) "none of the models is able to depict the observed inter-annual variability correctly," and that (7) "a simple multi-model ensemble approach with all the models getting the same weight does not improve much the forecast skill." |
| Wei, K., Xu, T., Du, Z., Gong, H. and Xie, B. 2014. How well do the current state-of-the-art CMIP5 models characterize the climatology of the East Asian winter monsoon? *Climate Dynamics* **43**: 1241-1255. | The East Asian Winter Monsoon (EAWM) influences not only East Asia but also convection and sea surface temperatures near the maritime continent, the Australian summer monsoon, the climate of North America, and the evolution, intensity and periodicity of ENSO, which facts point to the importance of climate models being able to adequately |

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| | represent the EAWM.<br><br>The models fail to do that because: (1) "both the CMIP3 and CMIP5 models overestimate the precipitation over the East Asia oceanic region, that (2) "the overestimation of precipitation by the CMIP3 and CMIP5 models is most likely due to the overestimation of convective clouds in East Asia," that in the case of the CMIP5 models (3) "the near surface northerlies are weaker than suggested by observations and the CMIP3 models," that (4) "the zonal sea level pressure difference between the Siberian high and Aleutian low is weaker than in observations and the CMIP3 models," that (5) the 500-hPa major trough strength is too strong in East Asia," and that (6) "the cold bias still exists in the current CMIP5 models." |
| Kwiatkowski, L., Halloran, P.R., Mumby, P.J. and Stephenson, D.B. 2014. What spatial scales are believable for climate model projections of sea surface temperature? *Climate Dynamics* **43**: 1483-1496. | "Earth system models (ESMs) provide high resolution simulations of variables such as sea surface temperature (SST) that are often used in off-line biological impact models." However, "accurately simulating the coastal zones represents a significant challenge for ESMs. The study found that "CMIP5 models have typically very poor skill and *often* perform *worse than chance* at capturing spatial patterns of SST warming anomalies between 1960-1980 and 1985-2005 in the coral regions analyzed." (Emphasis added.) The data show the "output from current generation ESMs is not yet suitable for making sub-regional projections of change in coral bleaching frequency and other marine processes linked to SST warming." |
| Davini, P. and Cagnazzo, C. 2014. On the misinterpretation of the North Atlantic Oscillation in CMIP5 models. *Climate Dynamics* **43**: 1497-1511. | The North Atlantic Oscillation or NAO "is the most prominent pattern of regional wintertime variability of the Northern Hemisphere." In light of the significance of this phenomenon, the study "analyzed a group of the CMIP5 models in order to detect which models are able to replicate it. Several state-of-the-art climate models were "unable to correctly simulate the physical processes connected to the NAO." |
| Mishra, U. and Riley, W.J. 2014. Active-layer thickness across Alaska: Comparing observation-based estimates with CMIP5 earth system model predictions. *Soil Science Society of America Journal* **78**: 894-902. | "Predicted active-layer (AL) thicknesses of permafrost-affected soils influence Earth system model predictions of carbon-climate feedbacks," But (CMIP5) predictions included "large interquartile ranges in predicted AL thicknesses, indicating substantial overestimate of current AL thickness, which might result in higher positive permafrost carbon feedback under future warming scenarios." The results indicate a "need for |

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| | better process representations and representation of natural spatial heterogeneity due to local environment (topography, vegetation and soil properties) in Earth system models to generate a realistic variation of regional scale AL thickness, which could reduce the existing uncertainty in predicting permafrost carbon-climate feedbacks.” |
| Song, Z.Y., Liu, H.L., Wang, C.Z., Zhang, L.P. and Qiao, F.L. 2014. Evaluation of the eastern equatorial Pacific SST seasonal cycle. *Ocean Science* **10**: 837-843. | The (CGCMs) of the Coupled Model Intercomparison Project Phase 3 (CMIP3) suffered from significant shortcomings in their ability to accurately model the seasonal sea surface temperature (SST) cycle of the *eastern equatorial Pacific* (EEP), and the updated CMIP5 models despite some improvements “to improve the capability of the CGCMs in simulating a realistic SST seasonal cycle in the EEP, both the local and remote climatological SST biases that exist in both CMIP3 and CMIP5 CGCMs…must be resolved.” |
| Lyon, B. 2014. Seasonal drought in the Greater Horn of Africa and its recent increase during the March-May long rains. *Journal of Climate* **27**: 7953-7975. | In a review of the atmospheric circulation and sea surface temperature (SST) conditions that are associated with meteorological drought on the seasonal time scale in the Greater Horn of Africa the study found that “while CMIP5 climate model projections generally show that the Greater Horn will become wetter during this century” observational data has shown the opposite result, and the model has done “a poor job capturing the annual cycle of rainfall and simulating historical decadal variability of the Greater Horn long rains and their relationship to global SST patterns.” The study concludes that “whether anthropogenic forcing will lead to a wetter or drier Greater Horn during the current century is seen to remain an open question.” |
| Lacagnina, C. and Selten, F. 2014. Evaluation of clouds and radiative fluxes in the EC-Earth general circulation model. *Climate Dynamics* **43**: 2777-2796. | “Despite the importance of clouds, their representation in general circulation models (GCMs) continues to account for much of the uncertainties in climate projections.” The study combined GCMs and compared the models’ output to real-world observational data obtained from numerous satellite and land-based sensors and concluded “the model weaknesses discussed above indicate that more effort is needed to improve the physical parameterizations employed.” |
| Wang, H., Long, L., Kumar, A., Wang, W., Schemm, J.-K.E., Zhao, M., Vecchi, G.A., Larow, T.E., Lim, Y.-K., Schubert, S.D., Shaevitz, D.A., Camargo, S.J., Henderson, N., Kim, D., Jonas, J.A. and Walsh, K.J.E. 2014. How well do global climate models simulate the variability of Atlantic tropical cyclones associated with ENSO? *Journal of Climate* **27**: | In this test of five state-of-the-art global climate models the authors note in comparison to “observational studies” the difference between the model simulations and real-world observations can be attributed to biases of the models. |

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| 5673-5692. | |
| Harrison, S.P., Bartlein, P.J., Brewer, S., Prentice, I.C., Boyd, M., Hessler, I., Holmgren, K., Izumi, K. and Willis, K. 2014. Climate model benchmarking with glacial and mid-Holocene climates. *Climate Dynamics* **43**: 671-688. | This evaluation of PMIP2 and CMIP5 climate models, uses paleo-climatic reconstructions of the Last Glacial Maximum (LGM, ca 21,000 years ago) to evaluate the abilities of today's state-of-the-art climate models to adequately replicate these two significant global climates of Earth's distant past, finding that (1) "most models overestimate the ocean cooling," that (2) "they do not capture the heterogeneity seen in the reconstructions," that (3) "spatial patterns in reconstructed LGM annual SST [sea surface temperature] anomalies ... are not well predicted by the models," and that (4) "the seasonal SST anomalies show no correlation with the reconstructions." As for (5) "all but two models underestimate the reconstructed annual cooling, with the largest median bias nearly 3.5°C and eight models having a bias larger than 1°C," that (6) "all the models underestimate the mean temperature of the coldest month reduction," with the smallest median bias being +2.4°C and the largest +7.3°C," that (7) "all models underestimate the LGM reduction in mean annual precipitation over land," and that (8) "most models also underestimate the increase in aridity." |
| Mauri, A., Davis, B.A.S., Collins, P.M. and Kaplan, J.O. 2014. The influence of atmospheric circulation on the mid-Holocene climate of Europe: a data-model comparison. *Climate of the Past* **10**: 1925-1938. | New seasonal (summer and winter) gridded temperature and precipitation reconstruction for mid-Holocene (MH, 6000 years BP) Europe, based on fossil and modern pollen data sets that are "greatly improved in both size and quality compared with previous studies." The data show ""little agreement between the reconstructed anomalies and those from 14 GCMs that performed mid-Holocene experiments as part of the PMIP3/CMIP5 project." |
| Alexander M.R. Bakker, "The Robustness of the Climate Modelling Paradigm," Ph.D. thesis (Jan. 8, 2015), available at http://dare.ubvu.vu.nl/handle/1871/52184. | Climate models are simply not credible tools, despite their hegemony in policymaking and science. |
| Paul Ballonoff, "A Fresh Look at Climate Change," 34 Cato Journal 113 (Feb. 24, 2014), available at http://object.cato.org/sites/cato.org/files/serials/files/cato-journal/2014/2/v34n1-6.pdf. | The author synthesizes scientific findings, underscoring the important qualification that models are not the same as scientific evidence. |
| Judith Curry, "The Global Warming Statistical Meltdown," *Wall Street Journal* (Oct. 9, 2014). | Multiple studies show lower levels of climate sensitivity than that given by GCMs. |
| H. Douville, *et al.*, "The Recent Global Warming Hiatus: What is the Role of Pacific Variability?," 42 Geophys. Rsch. Letters 880 (Feb. 16, 2015). | Even a model that correctly reproduces the warming hiatus will still overestimate warming compared to observed results, and other models fare worse. |
| John C. Fyfe, *et al.*, "Overestimated Global Warming over the Past 20 Years," 3 *Nature* | Models fail to reproduce either the actual global temperatures or slowdown in the increase over |

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| *Climate Change* 767, 767 (Sep. 2013). | the past 20 years. |
| N. Lewis & J.A. Curry, "The Implications for Climate Sensitivity of AR5 Forcing and Heat Uptake Estimates," *Climate Dynamics* (Sep. 25, 2014), available at http://link.springer.com/article/10.1007%2Fs00382-014-2342-y#page-1. | A doubling of $CO_2$ would likely result in an increase in temperature of only 1.64 ºC. |
| Richard Lindzen, "Can Increasing Carbon Dioxide Cause Climate Change?," 94 Proceedings of the Nat'l Acad. of Sciences of the United States 8335 (Aug. 5, 1997), available at http://www.pnas.org/content/94/16/8335.full. | Questioning whether $CO_2$ will even have a significant effect on climate change at all compared to natural varation, especially pole-to-equator differences. |
| Richard Lindzen & Yong-Sang Choi, "On the Determination of Climate Feedbacks from ERBE Data," 36 Geophys. Rsch. Letters L16705 (2009), available at http://www.drroyspencer.com/Lindzen-and-Choi-GRL-2009.pdf. | Models consistently overestimate climate sensitivity compared to observed data. |
| Richard Lindzen, *et al.*, "Does the Earth Have An Adaptive Infrared Iris?," 82 Bull. Am. Meteorological Soc'y 417 (Mar. 2001), available at http://www-eaps.mit.edu/faculty/lindzen/adinfriris.pdf. | A cooling polar effect--that climate models do not replicate--reduces temperature increases. |
| Thorsten Mauritsen & Bjorn Stevens, "Missing Iris Effect as a Possible Cause of Muted Hydrological Change and High Climate Sensitivity in Models," __ Nature Geosci. __ (Apr. 20, 2015) (advance online publication), available at http://www.nature.com/ngeo/journal/vaop/ncurrent/full/ngeo2414.html. | Including an iris effect moves models closer to matching observations. |
| Patrick J. Michaels & Paul C. Knappenberger, "The Collection of Evidence for a Low Climate Sensitivity Continues to Grow," *Cato Institute* (Sep. 25, 2014), available at http://www.cato.org/blog/collection-evidence-low-climate-sensitivity-continues-grow. | Studies show that IPCC climate sensitivity models consistently skew high. |
| Christopher Monckton, *et al.*, "Why Climate Models Run Hot: Results from an Irreducibly Simple Climate Model," 60 Sci. Bull. 122 (2015), available at http://wmbriggs.com/public/Monckton.et.al.pdf. | The author resolves discrepancies in IPCC methodology, demonstrating that IPCC's own data, correctly interpreted and applied, shows a much lower rate of warming. |
| Bjorn Stevens, "Rethinking the Lower Bound on Aerosol Radiative Forcing," __ J. Climate __ (2015) (early online release), available at http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00656.1. | Rises in temperature cannot be attributed to radiative forcing, as models assume. |
| Xianyao Chen & Ka-Kit Tung, "Varying Planetary Heat Sink Led to Global-Warming Slowdown and Acceleration," 345 *Science* 897 (Aug. 2014), available at http://www.sciencemag.org/content/345/6199/897. | "The man-made warming of the past 20 years has been so feeble that a shifting current in one ocean was enough to wipe it out altogether." |
| Paul J. Durack, *et al.*, "Quantifying | Warming of the upper ocean in the southern |

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| Underestimates of Long-Term Upper-Ocean Warming," 4 Nature Climate Change 999 (2014). | hemisphere has been underestimated. |
| W. Llovel, *et al.*, "Deep-Ocean Contribution to Sea Level and Energy Budget Not Detectable Over the Past Decade," 4 Nature Climate Change 1031 (2014). | The "missing energy" posited by global warming theories not found in deep ocean. |
| Laepple, T. and Huybers, P. 2014b. Ocean surface temperature variability: Large model-data differences at decadal and longer periods. Proceedings of the National Academy of Sciences USA **111**: 16,682-16,687. | Study found that centennial- and millennial-scale sea surface temperature variations were two orders of magnitude larger than decadal variations (which most models work with), suggesting that the variation makes prediction extremely difficult to accomplish accurately with the tools we presently have. |
| Zhao, T., Chen, L. and Ma, Z. 2014. Simulation of historical and projected climate change in arid and semiarid areas by CMIP5 models. Chinese Science Bulletin **59**: 412-429. | CMIP5 modeling of precipitation in arid and semi-arid areas is significantly out-of-tune with observations, and has degraded from the preductions in CMIP3. |
| Xu, Z., Chang, P., Richter, I., Kim, W. and Tang, G. 2014. Diagnosing southeast tropical Atlantic SST and ocean circulation biases in the CMIP5 ensemble. Climate Dynamics **43**: 3123-3145. | CMIP5 modeling is consistently warm-biased in measuring SST in the southeast Atlantic. |
| Cheruy, F., Dufresne, J.L., Hourdin, F. and Ducharne, A. 2014. Role of clouds and land-atmosphere coupling in midlatitude continental summer warm biases and climate change amplification in CMIP5 simulations. Geophysical Research Letters **41**: 6493-6500. | The CMIP5 models are warm-biased, especially in the mid-latitudes. Because of feedback effects, those warm biases result in overall warmer-than-appropriate predictions from the models. |
| Anandhi, A. and Nanjundiah, R.S. 2015. Performance evaluation of AR4 Climate Models in simulating daily precipitation over the Indian region using skill scores. *Theoretical and Applied Climatology* **119:** 551-566 | Coupled General Circulation Models utilized as part of the Intergovernmental Panel on Climate Change's fourth assessment report failed to accurately model Indian rainfall. |
| Davy, R. and Esau, I. 2014. Global climate models' bias in surface temperature trends and variability. *Environmental Research Letters* **9**: 10.1088/1748-9326/9/11/114024 | "Assessment of the CMIP5 model biases and error, with respect to observations and reanalysis, has highlighted the relatively poor performance of these models in stably-stratified conditions." |
| Roberts, M.J., Vidale, P.L., Mizielinski, M.S., Demory, M.-E., Schiemann, R., Strachan, J., Hodges, K., Bell, R. and Camp, J. 2015. Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *Journal of Climate* **28**: 574-596 | Coupled Model Intercomparison Project (CMIP5)-class models generally fall short of being able to provide information on local space and time scales. |
| Bao, Y., Gao, Y., Lu, S., Wang, Q., Zhang, S., Xu, J., Li, R., Li, S., Ma, D., Meng, X., Chen, H. and Chang, Y. 2014. Evaluation of CMIP5 earth system models in reproducing leaf area index and vegetation cover over the Tibetan Plateau.*Journal of Meteorological Research* **28**: 1041-1060 | Models perform poorly in reporoducing mean value of observed leaf area index and net primary production. |
| Mehrotra, R, Sharma, A., Bari, M., Tuteja, N. and Amirthanathan, G. 2014. An assessment of CMIP5 multi-model decadal hindcasts over | CMIP5 models fail to account for rainfall across Australia. |

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| Australia from a hydrological viewpoint. *Journal of Hydrology* **519**: 2932-2951. | |
| Wang, G., Dommenget, D. and Frauen, C. 2015. An evaluation of the CMIP3 and CMIP5 simulations in their skill of simulating the spatial structure of SST variability. Climate Dynamics 44: 95-114 | CMIP models fail to simulate natural internal spatial structure of sea surface temperature variability in all major ocean basins. |
| Su, T., Xue, F., Sun, H. and Zhou, G. 2015. The El Niño-Southern Oscillation cycle simulated by the climate system model of the Chinese Academy of Sciences. *Acta Oceanologica Sinica* **34**: 55-65 | Climate system model of the Chinese Academy of Sciences fails to properly account for El Niño-Southern Oscillation cycle. |
| Flannaghan, T.J., Fueglistaler, S., Held, I.M., Po-Chedley, S., Wyman, B. and Zhao, M. 2014. Tropical temperature trends in Atmospheric General Circulation Model [AGCM] simulations and the impact of uncertainties in observed SSTs.*Journal of Geophysical Research: Atmospheres* **119**: 13,327-13,337. | Researchers considering sea surface temperatures note that some models are better than others, some overestimating warming. The researchers conclude that "systematic uncertainties in SSTs need to be resolved before the fidelity of climate models' tropical temperature trend profiles can be assessed." |
| Sanap, S.D., Ayantika, D.C., Pandithurai, G. and Niranjan, K. 2014. Assessment of the aerosol distribution over Indian subcontinent in CMIP5 models. *Atmospheric Environment* **87**: 123-137. | Researchers considering aerosols, which "can have significant impact on regional climate through changes in radiative budget and modifications in precipitation processes, cloud properties and dynamical state of the atmosphere," examined aerosol distributions over the Indian subcontinent "as represented in 21 models from Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations, wherein model-simulated aerosol optical depth (AOD) is compared with Moderate Resolution Imaging Spectro-radiometer (MODIS) satellite observations," with the overall objective of determining the models' abilities to capture the spatial and temporal distributions of different aerosol species over the Indian subcontinent. The researchers found that "most of the CMIP5 models were unable to simulate the aerosol distribution correctly over the Indian subcontinent." |
| Kociuba, G. and Power, S.B. 2015. Inability of CMIP5 models to simulate recent strengthening of the Walker Circulation: Implications for projections. *Journal of Climate* **28**: 20-35. | Researchers examined the Earth's Walker Circulation (WC) and evaluated how well it is replicated by CMIP5 climate models between 1980 and 2012. The models showed a weakening of the WC whereas observational data showed the opposite. The researchers found that in light of the fact that "the reasons for the inconsistency between modeled and observed trends in the last three decades are not fully understood," "confidence in the model projections is reduced." |
| Parker, A. 2014. Present contributions to sea level rise by thermal expansion and ice melting and implications on coastal management. *Ocean & Coastal* | A researcher examined ARGO (Array for Realtime Geostrophic Oceanography) data that are available for the last decade but do not yet cover the deepest ocean layers (below 2000 |

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| *Management* **98**: 202-211. | m) that contain half of the world's ocean waters, as well as areas poleward of 60°N and 60°S latitudes, and writes that "there is basically no significant warming or change of salinity within the accuracy limits of the measurements," leading him to contend that "the lack of any significant difference in the spatial distribution in latitude, longitude and depth from one year to another year shows that the theoretically proposed increased heat is missing." Additionally, the researcher found that the ocean temperature changes derived from models "are in striking contrast with the measurements by ARGO." Additionally, the researcher found that according to real-world measurements, "sea levels have not risen by the thermal expansion effect or the melting of ice," and "true measurements conflict with theoretically derived ocean temperatures and sea level changes" of the models. |
| Nowack, P.J., Abraham, N.L., Maycock, A.C., Braesicke, P., Gregory, J.M., Joshi, M.M. Osprey, A. and Pyle, J.A. 2015. A large ozone-circulation feedback and its implications for global warming assessments. Nature Climate Change **5**: 41-45. | Most GCMs leave out simulating ozone behavior because it is computationally expensive. This article demonstrates that ozone is a necessary component for accuracy and substantially counteracts the negative effects of rising $CO_2$ concentrations. |
| Davy, R. and Esau, I. 2014. Global climate models' bias in surface temperature trends and variability. Environmental Research Letters **9**: 10.1088/1748-9326/9/11/114024. | CMIP5 models consistently overestimate surface air temperature, especially in stably stratified air boundary layers. |
| Previdi, M. and Polvani, L.M. 2014. Climate system response to stratospheric ozone depletion and recovery. Quarterly Journal of the Royal Meteorological Society **140**: 2401-2419. | Ozone recovery since 1987 is a critical and undermeasured factor that could "cancel the impacts of increasing greenhouse gases during the next half-century." |
| Saha, A., Ghosh, S., Sahana, A.S. and Rao, E.P. 2014. Failure of CMIP5 climate models in simulating post-1950 decreasing trend of Indian monsoon. *Geophysical Research Letters* **41**: 7323-7330. | Scientists found that the CIMP5 framework in climatology fails to "simulate the post-1950 decreasing trend of the ISMR" (Indian Summer Monsoon Rainfall) because these models fail to capture the other consequences of "warming of the Southern Indian Ocean and strengthening of cyclonic formation in the tropical Pacific Ocean" which has helped weaken monsoons in India. The key consequence to this research is that "using CMIP5 multi-model projections of ISMR for adaptation planning may lead to incorrect policies" |
| Ji, D., Wang, L., Feng, J., Wu, Q., Cheng, H., Zhang, Q., Yang, J., Dong, W., Dai, Y.., Gong, D., Zhang, R.-H., Wang, X., Liu, J., Moore, J.C., Chen, D. and Zhou, M. 2014. Description and basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1. *Geoscientific Model Development* **7**: 2039-2064. | Sixteen scientists challenged the BNU-ESM model in climatology, which "is being actively used by many researchers in prognostic simulations for both anthropogenic and geo-engineering forcing scenarios." Their research concluded that the model falls prey to "important biases with regard to observations" such as warm Sea Surface Temperature "discrepancies in the major upwelling regions," |

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| | "equatorward drift of mid-latitude westerly wind bands," and "tropical precipitation bias over the ocean." These findings prove significant failures in the BNU-ESM model to warrant further reexamination. |

| **III. The Manufactured "Consensus" Regarding Climate Science is Incorrect, Oversimplified, and Overstated** | |
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| Robert Carter, *et al.*, *The Small Print: What The Royal Society Left Out* (Global Warming Policy Foundation March 2015), available at http://www.thegwpf.org/content/uploads/2015/03/Shortguide.pdf. | The scientific "consensus" regarding climate change is incorrect and overstated. |
| J.A. Curry & P.J. Webster, "Climate Science and the Uncertainty Monster," 92 Bull. Am. Meteorological Soc. 1667 (2011), available at http://journals.ametsoc.org/doi/pdf/10.1175/2011BAMS3139.1. | Climate science has been fatally oversimplified. |
| Jason Scott Johnston, "Global Warming Advocacy: A Cross-Examination," Institute for Law and Economics Research Paper No. 10-08 (May 2010), available at http://ssrn.com/abstract=1612851. | The discrepancies between observed reality and "consensus" climate science lead directly to suboptimal policy choices. |
| Steven Koonin, *Climate Science is Not Settled*, Wall St. J., (Sep. 19, 2014), online at http://online.wsj.com/articles/climate-science-is-not-settled-1411143565. | Koonin, a former Obama administration official, writes that "[t]he idea that 'Climate science is settled' runs through today's popular and policy discussion. Unfortunately, that claim is misguided. It has not only distorted our public and policy debates on issues related to energy, greenhouse-gas emission and the environment. But is has inhibited the scientific and policy discussions that we need about our climate future." |
| Eija-Riitta Korhola, "The Rise and Fall of the Kyoto Protocol: Climate Change as a Political Process," Ph.D. dissertation (2014), available at https://helda.helsinki.fi/bitstream/handle/10138/136507/Therisea.pdf?sequence=1. | The climate change political process has become a salvific narrative that purports to locate all of the world's problems in anthropogenic warming then to resolve them. |
| Richard Lindzen, "Global Warming: The Origin and Nature of the Alleged Scientific Consensus," 15 CATO Review of Business & Government 89 (Spring 1992), available at http://object.cato.org/sites/cato.org/files/serials/files/regulation/1992/4/v15n2-9.pdf. | The scientific "consensus" is incorrect, and governmental instability is a greater threat than climate change. |
| Patrick J. Michaels & Paul C. Knappenberger, "What the New IPCC Global Warming Projections Should Have Looked Like," *Cato Institute* (Oct. 4, 2013), available at: http://www.cato.org/blog/what-ipcc-global-warming-projections-should-have-looked. | The authors adjust IPCC's projections to coincide with observed temperature trendlines rather than overheated models--finding drastically lower impacts. |
| Steve Rayner & Gwyn Prins, *The Wrong Trousers: Radically Rethinking Climate Policy* (Inst. for Science, Innovation and Society 2007). | The Kyoto Protocol locked policymakers into a dead-end set of policy choices by misdiagnosing the climate change problem as bounded and defined. |

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| Roy Spencer, "2014 as the Mildest Year: Why You are Being Misled on Global Temperatures," *Roy Spencer,* (Jan. 18, 2015), available at http://www.drroyspencer.com/ 2015/01/2014-as-the-mildest-year-why-you-are-being-misled-on-globaltemperatures/. | Politics and emotion are more responsible for changes in climate urgency than facts. |
| Richard S.J. Tol, "Quantifying the Consensus on Anthropogenic Global Warming in the Literature: A Re-Analysis," 73 Energy Policy 701 (2014). | There actually is no "consensus" in the scientific literature on climate change. |
| Richard S.J. Tol, "Quantifying the Consensus on Anthropogenic Global Warming in the Literature: Rejoinder," 73 Energy Policy 709 (2014). | The author replies to criticisms of his earlier article and finds a further flaw (confirmation bias). |
| David R. Legates, Willie Soon, William M. Briggs, and Christopher Monckton, "Climate Consensus and 'Misinformation': A Rejoinder to *Agnotology, Scientific Consensus, and the Teaching and Learning of Climate Change," Science & Education*, August 2013. | The authors note that Cook contended that 97.1 percent of the reviewed abstracts conclude humans are causing global warming. But, since most researchers agree that there is at least a very small effect, this statement means nothing. Cook also made the mistake of including in his 97 percent papers by well-known skeptical scientists who do not support the AGW theory. They conducted a recount of Cook's data that determined that only 64, or 0.5 percent, of 11,944 papers published since 1991 endorse the standard definition of consensus: That most warming since 1950 is anthropogenic. |
| [1]Jose Duarte, "Cooking Stove Use, Housing Associations, White Males, and the 97%," August 28, 2914, www.joseduarte.com/blog/ cooking-stove-use-housing-associations-white-males-and-the-97. | Duarte noted that the Cook paper included numerous psychology studies, marketing papers, and surveys of the general public as scientific endorsement of anthropogenic climate change – which invalidates Cook's research. Duarte finds that Cook's paper is not credible as a scientific product, given that it included psychology papers, and also given that it twice misrepresented its method (claiming not to count social science papers, and claiming to use independent raters), and the admitted cheating by some of the raters. It was essentially voided by its invalid method of using partisan and unqualified political activists to subjectively rate climate science abstracts on the issue on which their activism centers – which is inexcusable. Duarte concluded that "This paper is vacated. It doesn't represent knowledge of the consensus." |
| Joseph Bast and Roy Spencer, "The Myth of the Climate Change '97%,'" *Wall Street Journal*, May 26, 2014. | Another widely cited source for the consensus view is a 2009 article by Zimmerman and Doran that reported the results of a two-question online survey of selected scientists and claimed "97 percent of climate scientists agree" that global temperatures have risen and that humans are a significant contributing factor. However, Bast and Spencer note that the survey's questions do not reveal much of |



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| | interest. Most scientists who are skeptical of catastrophic global warming would nevertheless answer "yes" to both questions. The survey did not ask whether the human impact is large enough to constitute a problem. Nor did it include solar scientists, space scientists, cosmologists, physicists, meteorologists, or astronomers, who are the scientists most likely to be aware of natural causes of climate change. |
| Global Warming Petition Project," Oregon Institute of Science and Medicine, www.petitionproject.org. | With respect to "consensus," since 1998, more than 31,000 American scientists, including more than 9,000 with PhDs, have signed a public petition which states that there is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gases is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate. The Global Warming Petition Project, also known as the Oregon Petition, is a petition urging the U.S. government to reject the global warming Kyoto Protocol of 1997 and similar policies. It was organized and circulated by Arthur Robinson, president of the Oregon Institute of Science and Medicine in 1998, and again in 2007. Past National Academy of Sciences president Frederick Seitz wrote a cover letter endorsing the petition. |
| Hans von Storch, "A Survey of Climate Scientists Concerning Climate Science and Climate Change," 2010, www.academia.edu/2365610/A_Survey_of_Climate_Scientists_Concerning_Climate_Science _ and _ Climate Change. | This 2008 international survey of climate scientists conducted by German scientists Dennis Bray and Hans von Storch revealed deep disagreement regarding two-thirds of the 54 questions asked about their professional views. Responses to about half of those areas were skewed on the "skeptic" side, with no consensus to support any alarm. The majority did not believe that atmospheric models can deal with important influences of clouds, precipitation, atmospheric convection, ocean convection, or turbulence. Most also did not believe that climate models can predict precipitation, sea level rise, extreme weather events, or temperature values for the next 50 years. |
| Edward Maibach, *a National Survey of Television Meteorologists About Climate Change: Preliminary Findings*, Center for Climate Change Communication, George Mason University, March 29, 2010. | A 2010 survey of media broadcast meteorologists conducted by the George Mason University Center for Climate Change Communication found that 63 percent of 571 who responded believe global warming is mostly caused by natural, not human, causes. Those polled included members of the American Meteorological Society and the National Weather Association. |
| E. Maibach, N. Stenhouse, S. Cobb, R. Ban, A. Bleistein, et al., American Meteorological | A 2012 survey published by the American Meteorological Society found that only one in |

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| Society Member Survey on Global Warming: Preliminary Findings. Fairfax, VA: Center for Climate Change Communication. 2012. | four respondents agreed with UN IPCC claims that humans are primarily responsible for recent warming. And while 89 percent believe that global warming is occurring, only 30 percent said they were very worried. |
| "Causes of Climate Change Varied: Poll," *Edmonton Journal*, March 6, 2008. | A March 2008 canvas of 51,000 Canadian scientists with the Association of Professional Engineers, Geologists and Geophysics of Alberta (APEGGA) found that although 99 percent of 1,077 replies believe climate is changing, 68 percent disagreed with the statement that "…the debate on the scientific causes of recent climate change is settled." Only 26 percent of them attributed global warming to "human activity like burning fossil fuels." Regarding these results, APEGGA's executive director, Neil Windsor, commented, "We're not surprised at all. There is no clear consensus of scientists that we know of." |
| http://www.aktualnosci.pan.pl/images/stories/pliki/stanowiska_opinie/2008/stanowisko_pan_131207.pdf. | A 2009 report issued by the Polish Academy of Sciences PAN Committee of Geological Sciences, a major scientific institution in the EU, found that the purported climate consensus argument is becoming increasingly untenable. It states, in part, that: "Over the past 400,000 years – even without human intervention – the level of $CO_2$ in the air, based on the Antarctic ice cores, has already been similar four times, and even higher than the current value. At the end of the last ice age, within a time interval of a few hundred years, the average annual temperature changed over the globe several times. In total, it has gone up by almost 10° C in the northern hemisphere, and therefore the changes mentioned above were incomparably more dramatic than the changes reported today." The report concludes "The PAN Committee of Geological Sciences believes it necessary to start an interdisciplinary research based on comprehensive monitoring and modeling of the impact of other factors – not just the level of $CO_2$ – on the climate. Only this kind of approach will bring us closer to identifying the causes of climate change." |
| Judith Curry, Climate Change: No Consensus on Consensus," October 28, 2012, http://judithcurry.com/ 2012/10/28/climate-change-no-consensus-on-consensus/. | Curry concludes that "The manufactured consensus of the IPCC has had the unintended consequences of distorting the science, elevating the voices of scientists that dispute the consensus, and motivating actions by the consensus scientists and their supporters that have diminished the public's trust in the IPCC. Research from the field of science and technology studies are finding that manufacturing a consensus in the context of the IPCC has acted to hyper-politicize the |

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| | scientific and policy debates, to the detriment of both. Arguments are increasingly being made to abandon the scientific consensus seeking approach in favor of open debate of the arguments themselves and discussion of a broad range of policy options that stimulate local and regional solutions to the multifaceted and interrelated issues of climate change, land use, resource management, cost effective clean energy solutions, and developing technologies to expand energy access efficiently." |
| Richard Tol, "Mr. Obama, 97 Percent of Experts is a Bogus Number," May 28, 2015, http://www. foxnews.com/opinion/2015/05/28/climate-change-and-truth-mr-obama-97-percent-experts-do-not-agree-with.html. | IPCC author Richard Tol assessed the Cook paper and concluded that is an incompetent piece of research and "a treasure trove of how-not-to lessons for a graduate class on survey design and analysis." |

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| **IV. The Evidence Shows that Plants Will Flourish Under Moderately Higher $CO_2$ Conditions ("Greening"), Becoming Healthier and More Resistant to Pests and Disease** | |
| ***A. Research Shows That Moderately Increased $CO_2$ Levels are Beneficial to Plants, Resulting in Widespread "Greening," Increased Fertility, and a Healthier Biosphere*** | |
| Jiang, Z.J., Huang, X.-P. and Zhang, J.-P. 2010. Effects of $CO_2$ enrichment on photosynthesis, growth, and biochemical composition of seagrass *Thalassia hemprichii* (Ehrenb.) Aschers. *Journal of Integrative Plant Biology* **52**: 904-913 | Globally increasing $CO_2$ and ocean acidification may enhance seagrass survival in eutrophic coastal waters. |
| Peterson, A.G. and Abatzoglou, J.T. 2014. Observed changes in false springs over the contiguous United States. *Geophysical Research Letters* **41**: 2156-2162. | Any warming will lead to earlier plant blooming and decrease in "false springs," which harm budding plants. |
| Madhu, M. and Hatfield, J.L. 2013. Dynamics of plant root growth under increased atmospheric carbon dioxide. *Agronomy Journal* **105**: 657-669. | Increased $CO_2$ stimulates root growth of crop plants such as cotton and soybean. |
| Stutte, G.W., Eraso, I. and Rimando, A.M. 2008. Carbon dioxide enrichment enhances growth and flavonoid content of two *Scutellaria* species. *Journal of the American Society of Horticultural Science* **133**: 631-638. | Study of $CO_2$ effects on plants used in traditional Chinese herbal medicine showed not only increased yield but higher levels of medicinal flavonoid compounds. |
| Oliveira da Silva, C.E. and Ghini, R. 2014. Plant growth and leaf-spot severity on eucalypt at different $CO_2$ concentrations in the air. *Pesquisa Agropecuária Brasileira* **49**: 232-235. | Increasing levels of $CO_2$ not only increased robustness of eucalyptus, but also decreased the severity of known plant pathogen. |
| Saldanha, C.W., Otoni, C.G., Rocha, D.I., Cavatte, P.C., Detmann, K. da S.C.,, Tanaka, | Exposure to high $CO_2$ levels resulted in increased productivity for medicinal plant, |

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| F.A.O., Dias, L.L.C., DaMatta, F.M. and Otoni, W.C. 2014. $CO_2$-enriched atmosphere and supporting material impact the growth, morphophysiology and ultrastructure of in vitro Brazilian-ginseng [*Pfaffia glomerata* (Spreng.) Pedersen] plantlets. *Plant Cell, Tissue and Organ Culture* **118**: 87-99. | including more of the bioactive compound--to the point where it might be a commercially viable method of mass production. |
| Yu, Y., Zhang, W. and Huang, Y. 2014. Impact assessment of climate change, carbon dioxide fertilization and constant growing season on rice yields in China. *Climatic Change* **124**: 763-775. | Although rice yields are predicted to decrease at status quo $CO_2$ levels, they skyrocket if $CO_2$ fertilization is added to the model, and even more so if the growing season becomes constant. |
| Zong, Y. and Shangguan, Z. 2014. $CO_2$ enrichment improves recovery of growth and photosynthesis from drought and nitrogen stress in maize. *Pakistan Journal of Botany* **46**: 407-415. | Elevated levels of $CO_2$ helped maize plants recover more quickly from drought conditions, even when nitrogen was also restricted. |
| Marty, C. and BassiriRad, H. 2014. Seed germination and rising atmospheric $CO_2$ concentration: a meta-analysis of parental and direct effects. *New Phytologist* **202**: 401-414. | Meta-analysis of seed germination studies shows $CO_2$ enrichment for parent plants resulted in increased seed germination. |
| Baslam, M., Antolin, M.C., Gogorcena, Y., Munoz, F. and Goicoechea, N. 2014. Changes in alfalfa forage quality and stem carbohydrates induced by arbuscular mycorrhizal fungi and elevated atmospheric $CO_2$.*Annals of Applied Biology* **164**: 190-199. | $CO_2$-enriched alfalfa not only provided more and stronger leaves and stems for forage and other uses. |
| Martinez, C.A., Bianconi, M., Silva, L., Approbato, A., Lemos, M., Santos, L., Curtarelli, L., Rodrigues, A., Mello, T. and Manchon, F. 2014. Moderate warming increases PSII performance, antioxidant scavenging systems and biomass production in *Stylosanthes capitata* Vogel. *Environmental and Experimental Botany***102**: 58-67. | Important forage legume in Brazil showed stronger defense systems in response to warming. Study shows this effect may be generalizable to other plants. |
| Day, F.P., Schroeder, R.E., Stover, D.B., Brown, A.L.P., Butnor, J.R., Dilustro, J., Hungate, B.A., Dijkstra, P., Duval, B.D., Seiler, T.J., Drake, B.G. and Hinkle, C.R. 2013. The effects of 11 years of $CO_2$ enrichment on roots in a Florida scrub-oak ecosystem. New Phytologist 200: 778-787. | Day *et al.*, examining tree response to elevated $CO_2$ after fires and hurricanes, concluded that "elevated $CO_2$ may enhance root growth following disturbance and potentially speed up the recovery." |
| Temme, A.A., Cornwell, W.K., Cornelissen, J.H.C. and Aerts, R. 2013. Meta-analysis reveals profound responses of plant traits to glacial $CO_2$ levels. Ecology and Evolution 3: 4525-4535. | Wondering "whether the transition from current to higher $CO_2$ can be thought of as a continuation of the past trajectory of low to current $CO_2$ levels," Temme *et al.* "performed a meta-analysis of low $CO_2$ growth experiments on 34 studies with 54 species," quantifying "how plant traits vary at reduced $CO_2$ levels." In conclusion, they report that "on average across all species," a 50% reduction in current atmospheric $CO_2$ reduced net photosynthesis by 38%, intrinsic water use efficiency by 48% and total plant dry biomass by 47%. |

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| Muldowney, J., Mounsey, J. and Kinsella, L. 2013. Agriculture in the climate change negotiations; ensuring that food production is not threatened. Animal 7:s2: 206-211. | $CO_2$ enrichment and the consequent greening effect may be the only way to produce sufficient food for booming populations. |
| Li, Z., Lin, J., Zhang, T., Zhang, N., Mu, C. and Wang, J. 2014. Effects of summer nocturnal warming on biomass production of Leymus chinensis in the Songnen Grassland of China: From bud bank and photosynthetic compensation. Journal of Agronomy and Crop Science 200: 66-76. | In the concluding words of Li *et al.* in their paper's abstract, "these findings show that nocturnal warming in this ecosystem improves individual biomass accumulation due to photosynthetic compensation, and may enhance the population density and productivity of L. chinensis by increasing bud number in the below-ground bud bank during the early stage of ecological succession for grasslands dominated by L. chinensis." |
| Ushio, A., Hara, H. and Fukuta, N. 2013. Promotive effect of $CO_2$ enrichment on plant growth and flowering of Eustoma grandiflorum (Raf.) Shinn, under a winter culture regime. Journal of the Japanese Society of Horticultural Science: 10.2503/jjshs 1.CH-040. | Ushio *et al.* state that "the $CO_2$ enrichment of Eustoma not only improves the quality of cut flowers but also shortens the period to harvest during winter." And that such results are not unusual, they say that "an increase in the total number of flower buds and open flowers after $CO_2$ enrichment has been reported for many other plants, including chrysanthemum (Mortensen, 1986), rose (Mortensen, 1987, 1995), and dianthus (Mortensen, 1987)." |
| Wilcox, J. and Makowski, D. 2014. A meta-analysis of the predicted effects of climate change on wheat yields using simulation studies. Field Crops Research 156: 180-190. | Wilcox and Makowski "performed a literature search to compile peer-reviewed journal articles describing the response of wheat to climate change simulated using computer models." And in doing so, they say that "90 articles were found with yield data suitable for the meta-analysis." The two French researchers ultimately determined that "more than 50% of the simulated relative yield change resulted in yield losses when mean temperature change is higher than 2.3°C, or mean precipitation change is null or less, or when $CO_2$ concentration is lower than 395 ppm." However, their results showed that, on average, "the effects of high $CO_2$ concentrations (>640 ppm) outweighed the effects of increasing temperature (up to +2°C) and moderate declines in precipitation (up to -20%), leading to increasing yields." Wilcox and Makowski conclude that their results "provide an overall positive outlook for the future of wheat production." |
| Sershen, Perumal, A., Varghese, B., Govender, P., Ramdhani, S. and Berjak, P. 2014. Effects of elevated temperatures on germination and subsequent seedling vigor in recalcitrant Trichilia emetica seeds. South African Journal of Botany90: 153-162. | The researchers conclude that "elevated temperatures may improve the ability of T. emetica to compete with neighboring species during the seedling establishment phase, by enhancing seedling growth rates, leaf area, and biomass allocation to aerial parts of the plants." |
| Norikane, A., Teixeira da Silva, J.A. and Tanaka, M. 2013. Growth of *in vitro Oncidesa* | Super-elevated $CO_2$ enrichment and cold-cathode fluorescent lamp produced extremely |

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| plantlets cultured under cold cathode fluorescent lamps with super-elevated $CO_2$ enrichment. *AoB Plants* **5**: 10.1093/aobpla/plt044. | high growth rates and plant robustness for commercially useful species. |
| Naudts, K., Van den Berge, J., Farfan, E., Rose, P., AbdElgawad, H., Ceulemans, R., Janssens, I.A., Asard, H. and Nijs, I. 2014. Future climate alleviates stress impact on grassland productivity through altered antioxidant capacity. *Environmental and Experimental Botany* **99**: 150-158. | Plants exposed to warmer, $CO_2$-enriched conditions were better able to handle common stressors (drought, zinc toxicity, and nitrogen limitation), both alone and in combination. |
| Yang, P., Wu, W., Li, Z., Yu, Q., Inatsu, M., Liu, Z., Tang, P., Zha, Y., Kimoto, M. and Tang, H. 2014. Simulated impact of elevated $CO_2$, temperature, and precipitation on the winter wheat yield in North China Plain. *Regional Environmental Change* **14**: 61-74. | Increased $CO_2$ and temperature greatly increase yields of Chinese winter wheat. |
| Keenan, T., Serra, J.M., Lloret, F., Ninyerola, M. and Sabate, S. 2011. Predicting the future of forests in the Mediterranean under climate change, with niche- and process-based models: $CO_2$ matters! *Global Change Biology* **17**: 565-579. | "$CO_2$ fertilization through projected increased atmospheric $CO_2$ concentrations is shown to increase forest productivity in the mechanistic process-based model (despite increased drought stress) by up to three times that of the non-$CO_2$ fertilization scenario by the period 2050-2080, which is in stark contrast to projections of reduced habitat suitability from the niche-based models by the same period." |
| Zhao, Q., Liu, J., Khabarov, N., Obersteiner, M. and Westphal, M. 2014. Impacts of climate change on virtual water content of crops in China. *Ecological Informatics* **19**: 26-34. | The "integrated effects of precipitation, temperature and $CO_2$ concentration changes will benefit agricultural productivity and crop water productivity through all the future periods till the end of the century." Indeed, the study concludes that "climate change is likely to benefit food security and help alleviate water scarcity in China." |
| Kumari, S., and Agrawal, M. 2014. Growth, yield and quality attributes of a tropical potato variety (*Solanum tuberosum* L. cv. Kufri chandramukhi) under ambient and elevated carbon dioxide and ozone and their interactions. *Ecotoxicology and Environmental Safety* **101**: 146-156. | $CO_2$-induced changes in potato crops showed generally higher quality (resistance to black spots, greater biomass, and lower amounts of acrylamide when fried). |
| Zhang, Z., Liu, L., Zhang, M., Zhang, Y. and Wang, Q. 2014. Effect of carbon dioxide enrichment on health-promoting compounds and organoleptic properties of tomato fruits grown in greenhouse. *Food Chemistry***153**: 157-163. | $CO_2$-enriched greenhouse tomatoes produced superior fruit on multiple axes, including consumer-appealing qualities such as health and tastiness. |
| Nabity, P.D., Hillstrom, M.L., Lindroth, R.L. and DeLucia, E.H. Elevated $CO_2$ interacts with herbivory to alter chlorophyll fluorescence and leaf temperature in *Betula papyrifera* and *Populus tremuloides*. *Oecologia* **169**: 905-913. | Plants under enriched $CO_2$ conditions are better able to withstand being eaten by herbivores, repairing damage without dying. |
| Phillips, R.P., Meier, I.C., Bernhardt, E.S., Grandy, A.S., Wickings, K. and Finzi, A.C. | $CO_2$-enriched growing environment enhanced nitrogen availability, which the plants required |

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| 2012. Roots and fungi accelerate carbon and nitrogen cycling in forests exposed to elevated $CO_2$. *Ecology Letters* **15**: 1042-1049. | for robust growth. |
| Bunce, J.A. 2012. Responses of cotton and wheat photosynthesis and growth to cyclic variation in carbon dioxide concentration. *Photosynthetica* **50**: 395-400. | Previous experiments on $CO_2$-enriched growing environments used fluctuating $CO_2$ levels rather than constant, resulting in an underestimation of growth potential. |
| Gwynn-Jones, D., Jones, A.G., Waterhouse, A., Winters, A., Comont, D., Scullion, J., Gardias, R., Graee, B.J., Lee, J.A. and Callaghan, T.V. 2012. Enhanced UV-B and elevated $CO_2$ impacts sub-Arctic shrub berry abundance, quality and seed germination. *Ambio* **41** (Supplement 3): 256-268. | Higher $CO_2$ concentrations resulted in increased quantities of multiple nutrients (antioxidants) in alpine berries. Because high-antioxidant berries were preferred by birds, they would be spread more widely, suggesting a survival advantage. |
| Song, N., Zhang, X., Wang, F., Zhang, C. and Tang, S. 2012. Elevated $CO_2$ increases Cs uptake and alters microbial communities and biomass in the rhizosphere of *Phytolacca americana* Linn (pokeweed) and*Amaranthus cruentus* L. (purple amaranth) grown on soils spiked with various levels of Cs. *Journal of Environmental Radioactivity* **112**: 29-37. | High $CO_2$ levels increased the ability of pokeweed and purple amaranth to take up radioactive cesium isotopes, suggesting a role in bioremediation of contaminated areas. |
| Wang, R., Dai, S., Tang, S., Tian, S., Song, Z., Deng, X., Ding, Y., Zou, X., Zhao, Y. and Smith, D.L. 2012. Growth, gas exchange, root morphology and cadmium uptake responses of poplars and willows grown on cadmium-contaminated soil to elevated $CO_2$. *Environmental Earth Sciences* **67**: 1-13. | Increased $CO_2$ not only increased growth rates and biomass of two species of tree, but also enhanced their ability to pull cadmium, a common industrial pollutant, out of the soil. |
| Farfan-Vignolo, E.R. and Asard, H. 2012. Effect of elevated $CO_2$ and temperature on the oxidative stress response to drought in *Lolium perenne* L. and *Medicago sativa* L. *Plant Physiology and Biochemistry* **59**: 55-62. | Increased $CO_2$ buffered grassland plants against oxidative stress from drought, enhancing both the quality (low oxidative stress damage) and quantity of grasses compared to drought under ambient conditions. |
| Vanuytrecht, E., Raes, D., Willems, P. and Geerts, S. 2012. Quantifying field-scale effects of elevated carbon dioxide concentration on crops. *Climate Research* **54**: 35-47. | Consistently elevated $CO_2$ provided markedly greater benefits (compared to higher-but-fluctuating levels) for field-wide studies of major crops such as wheat, rice, and cotton. |
| Tian, Y., Chen, J., Chen, C., Deng, A., Song, Z., Zheng, C., Hoogmoed, W. and Zhang, W. 2012. Warming impacts on winter wheat phenophase and grain yield under field conditions in Yangtze Delta Plain, China. *Field Crops Research* **134**: 193-199. | Higher temperatures caused shorter growing cycle in winter wheat crops in Yangtze River valley, which in turn led to higher yields. |
| Dieleman, W.I.J., Vicca, S., Dijkstra, F.A., Hagedorn, F., Hovenden, M.I., Larsen, K., Morgan, J.A., Volder, A., Beier, C., Dukes, J.S., King, J., Leuzinger, S., Linder, S., Luo, Y., Oren, R., de Angelis, P., Tingey, D., Hoosbeek, M.R. and Janssens, I.A. 2012. Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of $CO_2$ and temperature. *Global Change Biology* **18**: | When elevated $CO_2$ and temperature are tested together, the added levels of $CO_2$ offset negative effects such as declining nitrogen availability. |

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| 2681-2693. | |
| Polley, H.W., Jin, V.L. and Fay, P.A. 2012. Feedback from plant species change amplifies $CO_2$ enhancement of grassland productivity. *Global Change Biology* **18**: 2813-2823. | Elevated $CO_2$ not only enhanced productivity of grassland, but also created species shifts that multiplied the effect through feedback mechanism. |
| Lam, S.K., Chen, D., Norton, R., Armstrong, R. and Mosier, A.R. 2012. Nitrogen dynamics in grain crop and legume pasture systems under elevated atmospheric carbon dioxide concentration: A meta-analysis. *Global Change Biology* **18**: 2853-2859. | Higher $CO_2$ levels helped legumes fix more nitrogen, which in turn helped sustain grain crops also raised in high-$CO_2$ environments. |
| Ameye, M., Wertin, T.M., Bauweraerts, I., McGuire, M.A., Teskey, R.O. and Steppe, K. 2012. The effect of induced heat waves on *Pinus taeda* and *Quercus rubra* seedlings in ambient and elevated $CO_2$ atmospheres. *New Phytologist* **196**: 448-461. | Only the worst (+ 12 C) heatwaves showed negative effects on tree photosynthesis, and even that leveled off after a short time. Moreover, higher $CO_2$ levels mitigated the negative effects even further. |
| Huang, L., Ren, Q., Sun, Y., Ye, L., Cao, H. and Ge, F. 2012. Lower incidence and severity of tomato virus in elevated $CO_2$ is accompanied by modulated plant induced defense in tomato. *Plant Biology* **14**: 905-913. | Elevated levels of $CO_2$ resulted in lower incidence of tomato yellow leaf curl virus, a major tomato pathogen. At the same time, plant height and aboveground biomass increased. |
| Roy, K.S., Bhattacharyya, P., Neogi, S., Rao, K.S. and Adhya, T.K. 2012. Combined effect of elevated $CO_2$ and temperature on dry matter production, net assimilation rate, C and N allocations in tropical rice (*Oryza sativa* L.). *Field Crops Research* **139**: 71-79. | Across several axes of health, rice plants exposed to both $CO_2$ and elevated temperature proved to be more productive and healthier than plants not so exposed. |
| Reineke, A. and Hauck, M. 2012. Larval development of *Empoasca vitis* and *Edwardsiana rosae* (Homoptera: Cicadellidae) at different temperatures on grapevine leaves. *Journal of Applied Entomology* **136**: 656-664. | Contrary to assumption that resurgence in grapeleaf pest was due to climate change, research shows that the pest larvae do not develop at all during warmer night and moderately warm days. |
| Han, J.-H., Cho, J.G., Son, I.-C., Kim, S.H., Lee, I.-B., Choi, I.M. and Kim, D. 2012. Effects of elevated carbon dioxide and temperature on photosynthesis and fruit characteristics of 'Niitaka' pear (*Pyrus pyrifolia* Nakai). *Horticulture, Environment and Biotechnology* **53**: 357-361. | Pear trees treated with elevated levels of $CO_2$ showed better growth, larger biomass, and overall increased fruit size and quality compared to normal levels. |
| Parn, H. 2012. Changes in the radial growth of two consecutive generations of Scots pine (*Pinys sylvestris* L.) stands. *Baltic Forestry* **18**: 12-24. | Newer trees showed more robust growth compared to older trees at the same cambial age, due to rising $CO_2$ levels. |
| Cho, K., Falloon, P., Gornall, J., Betts, R. and Clark, R. 2012. Winter wheat yields in the UK: uncertainties in climate and management impacts. *Climate Research* **54**: 49-68. | Using pessimistic climate change predictions, researchers showed that warming would have thoroughly positive effects on winter wheat growth in the United Kingdom. |
| Smith, A.R., Lukac, M., Bambrick, M., Miglietta, F. and Godbold, D.L. 2013. Tree species diversity interacts with elevated $CO_2$ to induce a greater root system response. *Global Change Biology* **19**: 217-228. | $CO_2$ exposure increased fine root biomass by 31%, and 68% in polyculture samples. |
| Lin, D., Xia, J. and Wan, S. 2010. Climate warming and biomass accumulation of | Warming generally increases terrestrial plant biomass, indicating enhanced terrestrial |

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| terrestrial plants: a meta-analysis. *New Phytologist* **188**: 187-198. | carbon uptake via plant growth and net primary productivity. |
| Ghannoum, O., Phillips, N.G., Sears, M.A., Logan, B.A., Lewis, J.D., Conroy, J.P. and Tissue, D.T. 2010b. Photosynthetic responses of two eucalypts to industrial-age changes in atmospheric [$CO_2$] and temperature. *Plant, Cell and Environment* **33**: 1671-1681. | Increased $CO_2$ concentration and temperature increases expected photosynthesis in eucalypt seedlings. |
| Mateos-Naranjo, E., Redondo-Gomez, S. Andrades-Moreno, L. and Davy, A.J. 2010. Growth and photosynthetic responses of the cordgrass *Spartina maritima* to $CO_2$ enrichment and salinity. *Chemosphere* **81**: 725-731. | Increasing $CO_2$ increases the growth of seagrass *spartina maritime*. |
| Qaderi, M.M., Kurepin, L.V. and Reid, D.M. 2006. Growth and physiological responses of canola (*Brassica napus*) to three components of global climate change: temperature, carbon dioxide and drought. *Physiologia Plantarum* **128**: 710-721. | Atmospheric $CO_2$ enrichment reverses the plant-growth-impeding consequences of drought stress. |
| Vanaja, M., Reddy, P.R.R., Lakshmi, N.J., Razak, S.K.A., Vagheera, P., Archana, G., Yadav, S.K., Maheswari, M. and Venkateswarlu, B. 2010. Response of seed yield and its components of red gram (*Cajanus cajan* L. Millsp.) to elevated $CO_2$. *Plant, Soil and Environment* **56**: 458-462. | Pigeon pea production in India is aided by increased $CO_2$ levels. |
| Ghasemzadeh, A., Jaafar, H.Z.E. and Rahmat, A. 2010. Elevated carbon dioxide increases contents of flavonoids and phenolic compounds, and antioxidant activities in Malaysian young ginger (*Zingiber officinale* Roscoe.) varieties. *Molecules* **15**: 7907-7922. | "The yield and pharmaceutical quality of Malaysian young ginger varieties can be enhanced by controlled environment production and $CO_2$ enrichment." |
| Brienen, R.J.W., Wanek, W. and Hietz, P. 2011. Stable carbon isotopes in tree rings indicate improved water use efficiency and drought responses of a tropical dry forest tree species. *Trees* **25**: 103-113. | Dry-forest tropical *M. acantholoba* trees "responded strongly to the increase in atmospheric $CO_2$ over the last four decades." |
| Zeng, Q., Liu, B., Gilna, B., Zhang, Y., Zhu, C., Ma, H., Pang, J., Chen, G. and Zhu, J. 2011. Elevated $CO_2$ effects on nutrient competition between a C3 crop (*Oryza sativa* L.) and a C4 weed (*Echinochloa crusgalli* L.). *Nutrient Cycling in Agroecosystems* **89**: 93-104. | "Rising atmospheric $CO_2$ concentration could alter the competition between rice and barnyard grass in paddy fields in favor of rice." |
| Chun, J.A., Wang, Q., Timlin, D., Fleisher, D. and Reddy, V.R. 2011. Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn. *Agricultural and Forest Meteorology* **151**: 378-384. | $CO_2$ increases soil water contents. |
| Chen, Y., Chen, Y., Xu, C. and Li, W. 2011. Photosynthesis and water use efficiency of *Populus euphratica* in response to changing groundwater depth and $CO_2$ concentration. *Environmental Earth Sciences* **62**: 119-125. | With respect to the plant water use efficiency of *Populus euphratica* trees, those growing "under a moderate drought stress display a strong responsiveness to $CO_2$ enrichment." Thus, $CO_2$ may offset the effects of natural |

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| | droughts. |
| Nakamura, I., Onoda, Y., Matsushima, N., Yokoyama, J., Kawata, M. and Hikosaka, K. 2011. Phenotypic and genetic differences in a perennial herb across a natural gradient of $CO_2$ concentration. *Oecologia* **165**: 809-818. | "Plants from higher $CO_2$ populations had an inherent potential for higher productivity." |
| Klady, R.A., Henry, G.H.R. and Lemay, V. 2011. Changes in high arctic tundra plant reproduction in response to long-term experimental warming. *Global Change Biology* **17**: 1611-1624. | Artificial warming "enhanced reproductive effort and success in most species," and the effects of warming on sexual reproduction were "more consistently positive and to a greater degree" in polar oasis vascular plant communities than in those of polar semi-deserts." |
| Schubert, B.A. and Jahren, A.H. 2011. Fertilization trajectory of the root crop *Raphanus sativus* across atmospheric $pCO_2$ estimates of the next 300 years. *Agriculture, Ecosystems and Environment* **140**: 174-181. | Biomass of the root crop *raphanus sativus* increased with the levels of $CO_2$ concentration. |
| Burkart, S., Manderscheid, R., Wittich, K.-P., Lopmeier, F.J. and Weigel, H.-J. Elevated $CO_2$ effects on canopy and soil water flux parameters measured using a large chamber in crops grown with free-air $CO_2$ enrichment. *Plant Biology* **13**: 258-269. | "$CO_2$-related water savings may improve crop water status and reduce the need for irrigation in Central Europe." |
| Deslippe, J.R., Hartmann, M., Mohn, W.W. and Simard, S.W. 2011. Long-term experimental manipulation of climate alters the ectomycorrhizal community of *Betula nana* in Arctic tundra. *Global Change Biology* **17**: 1625-1636. | "Warming profoundly alters nutrient cycling in tundra, and may facilitate the expansion of *B. nana* through the formation of mycorrhizal networks of larger size." |
| Robredo, A., Perez-Lopez, U., Miranda-Apodaca, J., Lacuesta, M., Mena-Petite, A. and Munoz-Rueda, A. 2011. Elevated $CO_2$ reduces the drought effect on nitrogen metabolism in barley plants during drought and subsequent recovery. *Environmental and Experimental Botany* **71**: 399-408. | "Elevated $CO_2$ mitigates many of the effects of drought on nitrogen metabolism and allows more rapid recovery following water stress." |
| Jia, Y., Tang, S.-r., Ju, X.-h., Shu, L.-n., Tu, S.-x., Feng, R.-w. and Giusti, L. 2011. Effects of elevated $CO_2$ levels on root morphological traits and Cd uptakes of two *Lolium* species under Cd stress. *Journal of Zhejiang University - SCIENCE B (Biomedicine & Beitechnology)* **12**: 313-325. | Under $CO_2$-enriched conditions, certain plants experience greater cadmium uptake, but less concentration in the plants' tissues. This finding may indicate the higher levels of $CO_2$ protect the plant. |
| Warren, J.M., Potzelsberger, E., Wullschleger, S.D., Thornton, P.E., Hasenauer, H. and Norby, R.J. 2011. Ecohydrologic impact of reduced stomatal conductance in forests exposed to elevated $CO_2$. *Ecohydrology* **4**: 196-210. | Elevated $CO_2$ could directly increase forest water balance increasing groundwater, streams, lake and rivers. |
| Robredo, A., Perez-Lopez, U., Miranda-Apodaca, J., Lacuesta, M., Mena-Petite, A. and Munoz-Rueda, A. 2011. Elevated $CO_2$ reduces the drought effect on nitrogen metabolism in barley plants during drought | Elevated $CO_2$ mitigates drought effects on nitrogen metabolism by improvement of photosynthesis and mitigation of water deficit. |

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| and subsequent recovery. *Environmental and Experimental Botany* **71**: 399-408. | |
| Rasineni, G.K., Guha, A. and Reddy, A.R. 2011. Elevated atmospheric $CO_2$ mitigated photoinhibition in a tropical tree species, *Gmelina arborea*. *Journal of Photochemistry and Photobiology B: Biology* **103**: 159-165. | Future growth in atmospheric $CO_2$ may have positive effects on photochemical efficiency in fast growing tropical tree species. |
| Polley, H.W., Fay, P.A., Jin, V.L. and Combs Jr., G.F. 2011 $CO_2$ enrichment increases element concentrations in grass mixtures by changing species abundances. *Plant Ecology* **212**: 945-957. | $CO_2$ enrichment resulted in greater concentrations of certain types of tallgrass prairie vegetation. |
| Pilegaard, K., Ibrom, A., Courtney, M.S., Hummelshoj, P. and Jensen, N.O. 2011. Increasing net $CO_2$ uptake by a Danish beech forest during the period from 1996 to 2009. *Agricultural and Forest Meteorology* **151**: 934-946. | Rising $CO_2$ results in Danish beech trees retaining actives leaves longer and the impact was generally positive. |
| Kathilankal, J.C., Mozdzer, T.J., Fuentes, J.D., McGlathery, K.J., D'Odorico, P. and Zieman, J.C. 2011. Physiological responses of *Spartina alterniflora* to varying environmental conditions in Virginia marshes. *Hydrobiologia* **669**: 167-181. | In a scenario of atmospheric warming and increased atmospheric $CO_2$ levels, *S. alterniflora* (smooth cordgrass) will likely respond positively to both changes. |
| Melillo, J.M., Butler, S., Johnson, J., Mohan, J., Steudler, P., Lux, H., Burrows, E., Bowles, F., Smith, R., Scott, L., Vario, C., Hill, T., Burton, A., Zhou, Y.-M. and Tang, J. 2011. Soil warming, carbon-nitrogen interactions, and forest carbon budgets. *Proceedings of the National Academy of Sciences USA* **108**: 9508-9512. | Forests find more nitrogen in the soils of a warming world. |
| Macinnis-Ng, C., Zeppel, M., Williams, M. and Eamus, D. 2011. Applying a SPA model to examine the impact of climate change on GPP of open woodlands and the potential for woody thickening. *Ecohydrology* **4**: 379-393. | As the air's $CO_2$ content rises, plant stomatal conductance decreases, such that water use per tree decreases and, therefore, soil water content increases, leading to increases in leaf area index that allow more light to be intercepted, enabling existing trees to grow bigger. |
| Tohidimoghadam, H.R., Ghooshchi, F. and Zahedi, H. 2011. Effect of UV radiation and elevated $CO_2$ on morphological traits, yield and yield components of canola (*Brassica napus* L.) grown under water deficit. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **39**: 213-219. | Increased UV exposure decreases plant growth and development, but $CO_2$ increases could improve yield, yield components and growth parameters for plants subjected to elevated levels of UV radiation. |
| Soule, P.T. and Knapp, P.A. 2011. Radial growth and increased water-use efficiency for ponderosa pine trees in three regions in the western United States. *The Professional Geographer* **63**: 370-391. | Increased intrinsic water use efficiency associated with rising $CO_2$ can positively impact tree growth rates in the western United States. |
| Herzschuh, U., Ni, J., Birks, H.J.B. and Bohner, J. 2011. Driving forces of mid-Holocene vegetation shifts on the upper Tibetan Plateau, with emphasis on changes in | As atmospheric $CO_2$ levels rise, we should see even further enhancement in the productivity of the Tibetan Plateau's vegetation, as well as that of similar high- |

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| atmospheric $CO_2$ concentrations. *Quaternary Science Reviews* **30**: 1907-1917. | elevation regions around the globe, which should be a significant and positive development for those parts of the planet. |
| Feng, Y., Lin, X., Zhang, J., Mao, T. and Zhu, J. 2011. Soil purple phototrophic bacterial diversity under double cropping (rice-wheat) with free-air $CO_2$ enrichment (FACE). *European Journal of Soil Science* **62**: 533-540. | Purple phototrophic bacteria respond positively to elevated $CO_2$ concentration which may indicate an enhanced microbial food chain and promote the growth and yield of crops. |
| McCalley, C.K., Strahm, B.D., Sparks, K.L., Eller, A.S.D. and Sparks, J.P. 2011. The effect of long-term exposure to elevated $CO_2$ on nitrogen gas emissions from Mojave Desert soils. *Journal of Geophysical Research* **116**: 10.1029/2011JG001667. | Long-term exposure to elevated $CO_2$ decreased reactive Nitrogen gas emissions from Mojave Desert soils. |
| Watanabe, M., Watanabe, Y., Kitaoka, S., Utsugi, H., Kita, K. and Koike, T. 2011. Growth and photosynthetic traits of hybrid larch F1 (*Larix gmelinii* var. *japonica x L. kaempferi*) under elevated $CO_2$ concentration with low nutrient availability. *Tree Physiology* **31**: 965-975. | Elevated $CO_2$ may increase the growth of hybrid larch F1 trees even under low nutrient availability. |
| Jin, C., Du, S., Wang, Y., Condon, J., Lin, X. and Zhang, Y. 2009. Carbon dioxide enrichment by composting in greenhouses and its effect on vegetable production. Journal of Plant Nutrition and Soil Science 172: 418-424. | The consequences of a slightly more than doubling of atmospheric $CO_2$ levels are: “the average percentage of yield increases of all three sites were 270%, 257%, 87%, 140% and 227% for celery, leaf lettuce, stem lettuce, oily sowthistle, and Chinese cabbage, respectively.” In addition, extra $CO_2$ from the composting units increased the concentration of vitamin C in all five species: “by 13%, 39%, 25%, 72% and 37% for celery, leaf lettuce, stem lettuce, oily sowthistle, and Chinese cabbage, respectively.” |
| Jackson, R.B., Cook, C.W., Pippen, J.S. and Palmer, S.M. 2009. Increased belowground biomass and soil $CO_2$ fluxes after a decade of carbon dioxide enrichment in a warm-temperate forest. Ecology 90: 3352-3366. | “On average, in elevated $CO_2$, fine-root biomass in the top 15 cm of soil increased by 24%,” and that in recent years the fine-root biomass increase “grew stronger, averaging ~30% at high $CO_2$,” while in terms of coarse roots having diameters greater than 2 mm and extending to a soil depth of 32 cm, they report that “biomass sampled in 2008 was “twice as great in elevated $CO_2$.” Concluding that “overall, the effect of elevated $CO_2$ belowground shows no sign of diminishing.” |
| Reich, P.B. 2009. Elevated $CO_2$ reduces losses of plant diversity caused by nitrogen deposition. Science 326: 1399-1402. | When the elevated soil N concentration was combined with the elevated atmospheric $CO_2$ concentration, however, species richness declined by only 5%, leading Reich to conclude that “elevated $CO_2$ reduces losses of plant diversity caused by nitrogen deposition.” |
| Martens, R., Heiduk, K., Pacholski, A. and Weigel, H.-J. 2009. Repeated 14 $CO_2$ pulse-labelling reveals an additional net gain of soil | “[W]heat plants grown under elevated $CO_2$ can contribute to an additional net carbon gain in soils.” |

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| carbon during growth of spring wheat under free air carbon dioxide enrichment (FACE). Soil Biology & Biochemistry 41: 2422-2429. | |
| Odland, A., Hoitomt, T. and Olsen, S.L. 2010. Increasing vascular plant richness on 13 high mountain summits in southern Norway since the early 1970s. *Arctic, Antarctic, and Alpine Research* **42**: 458-470. | Increase in vascular plant richness in 13 high mountain summits in southern Norway is attributable to climate change. |
| Moutinho-Pereira, J., Goncalves, B., Bacelar, E., Cunha, J.B., Coutinho, J. and Correia, C.M. 2009. Effects of elevated $CO_2$ on grapevine (*Vitis vinifera* L.): Physiological and yield attributes. *Vitis* **48**: 159-165. | Elevated $CO_2$ has a positive impact on photosynthetic rates of grapevine. |
| Feng, Y., Lin, X., Wang, Y., Zhang, J., Mao, T., Yin, R. and Zhu, J. 2009. Free-air $CO_2$ enrichment (FACE) enhances the biodiversity of purple phototrophic bacteria in flooded paddy soil. Plant and Soil 324: 317-328. | Real-time quantitative PCR analysis of pufM gene indicated that PPB abundance was stimulated by elevated $CO_2$ in bulk soil," and that "N fertilization enhanced the biodiversity of PPB under elevated atmospheric $CO_2$." |
| De Frenne, P., Graae, J.J., Kolb, A., Brunet, J., Chabrerie, O., Cousins, S.A.O., Decocq, G., Dhondt, R., Diekmann, M., Eriksson, O., Heinken, T., Hermy, M., Jogar, U., Saguez, R., Shevtsova, A., Stanton, S., Zindel, R., Zobel, M. and Verheyen, K. 2010. Significant effects of temperature on the reproductive output of the forest herb Anemone nemorosa L. Forest Ecology and Management 259: 809-817. | "Seed mass, germination percentage, germinable seed output and seedling mass all showed a positive response to increased GDH experienced by the parent plant." The data showed that "if climate warms, this will have a pronounced positive impact on the reproduction of A. nemorosa, especially in terms of seed mass, germination percentage and seedling mass," because "if more seeds germinate and resulting seedlings show higher fitness, more individuals may be recruited to the adult stage." |
| McCarthy, H.R., Oren, R., Johnsen, K.H., Gallet-Budynek, A., Pritchard, S.G., Cook, C.W., LaDeau, S.L., Jackson, R.B. and Finzi, A.C. 2010. Re-assessment of plant carbon dynamics at the Duke free-air $CO_2$ enrichment site: interactions of atmospheric [$CO_2$] with nitrogen and water availability over stand development. New Phytologist 185: 514-528. | McCarthy *et al.* state that "elevated $CO_2$ increased pine biomass production, starting in 1997 and continuing every year thereafter," that "the $CO_2$-induced enhancement remained fairly consistent as the stand developed," that "elevated $CO_2$ increased stand (pine plus all other species) biomass production every year from 1997 onwards with no trend over time," while noting that the average yearly increase in NPP caused by the approximate 54% increase in the air's $CO_2$ content was 28%. |
| Perez-Lopez, U., Robredo, A., Lacuesta, M., Munoz-Rueda, A. and Mena-Petite, A. 2010. Atmospheric $CO_2$ concentration influences the contributions of osmolyte accumulation and cell wall elasticity to salt tolerance in barley cultivars. Journal of Plant Physiology 167: 15-22. | The five researchers report that "elevated $CO_2$ permitted plant metabolism to be maintained at a better status under salt stress than did ambient $CO_2$," noting that "growth was reduced more at ambient than at elevated $CO_2$." They also found that "elevated $CO_2$ widens the range of salt concentrations at which osmotic adjustment continues to be efficient by providing the greater supply of carbon and ATP [Adenosine-5'-triphosphate]," which is a multifunctional nucleotide that transports chemical energy within cells for metabolism and is, in their words, "needed to perform the energetically |

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| | expensive salt tolerance mechanisms." |
| Vapaavuori, E., Holopainen, J.K., Holopainen, T., Julkunen-Titto, R., Kaakinen, S., Kasurien, A., Kontunen-Soppela, S., Kostiainen, K., Oksanen, E., Peltonen, P., Riikonen, J. and Tulva, I. 2009. Rising atmospheric $CO_2$ concentration partially masks the negative effects of elevated $O_3$ in silver birch (Betula pendula Roth). Ambio 38: 418-424. | Vapaavuori *et al.* report that, in general, the negative effects of elevated $O_3$ on the various growth parameters and properties of the trees "were mainly found in ambient $CO_2$," and that elevated $CO_2$ typically "reversed or diminished the effects of elevated $O_3$." |
| Weiss, I., Mizrahi, Y. and Raveh, E. 2010. Effect of elevated $CO_2$ on vegetative and reproductive growth characteristics of the CAM plants Hylocereus undatus and Selenicereus megalanthus. Scientia Horticulturae 123: 531-536. | Weiss *et al.* report that "H. undatus plants enriched with $CO_2$ demonstrated 52%, 22%, 18% and 175% increases, relative to plants measured in ambient $CO_2$, in total daily net $CO_2$ uptake, shoot elongation, shoot dry mass, and number of reproductive buds, respectively," while corresponding responses for S. megalanthus were 129%, 73%, 68% and 233%. In addition, they found there was a slight (7%) increase in the fruit fresh mass of H. undatus and a much greater 63% increase in the fruit fresh mass of S. megalanthus, due to the extra 620 ppm of $CO_2$ enrichment of the air in which the plants had been grown. |
| Li, J.H., Erickson, J.E., Peresta, G. and Drake, B.G. 2010. Evapotranspiration and water use efficiency in a Chesapeake Bay wetland under carbon dioxide enrichment. Global Change Biology 16: 234-245. | Rising concentrations of atmospheric $CO_2$ "could have significant impacts on the hydrologic cycles of coastal wetlands," noting that "reduced ET could increase carbon uptake by mitigating the effects of drought on carbon uptake," and "could also facilitate ground water recharge to counteract salinity intrusion in coastal areas caused by rising sea levels from global warming." |
| Anderson, L.J., Derner, J.D., Polley, H.W., Gordon, W.S., Eissenstat, D.M. and Jackson, R.B. 2010. Root responses along a subambient to elevated $CO_2$ gradient in a C3-C4 grassland. Global Change Biology 16: 454-468. | Anderson *et al.* report that based on the linear relationship they derived from all twenty of the ingrowth biomass assessments they conducted, there was "a 40% increase in the ingrowth root biomass ratio from 380 to 480 ppm as compared with a 36% increase from 280 to 380 ppm," but they say that excluding one extremely variable data point, and using a power function they fit to the data, "the contrast is even greater: a 50% increase from 380 to 480 ppm vs. a 41% increase from 280 to 380 ppm." |
| Way, D.A., LaDeau, S.L., McCarthy, H.R., Clark, J.S., Oren, R., Finzi, A.C. and Jackson, R.B. 2010. Greater seed production in elevated $CO_2$ is not accompanied by reduced seed quality in Pinus taeda L. Global Change Biology 16: 1046-1056. | "[I]ncreased production of high-quality seeds by woody species in response to rising $CO_2$ would give them a reproductive advantage over herbaceous species that produce more seeds but cannot maintain seed quality," and they opine that this phenomenon "may facilitate woody encroachment into herbaceous communities, a wide-spread phenomenon that has already been linked to rising $CO_2$." |
| Norikane, A., Takamura, T., Morokuma, M. | Relative to plants grown in vitro in ambient |

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| and Tanaka, M. 2010. In vitro growth and single-leaf photosynthetic response of Cymbidium plantlets to super-elevated $CO_2$ under cold cathode fluorescent lamps. Plant Cell Reports 29: 273-282. | air, the percentage increases in shoot and root dry weight due to enriching the air in which the plants grew by 3000 ppm $CO_2$ were, respectively, 216% and 1956% under the low light regime and 249% and 1591% under the high light regime, while corresponding increases for the plants grown in air enriched with an extra 10,000 ppm $CO_2$ were 244% and 2578% under the low light regime and 310% and 1879% under the high light regime. Similarly, in the ex vitro experiment, percentage increases in shoot and root dry weight due to enriching the air in which the plants grew by 3000 ppm $CO_2$ were, respectively, 223% and 436% under the low light regime and 279% and 469% under the high light regime, while corresponding increases for the plants grown in air enriched with an extra 10,000 ppm $CO_2$ were 271% and 537% under the low light regime and 332% and 631% under the high light regime. |
| Friend, A.D. 2010. Terrestrial plant production and climate change. Journal of Experimental Botany 61: 1293-1309. | When both climate and atmospheric $CO_2$ concentration were changed concurrently, global net primary production rose an average of 37.3%, driven by mean increases of 43.9-52.9% among C3 plants and 5.9% among C4 species. |
| Darbah, J.N.T., Kubiske, M.E., Nelson, N., Kets, K., Riikonen, J., Sober, A., Rouse, L. and Karnosky, D.F. 2010. Will photosynthetic capacity of aspen trees acclimate after long-term exposure to elevated $CO_2$ and $O_3$? Environmental Pollution 158: 983-991. | Results “suggest no long-term photosynthetic and stomatal acclimation to elevated $CO_2$, $O_3$ or $CO_2$ + $O_3$ in aspen trees exposed to elevated $CO_2$ and/or $O_3$ gases for 11 years.” And they add that the aspen trees “have sustained their maximum instantaneous photosynthesis stimulation for over a decade.” |
| Colleen Iversen of the Oak Ridge National Laboratory in Oak Ridge, Tennessee (USA) reviewed the pertinent scientific literature “to examine the potential mechanisms for, and consequences of, deeper rooting distributions under elevated $CO_2$ as they relate to ecosystem carbon and nitrogen cycling,” focusing primarily on forests. | Iversen writes that “experimental evidence from a diverse set of forested ecosystems indicates that fine roots of trees exposed to elevated $CO_2$ are distributed more deeply in the soil profile relative to trees grown under ambient $CO_2$.” In addition, she notes that “increased proliferation at depth in the soil has not been limited to fine roots: increased production of mycorrhizas (Pritchard *et al.*, 2008b) and coarse roots (Liberloo *et al.*, 2006) also occurred deeper in the soil under $CO_2$ enrichment.” |
| Jin, V.L. and Evans, R.D. 2010. Elevated $CO_2$ increases plant uptake of organic and inorganic N in the desert shrub Larrea tridentata. Oecologia 163: 257-266. | The two researchers report that “elevated $CO_2$ positively affected root uptake of N derived from all three N forms by day 10, with $NO_3$-derived N taken up at the highest rates,” and that “added glycine was taken up as intact amino acid within one hour of treatment application, indicating that L. tridentata can directly utilize soil organic sources,” while |

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| | noting that "to date, this study is the first to report organic N uptake by a plant species from a hot, arid ecosystem." |
| Bronson, D.R. and Gower, S.T. 2010. Ecosystem warming does not affect photosynthesis or aboveground autotrophic respiration for boreal black spruce. Tree Physiology 30: 441-449. | "[B]oth the older foliage, which developed before the experiment, and the new foliage, developed during the experiment, had similar rates of light-saturated net photosynthesis, foliage respiration and stem respiration across all treatments," which "underscores the ability of black spruce to maintain homeostasis in a 5°C warmer environment." Many global change models predict a doubling of respiration for every 10°C increase in temperature, but "the results from this and other whole-ecosystem warming experiments do not support this model assumption." |
| Darbah, J.N.T., Sharkey, T.D., Calfapietra, C. and Karnosky, D.F. 2010. Differential response of aspen and birch trees to heat stress under elevated carbon dioxide. Environmental Pollution 158: 1008-1014. | The findings are "in agreement with Idso and Kimball (1992), who reported that elevated $CO_2$ increased net photosynthetic rate in sour orange tree suggesting that elevated $CO_2$ ameliorates heat stress in tree leaves." In addition, they say their observations suggest "that elevated $CO_2$ ameliorated the negative effects of high temperature in three deciduous tree species," and "ameliorated high temperature stress in yellow birch trees (Betula alleghaniensis), concluding "that in the face of rising atmospheric $CO_2$ and temperature (global warming), trees will benefit from elevated $CO_2$ through increased thermotolerance." |
| McGrath, J.M., Karnosky, D.F. and Ainsworth, E.A. 2010. Spring leaf flush in aspen (Populus tremuloides) clones is altered by long-term growth at elevated carbon dioxide and elevated ozone concentration. Environmental Pollution 158: 1023-1028. | The three researchers report that the trees in the elevated $CO_2$ plots showed a 36% stimulation of leaf area index. In addition, they say that the photosynthetic operating efficiency of the $CO_2$-enriched aspen leaves was significantly enhanced by a whopping 51%. |
| Wang, X. and Taub, D.R. 2010. Interactive effects of elevated carbon dioxide and environmental stresses on root mass fraction in plants: a meta-analytical synthesis using pairwise techniques. Oecologia 163: 1-11. | The two researchers conclude that "under abiotic stresses, e.g., drought and higher $O_3$, elevated $CO_2$-grown plants will likely increase biomass allocation below-ground," where it can be used to construct more roots that can be used to acquire more water and nutrients. |
| Oliveira, V.F., Zaidan, L.B.P., Braga, M.R., Aidar, M.P.M. and Carvalho, M.A.M. 2010. Elevated $CO_2$ atmosphere promotes plant growth and inulin production in the cerrado species Vernonia herbacea. Functional Plant Biology 37: 223-231. | "[P]lants under elevated $CO_2$ presented increases in height (40%), photosynthesis (63%) and biomass of aerial (32%) and underground (47%) organs when compared with control plants." and "water use efficiency was significantly higher in treated plants, presenting a 177% increase at day 60." While concentration remained unchanged the significant $CO_2$-induced increase in underground organ biomass "a 24% increase in total fructan yield occurred." |

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| Darbah, J.N.T., Sharkey, T.D., Calfapietra, C. and Karnosky, D.F. 2010. Differential response of aspen and birch trees to heat stress under elevated carbon dioxide. Environmental Pollution 158: 1008-1014. | "[E]levated $CO_2$ protected photosynthesis of both species against moderate heat stress" by increasing "carboxylation capacity, photosynthetic electron transport capacity and triose phosphate use." In addition, they say they "observed significant increases in transpiration rates in both aspen clones and the birch trees under elevated $CO_2$." Hence, they conclude that, "in the face of rising atmospheric $CO_2$ and temperature (global warming), trees will benefit from elevated $CO_2$ through increased thermotolerance." |
| Rammig, A., Jonas, T., Zimmermann, N.E. and Rixen, C. 2010. Changes in alpine plant growth under future climate conditions. Biogeosciences 7: 2013-2024. | There were "highly significant correlations between mean air temperature in May/June and snow melt out, onset of plant growth, and plant height." Using these correlations to project plant growth under future climatic conditions they determined that (1) "melt out and onset of growth were projected to occur on average seventeen days earlier by the end of the century than in the control period from 1971-2000," and that in response to these changes (2) "plant height and biomass production were expected to increase by 77% and 45%, respectively," while in some cases, they found that (3) "projections of biomass production over a season resulted in changes of up to two-fold." |
| Alberton, O., Kuyper, T.W., Summerbell, R.C. 2010. Dark septate root endophytic fungi increase growth of Scots pine seedlings under elevated $CO_2$ through enhanced nitrogen use efficiency. Plant and Soil 328: 459-470. | Under elevated $CO_2$, shoot and root biomass increased significantly by 21% and 19%, respectively, relative to ambient, with "higher values over the final four weeks (increases of 40% and 30% for shoots and roots, respectively)." And "on average, shoot nitrogen concentration was 57% lower under elevated $CO_2$," and that "elevated $CO_2$ decreased root nitrogen concentration on average by 16%." "Surprisingly, even under reduced nitrogen availability, elevated $CO_2$ led to increases in both above-ground and below-ground plant biomass." |
| Prevost, D., Bertrand, A., Juge, C. and Chalifour, F.P. 2010. Elevated $CO_2$ induces differences in nodulation of soybean depending on bradyrhizobial strain and method of inoculation. Plant and Soil 331: 115-127. | "[E]levated $CO_2$ increased mass (+63%) and number (+50%) of soybean nodules, particularly medium and large, allowed a deeper nodule development, and increased shoot dry weight (+30%), shoot carbon uptake (+33%) and shoot nitrogen uptake (+78%), compared to ambient $CO_2$." |
| Stutte, G.W., Eraso, I. and Rimando, A.M. 2008. Carbon dioxide enrichment enhances growth and flavonoid content of two Scutellaria species. Journal of the American Society for Horticultural Science 133: 631-638. | "These results clearly demonstrate the potential to use controlled environments to increase the production and quality of Scutellaria species ... because the practice has the potential to increase the value of the product by reducing the time to harvest, increasing yield per unit area, and increasing bioactivity per gram of dry matter." |

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| Jia, Y., Tang, S., Wang, R., Ju, X., Ding, Y., Tu, S. and Smith, D.L. 2010. Effects of elevated $CO_2$ on growth, photosynthesis, elemental composition, antioxidant level, and phytochelatin concentration in Lolium mutiflorum and Lolium perenne under Cd stress. Journal of Hazardous Materials 180: 384-394. | Jia *et al.* found that elevated $CO_2$ significantly increased both net photosynthesis and plant water use efficiency, which led to increases in both shoot and root biomass at harvest. |
| Nakamura, M., Muller, O., Tayanagi, S., Nakaji, T. and Hiura, T. 2010. Experimental branch warming alters tall tree leaf phenology and acorn production. Agricultural and Forest Meteorology 150: 1026-1029. | Time of leaf flush in the spring was unaffected by warming; but they found that the growing season of canopy leaves was extended by later leaf fall, which on warmed branches occurred about 10 days later than it did on control branches. And, perhaps most impressive of all, they discovered that "when acorns were present, warmed branches had about double the number of acorns found on control branches." |
| Kelly, J.J., Bansal, A., Winkelman, J., Janus, L.R., Hell, S., Wencel, M., Belt, P., Kuehn, K.A., Rier, S.T. and Tuchman, N.C. 2010. Alteration of microbial communities colonizing leaf litter in a temperate woodland stream by growth of trees under conditions of elevated atmospheric $CO_2$. Applied and Environmental Microbiology 76: 4950-4959. | The 360-ppm $CO_2$ increase employed in their study boosted the simple phenolics concentrations of the aspen, maple and willow leaves by 16, 30 and 22%, respectively, while it boosted their condensed tannin concentrations by 60, 85 and 26%, respectively. |
| Khan, F.N., Lukac, M., Miglietta, F., Khalid, M. and Godbold, D.L. 2010. Tree exposure to elevated $CO_2$ increases availability of soil phosphorus. Pakistan Journal of Botany 42: 907-916. | The researchers' study "shows that increased tree growth under elevated $CO_2$ has not resulted in depletion of P pools in soils, but rather in replenishment and increased storage of P in the rooting zone," and that contrary to even their own expectations before beginning the experiment, "phosphorus limitation may therefore not reduce tree growth in a high $CO_2$ world." |
| McCormack, M.L., Pritchard, S.G., Breland, S., Davis, M.A., Prior, S.A., Runion, G.B., Mitchell, R.J. and Rogers, H.H. 2010. Soil fungi respond more strongly than fine roots to elevated $CO_2$ in a model regenerating longleaf pine-wiregrass ecosystem. Ecosystems 13: 901-916. | As the atmosphere's $CO_2$ content continues to rise, "greater biomass production in deeper soils in the coming decades has the potential to contribute to greater carbon storage in forest soils," since "carbon in deeper soil turns over (decomposes) more slowly than litter nearer the soil surface," and may act as a carbon sink as atmospheric $CO_2$ rises in the coming decades through increased biomass production and potentially through directed allocation of carbon to deeper soils," which is "consistent with the recent assertion that greater allocation of forest carbon to deeper soil is a general response to atmospheric $CO_2$-enrichment." |
| Bader, M.K.-F., Siegwolf, R. and Korner, C. 2010. Sustained enhancement of photosynthesis in mature deciduous forest trees after 8 years of free air $CO_2$ enrichment. Planta 232: 1115-1125. | Mean net photosynthetic rate of the upper-canopy foliage was 48% greater in the $CO_2$-enriched foliage than in the ambient-treatment foliage in July and 42% greater in September, yielding an average increase of 45% in response to the 45% increase in the |

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| | air's $CO_2$ content. The data suggest that "the enhancement of photosynthesis may persist in these mature deciduous trees under high future atmospheric $CO_2$ concentrations," "without reductions in photosynthetic capacity." |
| Lau, J.A., Shaw, R.G., Reich, P.B. and Tiffin, P. 2010. Species interactions in a changing environment: elevated $CO_2$ alters the ecological and potential evolutionary consequences of competition. Evolutionary Ecology Research 12: 435-455. | Finding that at the time of harvest, the $CO_2$-induced biomass stimulation "elevated $CO_2$ reduces the effects of competition on mean fitness ... and minimizes the strength of competition as a selective agent." |
| Sommer, R., Glazirina, M., Yuldashev, T., Otarov, A., Ibraeva, M., Martynova, L., Bekenov, M., Kholov, B., Ibragimov, N., Kobilov, R., Karaev, S., Sultonov, M., Khasanova, F., Esanbekov, M., Mavlyanov, D., Isaev, S., Abdurahimov, S., Ikramov, R., Shezdyukova, L. and de Pauw, E. 2013. Impact of climate change on wheat productivity in Central Asia. Agriculture, Ecosystems and Environment 178: 78-99. | Sommer *et al.* studied "crop growth and yield of 14 wheat varieties grown on 18 sites in key agro-ecological zones of Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan in response to CC were assessed," in a study where "three future periods affected by the two projections on CC (SRES A1B and A2) were considered and compared against historic (1961-1990) figures," and where "the impact on wheat was simulated with the CropSyst model distinguishing three levels of agronomic management." They conclude that "the overall simulated impact of climate change on wheat productivity in Central Asia is positive," adding that "a warmer climate explains most of this positive impact" and that "$CO_2$ fertilization adds to it." |
| Hao, X., Li, P., Feng, Y., Han, X., Gao, J., Lin, E. and Han, Y. 2013. Effects of fully open-air [$CO_2$] elevation on leaf photosynthesis and ultrastructure of Isatis indigotica Fort. PLOS ONE 8: e74600. | Hao *et al.* report that the net photosynthesis rates of fully-expanded upper leaves at 36, 53 and 84 days after planting were increased, respectively, by 13.1, 22.8 and 27.1%, while plant water use efficiencies were increased by 1.3, 28.9 and 20.7%. Elevated $CO_2$ increased the weight of root per plant by 17.4%," which for a 300-ppm increase in the air's $CO_2$ concentration would translate into to an increase of 37.6% for the root-derived adenosine. |
| McElrone, A.J., Hamilton, J.G., Krafnick, A.J., Aldea, M., Knepp, R.G. and DeLucia, E.H. 2010. Combined effects of elevated $CO_2$ and natural climatic variation on leaf spot diseases of redbud and sweetgum trees. Environmental Pollution 158: 108-114. | McElrone *et al.* report that "disease incidence and severity for both species were greater in years with above average rainfall," while "in years with above average temperatures, disease incidence for Liquidambar styraciflua was decreased significantly." On the other hand, they found that elevated $CO_2$ increased disease incidence and severity "in some years." However, they say that the "chlorophyll fluorescence imaging of leaves revealed that any visible increase in disease severity induced by elevated $CO_2$ was mitigated by higher photosynthetic efficiency in the remaining undamaged leaf tissue and in a halo surrounding lesions." |
| Runion, G.B., Prior, S.A., Rogers, H.H. and | "[T]he percentage of loblolly pine seedlings |

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| Mitchell, R.J. 2010. Effects of elevated atmospheric $CO_2$ on two southern forest diseases. New Forests 39: 275-285. | which died as a result of rust infection was generally significantly lower under elevated $CO_2$ in both runs of the experiment." The data suggest that "disease incidence -- regardless of pathogen type -- may be reduced as atmospheric $CO_2$ concentration continues to rise." |
| Fleischmann, F., Raidl, S. and Osswald, W.F. 2010. Changes in susceptibility of beech (Fagus sylvatica) seedlings towards Phytophthora citricola under the influence of elevated atmospheric $CO_2$ and nitrogen fertilization. Environmental Pollution 158: 1051-1060. | Infected beech seedlings in the low-N high-$CO_2$ treatment rose to the challenge presented by the pernicious pathogen and "enhanced [their] primary production rates in the second year of the experiment and increased above-ground biomass significantly as compared to control trees," thereby providing an exemplary illustration of the popular proverb that affirms that "whatever doesn't kill me makes me stronger." |
| Iversen, C.M., Hooker, T.D., Classen, A.T. and Norby, R.J. 2011. Net mineralization of N at deeper soil depths as a potential mechanism for sustained forest production under elevated [$CO_2$]. *Global Change Biology* **17**: 1130-1139. | The roots of $CO_2$-enriched sweetgum trees in Tennessee assist in greater nitrogen accumulation. |
| Wu, H.C. and Lin, C.C. 2013. Carbon dioxide enrichment during photoautotrophic micropropagation of *Protea cynaroides* L. plantlets improves in vitro growth, net photosynthetic rate, and acclimatization. *HortScience* **48**: 1293-1297. | Wu and Lin conclude that "the high survival percentage and improvement in the overall growth of *P. cynaroides* during acclimatization was a direct result of $CO_2$ enrichment and the promotion of photoautrotrophic growth in vitro." |
| Drake, B.G. 2014. Rising sea level, temperature, and precipitation impact plant and ecosystem responses to elevated $CO_2$ on a Chesapeake Bay wetland: review of a 28-year study. *Global Change Biology* **20**: 3329-3343. | "The question of whether rising atmospheric $CO_2$ will cause the land sink for anthropogenic carbon to expand or contract has been the basis for most ecosystem studies to date." We now have, from the Chesapeake Bay study, "strong evidence that shoot and root biomass and net ecosystem production increased significantly" under real-world conditions of growing fossil fuel usage. The long duration of the Chesapeake Bay wetland study allows for a test of "the idea that some process, such as progressive nitrogen limitation, may constrain ecosystem responses to elevated $CO_2$ in native ecosystems." But contrary to that expectation ecosystems will continue to accumulate carbon as the air's $CO_2$ content continues its upward trajectory. |
| Peters, E.B., Wythers, K.R., Zhang, S., Bradford, J.B. and Reich, P.B. 2013. Potential climate change impacts on temperate forest ecosystem processes. *Canadian Journal of Forest Research* **43**: 939-950. | For the period 1960-2099, the data indicated that "changes in evapotranspiration could range from -3% to +6%, runoff could increase from 2% to 22%, and net nitrogen mineralization could increase 10% to 12%," while average regional productivity could increase from a substantial 67% to 142%. The increased productivity "was almost entirely driven by $CO_2$ fertilization effects, rather than by temperature or precipitation." |

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| Attavanich, W. and McCarl, B.A. 2014. How is $CO_2$ affecting yields and technological progress? A statistical analysis. *Climatic Change* **124**: 747-762. | The study describes the impacts of climate, crop production technology and atmospheric carbon dioxide ($CO_2$) enrichment on current and future crop yields. The primary econometric findings, were that: (1) "yields of C3 crops (soybeans, cotton and wheat) directly respond to the elevated $CO_2$, while yields of C4 crops (corn and sorghum) do not, but they are found to indirectly benefit from elevated $CO_2$ in times and places of drought stress," that (2) "ignoring atmospheric $CO_2$ in an econometric model of crop yield likely leads to overestimates of the pure effects of technological progress on crop yields," in light of the fact that "$CO_2$ contributes about 51, 15, 17, 9 and 1% of yield growth of cotton, soybeans, wheat, corn and sorghum, respectively," and that (3) in terms of projections, "the effect of $CO_2$ fertilization generally outweighs the effect of climate change on mean crop yields in many regions, resulting in an increase of 7-22, 4-47, 5-26, 65-96 and 3-35% for yields of corn, sorghum, soybeans, cotton and wheat, respectively." |
| Liu, H., Ge, Q., Zheng, J., Hao, Z. and Zhang, X. 2014. Crop yield and temperature changes in North China during 601-900 AD. *Advances in Meteorology* **2014**: 10.1155/2014/137803. | The conclusion of the IPCC's Fifth Assessment Report that warming harms crops more than it helps, based on studies over the past 50 years, is contradicted by studies based on historical data for the past several *centuries* which that "climate warming is good for crop harvests while climate cooling is bad for crop harvests in the world's main crop production areas such as Europe and China in the temperate region." Based on the data they concluded that "crop yield increased by 6.9% per 1°C warming." |
| Taylor, B.N., Strand, A.E., Cooper, E.R., Beidler, K.V., Schonholz, M. and Pritchard, S.G. 2014. Root length, biomass, tissue chemistry and mycorrhizal colonization following 14 years of $CO_2$ enrichment and 6 years of N fertilization in a warm temperate forest. *Tree Physiology* **34**: 955-965. | Root systems serve important roles in carbon (C) storage and the acquisition of nitrogen (N) - which is required for the increased photosynthesis typically observed in $CO_2$-enriched atmospheres. An important implication of these findings, is that "studies measuring only biomass might overlook shifts in root systems that better reflect treatment effects on the potential for soil resource uptake," and an increase in fine root exploration may be "a primary means for acquiring additional soil resources under elevated $CO_2$" that "has the potential to facilitate increased soil resource uptake allowing for a sustained response to elevated $CO_2$." |
| Pretzsch, H, Biber, P., Schutze, G., Uhl, E. and Rotzer, T. 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nature Communications* **5**: | Data that had been obtained from long-term experimental forest plots established some 140 years earlier in Central European regions where time series of temperature and |

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| 10.1038/ncomms5967. | precipitation date back all the way to 1781 indicate that most stands "have not reached a final constant yield plateau," which suggests that coincident with "an increase in resource supply ($CO_2$, N), together with an extended growing season accompanied by changes in other climatic variables." And they note, in this regard, that this growth stimulation "surprisingly occurred during the period when acid rain (1970-1990) and drought episodes (1976 and 2003) suggest decreased productivity should have occurred." |
| Chen, J., Tian, Y., Zhang, X., Zheng, C., Song, Z., Deng, A. and Zhang, W. 2014. Nighttime warming will increase winter wheat yield through improving plant development and grain growth in North China. *Journal of Plant Growth Regulation* **33**: 397-407. | Increase in nighttime temperature (1) "extended the duration of grain filling," (2) "promoted the filling rates of the superior and inferior grains," which (3) "resulted in a significant increase in the 1,000-grain weight by 6.3%," that (4 and 5) "significantly increased wheat aboveground biomass and grain yield by 12.3 and 12.0%, respectively. In light of these findings, "wheat production in North China may benefit from predicted climatic warming." |
| Roger A. Sedjo & Brent Sohngen, "What are the Impacts of Global Warming on U.S. Forests, Regions, and the U.S. Timber Industry?," 12 Penn. St. Envt'l L. Rev. 95 (Winter 2004). | Warming has a positive net impact on U.S. timber production. |
| Ying Sun, *et al.*, "Impact of Mesophyll Diffusion on Estimated Global Land $CO_2$ Fertilization," 111 Proceedings Nat'l Acad. Scis. 15774 (Nov. 4, 2014). | Models consistently underestimate effects of $CO_2$ fertilization. |
| J. Wilcox, & D. Makowski, "A Meta-Analysis of the Predicted Effects of Climate Change on Wheat Yields Using Simulation Studies," 156 Field Crops Research 180 (2014). | Beneficial effects of $CO_2$ on agriculture will outweigh the detrimental effects. |
| Ghini, R., de O. Mac Leod, R.E., Neto, A.T., Cardoso, D.C., Bettiol, W., de Morais, L.A.S. and Vique, B. 2014. Increased atmospheric carbon dioxide concentration: effects on eucalypt rust (Puccinia psidii), C:N ratio and essential oils in eucalypt clonal plantlets. Forest Pathology **44**: 409-416. | Increased $CO_2$ concentrations result in greater resilience to eucalypt rust pustules without affecting production of essential oils. |
| Tognetti, R., Lombardi, F., Lasserre, B., Cherubini, P. and Marchetti, M. 2014. Tree-ring stable isotopes reveal twentieth-century increases in water-use efficiency of Fagus sylvatica and Nothofagus spp. in Italian and Chilean mountains. PLOS ONE **9**: e113136. | Intrinsic water-use efficiency has improved dramatically for trees in Italy and Chile as a result of both slight warming and increased $CO_2$ levels. |
| Beidler, K.V., Taylor, B.N., Strand, A.E., Cooper, E.R., Schonholz, M. and Pritchard, S.G. 2015. Changes in root architecture under elevated concentrations of $CO_2$ and nitrogen reflect alternate soil exploration strategies. *New Phytologist* **205:** 1153-1163 | Increases in $CO_2$ concentration on fine-root properties of the loblolly pine result in "more efficient in nutrient acquisition and may be allowing plants to effectively exploit larger volumes of soil, thereby pre-empting progressive nutrient limitations." |

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| Olsen, Y.S., Potouroglou, M., Garcias-Bonet, N. and Duarte, C.M. 2015. Warming reduces pathogen pressure on a climate-vulnerable seagrass species. *Estuaries and Coasts* **38:** 659-667 | Warming decreases the occurrence and severity of *Labyrinthula* infection in *Posidonia oceanica*. |
| Mendes de Sa, C.E., Negreiros, D., Fernandes, G.W., Dias, M.C. and Franco, A.C. 2014. Carbon dioxide-enriched atmosphere enhances biomass accumulation and meristem production in the pioneer shrub *Baccharis dracunculifolia*(Asteraceae). *Acta Botanica Brasillica* **28**: 646-650 | Seedlings of *Baccharis dracunculifolia* – a key pioneer Neotropical shrub and medicinal plant found in Brazil – respond well to elevated $CO_2$. |
| Sreeharsha, R.V., Sekhar, K.M. and Reddy, A.R. 2015. Delayed flowering is associated with lack of photosynthetic acclimation in Pigeon pea (*Cajanus cajan* L.) grown under elevated $CO_2$. *Plant Science* **231**: 82-93 | Increased levels of $CO_2$ benefit pigeonpea, an important legume crop of equatorial and semiarid parts of the world. |
| Saurer, M., Spahni, R., Frank, D.C., Joos, F., Leuenberger, M., Loader, N.J., McCarroll, D., Gagen, M., Poulter, B., Siegwolf, R.W., Andreu-Hayles, L., Boettger, T., Linan, I.D., Fairchild, I.J., Friedrich, M., Gutierrez, S., Haupt, M., Hilasvuori, E., Heinrich, I., Helle, G., Grudd, H., Jalkanen, R., Levanic, T., Linderholm, H.W., Robertson, I., Sonninen, E., Treydte, K., Waterhouse, J.S., Woodley, E.J., Wynn, P.M. and Young, G.H.F. 2014. Spatial variability and temporal trends in water-use efficiency of European forests. *Global Change Biology* **20**: 3700-3712. | Scientists found that increased atmospheric $CO_2$ has increased "water-use efficiency" in trees and forests. Most especially of note was that European forests, which had been facing facing decreased soil-water availability, experienced the strongest increase in water-use efficiency as a result of atmospheric $CO_2$. The key consequence to this research further bolsters the argument that atmospheric $CO_2$ and climate change will have a "profound effect on the physiology of trees." |
| Soulé, P.T. and Knapp, P.A. 2015. Analyses of intrinsic water-use efficiency indicate performance differences of ponderosa pine and Douglas-fir in response to $CO_2$ enrichment. *Journal of Biogeography* **42**: 144-155. | Scientists researching several tree species within the U.S. Forest Service found that the various trees had exponentially increased intrinsic water-use efficiency correlated with the increase in atmospheric $CO_2$ and increasing temperatures. This suggests "either increased net photosynthesis or decreased stomatal conductance, or both." The consequence to this research is the wider positive implication of climate change, which is that the positive "response occurred at all sites, suggesting a pan-regional effect." |
| ***B. Observational Data Show That the Earth is Already "Greening"*** | |
| Nyssen, J., Frankl, A., Haile, M., Hurni, H., Descheemaeker, K., Crummey, D., Ritler, A., Portner, B., Nievergelt, B., Moeyersons, J., Munro, N., Deckers, J., Billi, P. and Poesen, J. 2014. Environmental conditions and human drivers for changes to north Ethiopian mountain landscapes over 145 years. *Science of the Total Environment* **485-486**: 164-179. | Newly discovered photographs of Ethiopian highlands compared to contemporary photos show better conditions for woody vegetation, conservation structures, and land management compared to old pictures, with a strong tendency toward vegetation increase. |
| Johnson, S.E. and Abrams, M.D. 2009. Age class, longevity and growth rate relationships: | Greater growth rates of older trees of the current era compared to older trees of older |

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| protracted growth increases in old trees in the eastern United States. *Tree Physiology* **29**: 1317-1328. | times "may be due to a stimulatory effect of anthropogenic global change defined in the broadest sense," including "increased $CO_2$ levels, warming temperatures, increased precipitation, and changes in precipitation chemistry." |
| Liu, S., Liu, R. and Liu, Y. 2010. Spatial and temporal variation of global LAI during 1981-20006. *Journal of Geographical Sciences* **20**: 323-332. | Leaf area index (LAI) has increased in between July 1981 and December 2006. |
| Crimmins, S.M., Dobrowski, S.Z., Greenberg, J.A., Abatzoglou, J.T. and Mynsberge, A.R. 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science* **331**: 324-327. | Certain species of plants in California are experiencing an increase in their optimum temperature due to both climatic warming and downhill shifts. |
| Piao, S., Ciais, P., Lomas, M., Beer, C., Liu, H., Fang, J., Friedlingstein, P., Huang, Y., Muraoka, H., Son, Y. and Woodward, I. 2011. Contribution of climate change and rising $CO_2$ to terrestrial carbon balance in East Asia: A multi-model analysis. *Global and Planetary Change* **75**: 133-142. | Increases in $CO_2$ concentration and temperature served to enhance terrestrial vegetative productivity in East Asia. |
| Forbes, B.C., Fauria, M.M. and Zetterberg, P. 2010. Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. Global Change Biology 16: 1542-1554. | There was "a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981-2005, confirming a parallel 'greening' trend reported for similarly warming North American portions of the tundra biome," and "the standardized growth curve suggests a significant increase in shrub willow growth over the last six decades." These findings "are in line with field and remote sensing studies that have assigned a strong shrub component to the reported greening signal since the early 1980s," and "provides the best proxy assessment to date that deciduous shrub phytomass has increased significantly in response to an ongoing summer warming trend." |
| Dolanc, C.R., Safford, H.D., Dobrowski, S.Z. and Thorne, J.H. 2014. Twentieth century shifts in abundance and composition of vegetation types of the Sierra Nevada, CA, US. *Applied Vegetation Science* **17**: 442-455. | Study of Sierra Nevada trees shows significant positive effects on density across nine different subtypes of forest. On upper-slope forests, this should be attributed to increased $CO_2$. |
| Zhou, W., Gang, C., Chen, Y., Mu, S., Sun, Z. and Li, J. 2014. Grassland coverage inter-annual variation and its coupling relation with hydrothermal factors in China during 1982-2010. *Journal of Geographical Sciences* **24**: 593-611. | Key finding is that grasslands in China--biggest terrestrial ecosystem in the country--showed statistically significant increase in vegetation correlated with $CO_2$ (controlling for temperature and precipitation). |
| Andela, N., Liu, Y.Y., van Dijk, A.I.J.M., de Jeu, R.A.M. and McVicar, T.R. 2013. Global changes in dryland vegetation dynamics (1988-2008) assessed by satellite remote sensing: comparing a new passive microwave | The study concludes at least in part that "spatial distribution of trends suggests that a global driver (e.g., $CO_2$ fertilization) is causing a change in relative performance of woody vegetation compared to herbaceous |

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| vegetation density record with reflective greenness data. Biogeosciences 10: 6657-6676. | vegetation." |
| Eastman, J.R., Sangermano, F., Machado, E.A., Rogan, J. and Anyamba, A. 2013. Global trends in seasonality of Normalized Difference Vegetation Index (NDVI), 1982-2011. Remote Sensing 5: 4799-4818. | Eastman *et al.* conclude that "from this remarkable 30-year archive of satellite imagery, we thus see evidence of a greening trend." |
| Ichii, K., Kondo, M., Okabe, Y., Ueyama, M., Kobayashi, H., Lee, S.-J., Saigusa, N., Zhu, Z. and Myneni, R.B. 2013. Recent changes in terrestrial gross primary productivity in Asia from 1982 to 2011. Remote Sensing 5: 6043-6062. | The researchers found that approximately 40% of Asia's non-ice-covered land mass experienced a significant increase in the NDVI over the last 30 years and that "a modeled sensitivity analysis showed that the increases in GPP are explained by increased temperature and precipitation in Siberia," and that "precipitation, solar radiation and $CO_2$ fertilization are important factors in the tropical regions." |
| Fisher, J.B., Sikka, M., Sitch, S., Ciais, P., Poulter, B., Galbraith, D., Lee, J.-E., Huntingford, C., Viovy, N., Zeng, N., Ahistrom, A., Lomas, M.R., Levy, P.E., Frankenberg, C., Saatchi, S. and Malhi, Y. 2013. African tropical rainforest net carbon dioxide fluxes in the twentieth century. Philosophical Transactions of the Royal Society B 368: 10.1098/rstb.2012.0376. | Fisher *et al.* write that "the recent increase in plant productivity has been attributed to the $CO_2$ fertilization effect," citing a wealth of studies that have come to this conclusion, including those of Amthor (1995), Lloyd and Farquhar (1996), Cao *et al.* (2001), Lewis *et al.* (2004), Friedlingstein *et al.* (2006), Stephens *et al.* (2007), Ciais *et al.* (2009), Lewis *et al.* (2009), Malhi (2010), Ballantyne *et al.* (2012) and Higgins and Scheiter (2012). And in regard to a more recent African study that has yet to appear in print, they write that its authors "found that gross primary production increased over the past 30 years even though soil moisture decreased." |
| Brunelle, A., Minckley, T.A., Delgadillo, J. and Blissett, S. 2014. A long-term perspective on woody plant encroachment in the desert southwest, New Mexico, USA. *Journal of Vegetation Science* **25**: 829-838. | Increased $CO_2$ from onset of Industrial Revolution (circa 1750) has led to increased growth of woody pine-oak forest systems moving into otherwise barren arid climate in Southwestern New Mexico. Other changes in climate and local natural system rejected as causes. |
| Ek, C. and Godissart, J. 2014. Carbon dioxide in cave air and soil air in some karstic areas of Belgium. A prospective view. *Geologica Belgica* **17**: 102-106. | Evidence of greening effect extends to caves, where $CO_2$ has increased dramatically since 1966. |
| Song, Y., Yu, J. and Huang, B. 2014. Elevated $CO_2$-mitigation of high temperature stress associated with maintenance of positive carbon balance and carbohydrate accumulation in Kentucky bluegrass. *PLOS ONE* **9**: e89725. | High $CO_2$ levels allowed Kentucky bluegrass to withstand stresses from higher temperatures. |
| Chen, B., Xu, G., Coops, N.C., Ciais, P., Innes, J.L., Wang, G., Myneni, R.B., Wang, T., Krzyzanowski, J., Li, Q., Cao, L. and Liu, Y. 2014. Changes in vegetation photosynthetic activity trends across the Asia-Pacific region | The Asia-Pacific region has shown strong increases in vegetation and photosynthesis. |

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| over the last three decades. *Remote Sensing of Environment* **144**: 28-41. | |
| Wu, C., Hember, R.A., Chen, J.M., Kurz, W.A., Price, D.T., Boisvenue, C., Gonsamo, A. and Ju, W. 2014. Accelerating forest growth enhancement due to climate and atmospheric changes in British Colombia, Canada over 1956-2001. *Scientific Reports* **4**: 10.1038/srep04461. | Growth in British Columbia forests attributed primarily to localized climate changes, and secondarily to increased $CO_2$ and nitrogen. |
| Pretzsch, H., Biber, P., Schutze, G. and Bielak, K. 2014. Changes of forest stand dynamics in Europe. Facts from long-term observational plots and their relevance for forest ecology and management. *Forest Ecology and Management* **316**: 65-77. | Observation plots of forest in Central Europe that have been measured for over a century are showing fertility and robustness not seen in the past, with trees reaching threshold sizes decades earlier than in the past. Moreover, scientists suggest cultivated multi-species forests that may increase resilience to changes in climate even further. |
| Tremblay, B., Levesque, E. and Boudreau, S. 2012. Recent expansion of erect shrubs in the Low Arctic: evidence from Eastern Nunavik. *Environmental Research Letters* **7**: 10.1088/1748-9326/7/3/035501. | Greening effects visible even in Kangiqsualujjuaq, Eastern Nunavik, Canada, a sub-arctic tundra ecosystem--providing *in situ* evidence of a theorized colonization by shrubs. |
| Xu, X., Piao, S., Wang, X., Chen, A., Ciais, P. and Myneni, R.B. 2012. Spatio-temporal patterns of the area experiencing negative vegetation growth anomalies in China over the last three decades. *Environmental Research Letters* **7**: 10.1088/1748-9326/7/3/035701. | Despite more droughts and heatwaves since the 1980s, research showed fewer places with negative vegetation growth over time in China. |
| Salguero-Gomez, R., Siewert, W., Casper, B.B. and Tielborger, K. 2012. A demographic approach to study effects of climate change in desert plants. *Philosophical Transactions of the royal Society B* **367**: 3100-3114. | Desert vegetation, thought to be especially susceptible to climate change effects, turns out to flourish under conditions of higher (Utah) and lower (Negev Desert, Israel) precipitation. |
| Henry, G.H.R., Harper, K.A., Chen, W., Deslippe, J.R., Grant, R.F., Lafleur, P.M., Levesque, E., Siciliano, S.D. and Simard, S.W. 2012. Effects of observed and experimental climate change on terrestrial ecosystems in northern Canada: results from the Canadian IPY program. *Climatic Change* **115**: 207-234. | Both tundra and taiga in Canada (40% of land) show more vegetation over past 20-50 years. All of the studied sites were carbon sinks, and would remain so for 50-100 years even under conditions of climate change. |
| Zhao, X., Zhou, D. and Fang, J. 2012. Satellite-based studies on large-scale vegetation changes in China. *Journal of Integrative Plant Biology* **54**: 713-728. | Satellite images for China show statistically significant levels of greening over the past 2-3 decades. |
| Bonal, D., Ponton, S., Le Thiec, D., Richard, B., Ningre, N., Herault, B., Ogee, J., Gonzalez, S., Pignal, M., Sabatier, D. and Guehl, J.-M. 2011. Leaf functional response to increasing atmospheric $CO_2$ concentrations over the last century in two northern Amazonian tree species: a historical $\delta^{13}C$ and $\delta^{18}O$ approach using herbarium samples. *Plant, Cell and Environment* **34**: 1332-1344. | Increase in $CO_2$ in two northern Amazonia tree species results in water-use efficiency and is consistent with the greening of the earth. |
| Zhao, X., Tan, K., Zhao, S. and Fang, J. 2011. | Northwest China has experienced greening. |

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| Changing climate affects vegetation growth in the arid region of the northwestern China. *Journal of Arid Environments* **75**: 946-952. | |
| Fengjin, X. and Lianchun, S. 2011. Analysis of extreme low-temperature events during the warm season in Northeast China. *Natural Hazards* **58**: 1333-1344. | With ever fewer extreme minimum temperature events occurring in response to the warmer temperatures of the past few decades, farmers in Northeast China have been able to harvest greater amounts of rice, sorghum, corn, soybeans and other major crops than would otherwise have been possible, thanks to the warming experienced in that particular part of the world. |
| Ciais, P., Piao, S.-L., Cadule, P., Friedlingstein, P. and Chedin, A. 2009. Variability and recent trends in the African terrestrial carbon balance. Biogeosciences 6: 1935-1948. | Land use flux due to deforestation in Africa was "a source of 0.13 Pg C per year," and that "this implies that climatic trends (mainly increasing precipitation) and $CO_2$ increase (the fertilization effect), are causing a sink of 0.28 Pg C per year which offsets the land-use source." "The trend of gross primary production is closely matching the trend in satellite observed NDVI," and their simulated trend in gross primary production "is also consistent with an increased vegetation activity over [the] Sahel," while at the continental-scale the gross primary production trend can be largely (70%) explained by the $CO_2$ fertilization effect. |
| Gloor, M., Phillips, O.L., Lloyd, J.J., Lewis, S.L., Malhi, Y., Baker, T.R., Lopez-Gonzalez, G., Peacock, J., Almeida, S., Alves de Oliveira, A.C., Alvarez, E., Amaral, I., Arroyo, L, Aymard, G., Banki, O., Blanc, L., Bonal, D., Brando, P., Chao, K.-J., Chave, J., Davila, N., Erwin, T., Silva, J., DiFiore, A., Feldpausch, T.R., Freitzs, A., Herrera, R., Higuchi, N., Honorio, E., Jimenez, E., Killeen, T., Laurance, W., Mendoza, C., Monteagudo, A., Andrade, A. Neill, D., Nepstad, D., Nunez Vargas, P., Penuela, M.C., Pena Cruz, A., Prieto, A., Pitman, N., Quesada, C., Salomao, R., Silveira, M., Schwarz, M., Stropp, J., Ramirez, F., Ramirez, H., Rudas, A., ter Steege, H., Silva, N., Torres, A., Terborgh, J., Vasquez, R. and van der Heijden, G. 2009. Does the disturbance hypothesis explain the biomass increase in basin-wide Amazon forest plot data? Global Change Biology 15: 2418-2430. | "The disturbance process in Amazon old-growth forests as recorded in 135 forest plots of the RAINFOR network up to 2006, and other independent research programs, and explore the consequences of sampling artifacts using a data-based stochastic simulator." These results lend "further support to the notion that currently observed biomass gains for intact forests across the Amazon are actually occurring over large scales at the current time, presumably as a response to climate change," which in many of their earlier papers is explicitly stated to include the aerial fertilization effect of the historical increase in the air's $CO_2$ content. |
| Dong, J., Liu, J., Tao, F., Xu, X. and Wang, J. 2009. Spatio-temporal changes in annual accumulated temperature in China and the effects on cropping systems, 1980s to 2000. Climate Research 40: 37-48. | Dong *et al.* report that "since the late 1980s, AAT10 has noticeably risen in most of China." More specifically, they indicate that 1.22 x 1015 km2 of land moved from the potato accumulated temperature zone (ATZ) to the spring wheat ATZ, that 3.16 x 1015 km2 of land moved from the spring wheat ATZ to the winter wheat ATZ, and that 1.64 x 1015 km2 |

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| | of land moved from the winter wheat ATZ to the rice ATZ. In addition, they determined that farmers changed from a single crop per year to three crops in two years in many regions, while "the growth boundary of winter wheat moved northward." |
| Lewis, S.L., Lloyd, J., Sitch, S., Mitchard, E.T.A. and Laurance, W.F. 2009. Changing ecology of tropical forests: Evidence and drivers. Annual Review of Ecology, Evolution, and Systematics 40: 529-549. | Both theory and experiments suggest that over the past several decades "plant photosynthesis should have increased in response to increasing $CO_2$ concentrations, causing increased plant growth and forest biomass." "[L]ong-term plot data collectively indicate an increase in carbon storage, as well as significant increases in tree growth, mortality, recruitment, and forest dynamism." Satellite measurements "indicate increases in productivity and forest dynamism," and that five Dynamic Global Vegetation Models, incorporating plant physiology, competition, and dynamics, all predict increasing gross primary productivity, net primary productivity, and carbon storage when forced using late-twentieth century climate and atmospheric $CO_2$ concentration data." "Collectively," "these results point toward a widespread shift in the ecology of tropical forests, characterized by increased tree growth and accelerating forest dynamism, with forests, on average, getting bigger (increasing biomass and carbon storage)." |
| Xiong, W., Conway, D., Lin, E. and Holman, I. 2009. Potential impacts of climate change and climate variability on China's rice yield and production. Climate Research 40: 23-35. | With projected climate changes, "single rice cropping may expand further north in China, and double rice cropping may move to the northern portion of the Yangtze River basin." "[M]ean rice production is estimated to increase by 2.7 to 19.2% considering the combined effects of climate change, $CO_2$ and shifting rice-producing areas." |
| McMahon, S.M., Parker, G.G. and Miller, D.R. 2010. Evidence for a recent increase in forest growth. Proceedings of the National Academy of Sciences USA: 10.1073/pnas.0912376107. | "[R]ecent biomass accumulation greatly exceeded the expected growth caused by natural recovery," noting that in stands younger than 50 years the observed rate increase was generally at least one-third of total growth, and that in older stands it typically was "the majority of growth," even though theory would suggest that "old forests should grow very little as they approach equilibrium." |
| Hudson, J.M.G. and Henry, G.H.R. 2009. Increased plant biomass in a High Arctic heath community from 1981 to 2008. Ecology 90: 2657-2663. | "[S]atellite-based remote sensing models, such as green trends derived from the normalized difference vegetation index [(NDV)], and global vegetation and ecosystem process simulations of the terrestrial carbon cycle, indicate increasing trends in vegetation photosynthetic activity and net primary production in the Arctic over |

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| | the past several decades." As a result "it is likely that warming directly increased plant growth and reproduction and indirectly increased resource supply," and that "increased temperatures also lengthened the growing season, increased soil temperature, deepened the active [soil] layer, and consequently may have influenced nutrient uptake in the plant community." |
| Springsteen, A., Loya, W., Liebig, M. and Hendrickson, J. 2010. Soil carbon and nitrogen across a chronosequence of woody plant expansion in North Dakota. Plant and Soil 328: 369-379. | Soil carbon content rose by 26% across the chronosequence from grassland to woodland within the 0-15 cm soil depth, while total soil nitrogen content rose by 31%. And they add that the rate of woody shrub expansion from 1963 to 1988 (25 years) was ~1,800 m2 per year at their study site, while from 1988 to 2005 (17 years) it was ~3,800 m2 per year, or just a little more than doubled. |
| Qian, B., Zhang, X., Chen, K., Feng, Y. and O'Brien, T. 2010. Observed long-term trends for agroclimatic conditions in Canada. Journal of Applied Meteorology and Climatology 49: 604-618. | The data show "a significant lengthening of the growing season due to a significantly earlier start and a significantly later end of the growing season," and they say that "significant positive trends are also observed for effective growing degree-days and crop heat units at most locations across the country." They also report that "the occurrence of extremely low temperatures has become less frequent during the non-growing season, implying a more favorable climate for overwinter survival," and "the total numbers of cool days, frost days, and killing-frost days within a growing season have a decreasing trend," so that "crops may also be less vulnerable to cold stress and injury during the growing season." |
| Erasmi, S., Schucknecht, A., Barbosa, M.P. and Matschullat, J. 2014. Vegetation greenness in northeastern Brazil and its relation to ENSO warm events. *Remote Sensing* **6**: 3041-3058. | "One of the key indicators to evaluate the existence of alterations in vegetation productivity is the trend in long-term vegetation greenness." Several studies have "explicitly reported a 'greening' of semi-arid regions worldwide." The vegetative productivity in northeastern Brazil has increased notwithstanding increasing concentrations of atmospheric $CO_2$ and global warming. |
| Bowman, D.M.J.S., Murphy, B.P. and Banfai, D.S. 2010. Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? Landscape Ecology 25: 1247-1260. | It is "most likely that the expansion of rainforest patches is related to global climate change via increased rainfall and/or the $CO_2$ 'fertilizer effect'," since the expansion of Australia's monsoon rainforests occurred "despite hostile fire regimes." This conclusion "is consistent with the recent finding from South Africa that strongly contrasting localized land management practices had little effect on the dramatic expansion of forest patches into the surrounding savanna |

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| | in the latter half of the 20th century, strongly implicating global environmental change.” |
| Randall J. Donohue, *et al.*, “Impact of CO2 Fertilization on Maximum Foliage Cover Across the Globe’s Warm, Arid Environments,” 40 Geophys. Rsch. Letters 1 (June 2013). | The authors confirm that $CO_2$ fertilization is the cause of widespread observed “greening.” |
| J. Ronald Eastman, *et al.*, “Global Trends in Seasonality of Normalized Difference Vegetation Index (NDVI), 1982-2011,” 5 Remote Sensing 4799-4818 (2013). | The authors find significant non-anthropogenic greening effects across more than half of the world’s lands. |
| Russell, J.M. and Ward, D. 2014. Remote sensing provides a progressive record of vegetation change in northern KwaZulu-Natal, South Africa, from 1944 to 2005. International Journal of Remote Sensing **35**: 904-926. | Vegetation increased in study sites in South Africa even when rainfall was below average, and it was not synchronized with a rise in temperature. Researchers conclude that the effect of increased $CO_2$ concentrations was likely driving the increased vegetation. |
| William Happer, “The Myth of Carbon Pollution,” presented at the George Marshall Institute, Washington, D.C., October 15, 2014. | Professor William Happer – the former head of basic research at DOE -- finds that greening of the planet is already being observed, that any modest warming from more $CO_2$ will be beneficial, and that crop yields will increase substantially. |
| ***C. Plant Absorption of $CO_2$ is a Significant Carbon Sink, and Collateral Effects of Increased Vegetation Reduce Carbon in Other Ways.*** | |
| Song, Z., Liu, H., Li, B. and Yang, X. 2013. The production of phytolith-occluded carbon in China’s forests: implications to biogeochemical carbon sequestration. Global Change Biology 19: 2907-2915. | The authors write that “one of the most promising biogeochemical carbon sequestration mechanisms is the occlusion of carbon within phytoliths, the silicified features which are deposited within plant tissues (Parr and Sullivan, 2005; Song *et al.*, 2012a, b).” Song *et al.* stated in the concluding sentence of their paper’s abstract that “forest management practices such as bamboo afforestation and reforestation may significantly enhance the long-term terrestrial carbon sink and contribute to mitigation of global climate warming.” |
| Klein, E.S., Yu, Z. and Booth, R.K. 2013. Recent increase in peatland carbon accumulation in a thermokarst lake basin in southwestern Alaska. Palaeogeography, Palaeoclimatology, Palaeoecology 392: 186-195. | Conclusions of Klein *et al.* “suggest that drainage of thermokarst lakes in northern regions could produce basins that accumulate organic-rich peat,” noting that “these vegetated basins might be a persistent C sink that increases with warming,” to the extent that “the C accumulated in these vegetated drained basins under current warming might help offset some of the C released from thawing permafrost and thermokarst features in northern regions.” |
| Jeong, S.-J., Ho, C.-H., Kim, K.-Y., Kim, J., Jeong, J.-H. and Park, T.-W. 2010. Potential impact of vegetation feedback on European heat waves in a 2 x $CO_2$ climate. Climatic Change 99: 625-635. | The six scientists say their calculations indicate that “the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included,” adding that “examination of the simulated |

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| | surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapotranspiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." In addition, they state that "the greening also tends to reduce the frequency and duration of heat waves." |
| Song, Z., Wang, H., Strong, P.J. and Guo, F. 2014. Phytolith carbon sequestration in China's croplands. European Journal of Agronomy 53: 10-15. | Song *et al.* conclude the report of their work by noting that their data indicate that "beneficial cropland management practices such as rational irrigation and fertilizer application, and crop pattern optimization may be taken to further enhance the phytolith C sink in croplands," to the extent that "global climate change could be partially offset by increasing cropland phytolith C sequestration at both a national and global scale." |
| Schrumpf, M., Kaiser, K. and Schulze, E.-D. 2014. Soil organic carbon and total nitrogen gains in an old growth deciduous forest in Germany. *PLOS ONE* **9**: e89364. | Old-growth forests continue to be carbon sinks. |
| Stephenson, N.L., Das, A.J., Condit, R., Russo, S.E., Baker, P.J., Beckman, N.G., Coomes, D.A., Lines, E.R., Morris, W.K., Ruger, N., Alvarez, E., Blundo, C., Bunvavejchewin, S., Chuyong, G., Davies, S.J., Duque, A., Ewango, C.N., Flores, O., Franklin, J.F., Grau, H.R., Hao, Z., Harmon, M.E., Hubbell, S.P., Kenfack, D., Lin, Y., Makana, J.-R., Malizia, A., Malizia, L.R., Pabst, R.J., Pongpattananurak, N., Su, S.-H., Sun, I.-F., Tan, S., Thomas, D., van Mantgem, P.J., Wang, X., Wiser, S.K. and Zavala, M.A. 2014. Rate of tree carbon accumulation increases continuously with tree size. *Nature* **507**: 90-93. | As trees grow larger, they sequester more carbon. Moreover, these are the trees that are growing most rapidly as $CO_2$ increases--across different regions and competitive environments. |
| Poulter, B., Frank, D., Ciais, P., Myneni, R.B., Andela, N., Bi, J., Broquet, G., Canadell, J.G., Chevallier, F., Liu, Y.Y., Running, S.W., Sitch, S. and an der Werf, G.R. 2014. Contribution of semi-arid ecosystems to inter-annual variability of the global carbon cycle. *Nature* **509**: 600-604. | Semi-arid ecosystems have taken prominence as carbon sinks over the past 30 years. |
| Zhou, X., Chen, C., Wang, Y, Smaill, S. and Clinton, P. 2013. Warming rather than increased precipitation increases soil recalcitrant organic carbon in a semiarid grassland after 6 years of treatments. PLOS ONE 8: e53761. | Zhou *et al.* ultimately concluded that "given that the absolute increase of SOC in the recalcitrant SOC pool was much greater than the decrease in labile SOC, and that the mean residence time of recalcitrant SOC is much greater, our results suggest that soil C storage at 10-20 cm depth may increase with increasing temperature in this semiarid grassland." |
| Zhuang, Q., He, J., Lu, Y., Ji, L., Xiao, J. and Luo, T. 2010. Carbon dynamics of terrestrial ecosystems on the Tibetan Plateau during the | The six scientists report that "during the 20th century, the Tibetan Plateau changed from a small carbon source or neutral in the early |

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| 20th century: an analysis with a process-based biogeochemical model. Global Ecology and Biogeography 19: 649-662. | part of the century to a sink later," noting that "net primary production and soil respiration increased by 0.52 and 0.22 Tg C/year, respectively, resulting in a regional carbon sink increase of 0.3 Tg C/year," so that "by the end of the century, the regional carbon sink reached 36Tg C/year and carbon storage in vegetation and soils is 32 and 16 Pg C, respectively." Zhuang *et al.* say the "increasing soil temperature and deepening active layer depth enhanced soil respiration, increasing the net nitrogen mineralization rate," and that "together with the [positive] effects of warming air temperature and rising $CO_2$ concentrations on photosynthesis, the stronger plant nitrogen uptake due to the enhanced available nitrogen stimulate[d] plant carbon uptake, thereby strengthening the regional carbon sink as the rate of increase in net primary production was faster than that of soil respiration." |
| Xia, J., Liu, S., Liang, S., Chen, Y., Xu, W. and Yuan, W. 2014. Spatio-temporal patterns and climate variables controlling of biomass carbon stock of global grassland ecosystems from 1982 to 2006. *Remote Sensing* **6**: 1783-1802. | The carbon storage capacity of grasslands at worldwide sites showed a marked increase, positively correlated with temperature and precipitation. |
| Cheng, C.-H., Hung, C.-Y., Chen, C.-P. and Pei, C.-W. 2013. Biomass carbon accumulation in aging Japanese cedar plantations in Xitou, central Taiwan. Botanical Studies 54: 60. | Cheng *et al.* conclude that "if Japanese cedar stands are not harvested, they can provide a carbon sink by storing carbon in tree biomass," such that "in association with the increases in tree DBH with stand age, maintaining this ageing process can be a forest management mechanism for the reduction of greenhouse gas emissions." |
| Shevliakova, E., Stouffer, R.J., Malyshev, S., Krasting, J.P., Hurtt, G.C. and Pacala, S.W. 2013. Historical warming reduced due to enhanced land carbon uptake. Proceedings of the National Academy of Sciences USA 110: 16,730-16,735. | The study states that historical $CO_2$-enhanced vegetation growth "lowered the historical atmospheric $CO_2$ concentration by fully 85 ppm," thereby avoiding what they calculated to be "an additional 0.31 ± 0.06°C warming." |
| Lugo, J.B., Deslauriers, A. and Rossi, S. 2012. Duration of xylogenesis in black spruce lengthened between 1950 and 2010. *Annals of Botany* **110**: 1099-1108. | Rising temperatures in Québéc forests have prolonged the period of xylogenesis (wood formation) for black spruce, with the effect of "removing the thermal constraints to the activity of carbon sinks in trees." |
| Sandoval-Soto, L., Kesselmeier, M., Schmitt, V., Wild, A. and Kesselmeier, J. 2012. Observations of the uptake of carbonyl sulfide (COS) by trees under elevated atmospheric carbon dioxide concentrations. *Biogeosciences* **9**: 2935-2945. | Increased $CO_2$ levels result in lower levels of uptake for carbonyl sulfide--a key molecule that rises to the upper atmosphere to disperse solar radiation. The less plants take it up, the more carbonyl sulfide is available to exert a cooling influence on the Earth. |
| Lane, R.W., Menon, M., McQuaid, J.B., Adams, D.G., Thomas, A.D., Hoon, S.R. and Dougill, A.J. 2013. Laboratory analysis of the effects of elevated atmospheric carbon dioxide | In addition to vegetation, biological soil crusts (BSCs) can enhance carbon sink capacities. Lane *et al.* state that "BSCs have the potential to fix carbon under limited soil |

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| on respiration in biological soil crusts. Journal of Arid Environments 98: 52-59. | moisture availability and nutrient poor soils (typical of drylands)," especially in the case of BSCs dominated by nitrogen fixing cyanobacteria. And, therefore, they conclude that "undisturbed BSC-covered drylands could be enhanced carbon sinks, and play an increasingly significant role in global carbon budgets in years to come." |
| Cai, S. and Yu, Z. 2011. Response of a warm temperate peatland to Holocene climate change in northeastern Pennsylvania. *Quaternary Research* **75**: 531-540. | "Northern peatlands can continue to serve as carbon sinks under a warmer and wetter climate, providing a negative feedback to climate warming." |
| Flanagan, L.B. and Syed, K.H. 2011. Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. *Global Change Biology* **17**: 2271-2287. | In the absence of fire or other major disturbance, significant net carbon sequestration could continue for decades in the peatlands of Athabasca, Alberta, Canada and help to reduce the positive feedback of climate change on increasing atmospheric $CO_2$ concentration. |
| Zhou, L., Dai, L., Wang, S., Huang, X., Wang, X., Qi, L., Wang, Q., Li, G., Wei, Y. and Shao, G. 2011. Changes in carbon density for three old-growth forests on Changbai Mountain, Northeast China: 1981-2010. *Annals of Forest Science* **68**: 953-958. | Old-growth forests on Changbai Mountain in Northeast China can continue to accumulate carbon, rebutting assumption that forests reach their maximum productivity at an intermediate age. |
| Wan, S., Xia, J., Liu, W. and Niu, S. 2009. Photosynthetic overcompensation under nocturnal warming enhances grassland carbon sequestration. Ecology 90: 2700-2710. | "[N]octurnal warming increased leaf respiration of two dominant grass species by 36.3%, enhanced consumption [drawdown] of carbohydrates in the leaves (72.2% and 60.5% for sugar and starch, respectively), and consequently stimulated plant photosynthesis by 19.8% in the subsequent days." "[T]he enhancement of plant photosynthesis overcompensated the increased carbon loss via plant respiration under nocturnal warming and shifted the steppe ecosystem from a minor carbon source (1.87 g C/m2/year) to a carbon sink (21.72 g C/m2/year) across the three growing seasons." The data show that "plant photosynthetic overcompensation may partially serve as a negative feedback mechanism for [the] terrestrial biosphere to climate warming," where "the photosynthetic overcompensation induced by nocturnal warming can ... regulate terrestrial carbon sequestration and negatively feed back to climate change." |
| Churkina, G., Brovkin, V., von Bloh, W., Trusilova, K., Jung, M. and Dentener, F. 2009. Synergy of rising nitrogen depositions and atmospheric $CO_2$ on land carbon uptake moderately offsets global warming. Global Biogeochemical Cycles 23: 10.1029/2008GB003291. | Churkina *et al.* first determined that their global- and continental-scale estimates of land carbon uptake in the 1990s were "consistent with previously reported data." This comparison with the real world gave them confidence in the results their modeling exercise projected for the future, namely, that "increasing nitrogen deposition and the |

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| | physiological effect of elevated atmospheric $CO_2$ on plants have the potential to increase the land carbon sink, to offset the rise of $CO_2$ concentration in the atmosphere, and to reduce global warming." More specifically, they found that predicted changes in climate, $CO_2$ and nitrogen deposition for the year 2030 were sufficient to offset atmospheric $CO_2$ by a sizable 41 ppm. And if likely land use changes were included in the calculations, the offset rose to a huge 76 ppm. |
| Doherty, R.M., Sitch, S., Smith, B., Lewis, S.L. and Thornton, P.K. 2010. Implications of future climate and atmospheric $CO_2$ content for regional biogeochemistry, biogeography and ecosystem services across East Africa. Global Change Biology 16: 617-640. | Doherty *et al.* report that "all simulations showed future increases in tropical woody vegetation over the region at the expense of grasslands," noting that "regional increases in net primary productivity (18-36%) and total carbon storage (3-13%) by 2080-2099 compared with the present-day were common to all simulations," and that "seven out of nine simulations continued to show an annual net land carbon sink in the final decades of the 21st century because vegetation biomass continued to increase." |
| Pan, Y., Birdsey, R., Hom, J. and McCullough, K. 2009. Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. Mid-Atlantic temperate forests. Forest Ecology and Management 259: 151-164. | For previously harvested and currently regrowing forests, "the 'fertilization' effect by elevated $CO_2$ likely enhances more sustainable carbon storage such as woody biomass (including coarse roots)." "[T]he change in atmospheric composition, particularly elevated $CO_2$, will gradually account for more of the carbon sink of temperate forests in the Mid-Atlantic region." "[S]uch a significant 'fertilization effect' on the forest carbon sequestration could eventually result in a 'greener world' after a long period of chronic change in atmospheric composition and cumulative impact." |
| Brantley, S.T. and Young, D.R. 2010. Shrub expansion stimulates soil C and N storage along a coastal soil chronosequence. Global Change Biology 16: 2052-2061. | Although soil $CO_2$ efflux was indeed stimulated by shrub encroachment in the younger soils, "soil $CO_2$ efflux did not vary between shrub thickets and grasslands in the oldest soils, and increases in $CO_2$ efflux in shrub thickets did not offset contributions of increased litterfall to SOC." The expansion of shrubs on barrier islands -- which often have low levels of soil carbon but a high potential for ANPP -- has the ability "to significantly increase ecosystem C sequestration." "[S]timulation of N storage beneath shrub thickets will also favor future growth of species with lower nutrient use efficiencies than native grasses, including climax maritime forest species that could sequester additional C in biomass." |
| Janssens, I.A., Dieleman, W., Luyssaert, S., | The data revealed that "nitrogen deposition |

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| Subke, J.-A., Reichstein, M., Ceulemans, R., Ciais, P., Dolman, A.J., Grace, J., Matteucci, G., Papale, D., Piao, S.L., Schulze, E.-D., Tang, J. and Law, B.E. 2010. Reduction of forest soil respiration in response to nitrogen deposition. Nature Geoscience 3: 315-322. | impedes organic matter decomposition, and thus stimulates carbon sequestration, in temperate forest soils where nitrogen is not limiting microbial growth." What is more, "the concomitant reduction in soil carbon emissions is substantial," being "equivalent in magnitude to the amount of carbon taken up by trees owing to nitrogen fertilization." As a result "the size of the nitrogen-induced inhibition of below-ground respiration is of the same order of magnitude as the forest carbon sink." And "this effect has not been included in current carbon-cycle models," suggesting that when it is included, it will contribute much to "climate change mitigation." |
| Gloor, M., Sarmiento, J.L. and Gruber, N. 2010. What can be learned about carbon cycle climate feedbacks from the $CO_2$ airborne fraction? Atmospheric Chemistry and Physics 10: 7739-7751. | The three researchers determined that increases in atmospheric levels of $CO_2$ do not reduce earth's carbon sink efficiency. |
| Frey, S.D., Ollinger, S., Nadelhoffer, K., Bowden, R., Brzostek, E., Burton, A., Caldwell, B.A., Crow, S., Goodale, C.L., Grandy, A.S., Finzi, A., Kramer, M.G., Lajtha, K., LeMoine, J., Martin, M., McDowell, W.H., Minocha, R., Sadowsky, J.J., Templer, P.H. and Wickings, K. 2014. Chronic nitrogen additions suppress decomposition and sequester soil carbon in temperate forests. *Biogeochemistry* **121**: 305-316. | "The terrestrial biosphere sequesters up to a third of annual anthropogenic carbon dioxide emissions," This study revealed that the two decades of experimental N additions, "resulted in an 11-38% increase in ecosystem C storage in a hardwood stand, representing an accumulation of 20-30 kg C per kg of N added." "Soil C responses to long-term N additions have yet to be incorporated into global-scale C balance models," and "this is needed to accurately simulate future changes in terrestrial C storage in response to atmospheric N deposition." |
| Kelley, D.I. and Harrison, S.P. 2014. Enhanced Australian carbon sink despite increased wildfire during the 21st century. Environmental Research Letters **9**: 10.1088/1748-9326/9/10/104015. | Even with increased risk of wildfire, Australia's ecosystem will be able to sequester more carbon if $CO_2$ levels keep increasing than under low-$CO_2$ scenarios. |
| ***D. Plants Are Capable Of Adapting To Moderate Warming*** | |
| Crimmins, S.M., Dobrowski, S.Z., Greenberg, J.A., Abatzoglou, J.T. and Mynsberge, A.R. 2011. Changes in climatic water balance drive downhill shifts in plant species' optimum elevations. *Science* **331**: 324-327. | Temperature is not the all-important factor when it comes to determining how plants will migrate in the face of a suite of multiple climatic factors in a state of flux. Plants can actually alter what may have long been their standard optimum operating temperature when changing environmental conditions require such a change. |
| Fang, J., Kato, T., Guo, Z., Yang, Y., Hu, H., Shen, H., Zhao, X., Kishimoto-Mo, A.W., Tang, Y. and Houghton, R.A. 2014. Evidence for environmentally enhanced forest growth. *Proceedings of the National Academy of Sciences USA* **111**: 9527-9532. | Examination of Japanese forests shows that ability of trees to absorb $CO_2$ does not decline over time as much as expected. Also, the absorption can be affected by growth spurred by increased $CO_2$. |
| Frei, E.R., Ghazoul, J. and Pluess, A.R. 2014. | Different species of plant from different |

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| Plastic responses to elevated temperature in low and high elevation populations of three grassland species. *PLOS ONE* **9**: e98677. | elevations were examined at higher temperatures. All showed evolutionary adaptation and trait plasticity that would allow survival under hotter conditions. |
| Drewry, D., Kumar, P. and Long, S.P. 2014. Simultaneous improvement in productivity, water use, and albedo through crop structural modification. *Global Change Biology* **20**: 1955-1967. | It would be possible to breed plants to select for productivity, water use, and albedo in a way that would increase food production while mitigating the effects of warming. |
| Hardtle, W., Niemeyer, T., Assmann, T., Aulinger, A., Fichtner, A., Lang, A., Leuschner, C., Neuwirth, B., Pfister, L., Quante, M., Ries, C., Schuldt, A. and von Oheimb, G. 2013. Climatic responses of tree-ring width and δ13C signatures of sessile oak (Quercus petraea Liebl.) on soils with contrasting water supply. Plant Ecology 214: 1147-1156. | Hardtle *et al.* conclude that "Q. petraea showed little climate sensitivity and was able to recover from climate extreme events even at tree-ages beyond 200 years" and their findings "indicate the importance of Q. petraea as an adaptive tree species in forest ecosystems of Central Europe under shifting climatic conditions." |
| Frei, E.R., Ghazoul, J., Matter, P., Heggli, M. and Pluess, A.R. 2014. Plant population differentiation and climate change: responses of grassland species along an elevational gradient. Global Change Biology 20: 441-455. | Quoting Frei *et al.*, "we conclude that, for our study species, the expected upward shift of optimal climatic conditions will not necessarily lead to a shift of population and species ranges to higher elevations in the context of climate change," since "plasticity will buffer the detrimental effects of climate change." |
| Tinner, W., Colombaroli, D., Heiri, O., Henne, P.D., Steinacher, M., Untenecker, J., Vescovi, E., Allen, J.R.M., Carraro, G., Conedera, M., Joos, F., Lotterr, A.F., Luterbacher, J., Samartrin, S. and Valsecchi, V. 2013. The past ecology of Abies alba provides new perspectives on future responses of silver fir forests to global warming. Ecological Monographs83: 419-439. | The study finds that the future geographic range of silver fir trees is unlikely to contract, even if climate should become significantly warmer than today. |
| Keller, S.R., Soolanayakanahally, R.Y., Guy, R.D., Silim, S.N., Olson, M.S. and Tiffin, P. 2011. Climate-driven local adaptation of ecophysiology and phenology in balsam poplar, *Populus balsamifera* L. (Salicaceae). *American Journal of Botany* **98**: 99-108. | "Balsam poplar is both highly variable and capable of a broad range of adaptive physiological responses to a changing climate." |
| Chen, C.P., Sakai, H., Tokida, T., Usui, Y., Nakamura, H. and Hasegawa, T. 2014. Do the rich always become richer? Characterizing the leaf physiological response of the high-yielding rice cultivar Takanari to free-air $CO_2$ enrichment. Plant & Cell Physiology 55: 381-391. | "[T]he development of crops which are well suited to growth under future environmental conditions such as higher atmospheric $CO_2$ concentrations is essential to meeting the challenge of ensuring food security in the face of the growing human population and changing climate," and, the Takanari rice cultivar "may be a valuable resource for rice breeding programs which seek to increase crop productivity under current and future $CO_2$ concentrations." |
| Marinciu, C., Mustatea, P., Serban, G., Ittu, G. and Sauleseu, N.N. 2013. Effects of climate change and genetic progress on performance of wheat cultivars, during the last twenty years in south Romania. *Romanian Agricultural* | New wheat cultivars easily offset any observed negative effects of climate change. |

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| *Research*, No. 30, Online ISSN 2067-5720. | |
| Cullen, B.R., Eckard, R.J. and Rawnsley, R.P. 2012. Resistance of pasture production to projected climate changes in south-eastern Australia. *Crop and Pasture Science* **63**: 77-86. | Adaptation strategies will enable Australian pastures to withstand temperature rises of up to 2 C. |
| Hahn, T., Kettle, C.J., Ghazoul, J., Frei, E.R., Matter, P. and Pluess, A.R. 2012. Patterns of genetic variation across altitude in three plant species of semi-dry grasslands. *PLoS ONE* **7**: e41608. | Plant populations do not lose genetic variation at upper altitudinal edges. |
| Zhang, Y.-Y., Fischer, M., Colot, V. and Bossdorf, O. 2012. Epigenetic variation creates potential for evolution of plant phenotypic plasticity. *New Phytologist* **197**: 314-322. | Rapid evolution based on inherent gene variations--including plasticity and adaptability--is possible. |
| Osorio, M.L., Osorio, J., Vieira, A.C., Goncalves, S. and Romano, A. 2011. Influence of enhanced temperature on photosynthesis, photooxidative damage, and antioxidant strategies in *Ceratonia siliqua* L. seedlings subjected to water deficit and rewatering. *Photosynthetica* **49**: 3-12. | Tests involving the Carob or St. John's Bread Tree determined that they have a remarkable ability to quickly restore physiological activity after drought upon rehydration. |
| Vigouroux, Y., Mariac, C., De Mita, S., Pham, J.-L., Gerard, B., Kapran, I., Sagnard, F., Deu, M., Chantereau, J., Ali, A., Ndjeunga, J., Luong, V., Thuillet, A.-C., Saidou, A.-A. and Bezancon, G. 2001. Selection for earlier flowering crop associated with climatic variations in the Sahel. *PLos ONE* **6**: 10.1371/journal.pone.0019563. | "Recurrent drought can lead to selection for earlier flowering in a major Sahelian crop." |
| Ettinger, A.K., Ford, K.R. and Hille Ris Lambers, J. 2011. Climate determines upper, but not lower, altitudinal range limits of Pacific Northwest conifers. *Ecology* **92**: 1323-1331. | The study funds a lack of climatic constraints on range limits of Pacific Northwest conifers. |
| Rasineni, G.K., Guha, A. and Reddy, A.R. 2011. Responses of *Gmelina arborea*, a tropical deciduous tree species, to elevated atmospheric $CO_2$: Growth, biomass productivity and carbon sequestration efficacy. *Plant Science* **181**: 428-438. | There are management options for creating short-rotation deciduous tree plantations to achieve increased sequestration of carbon in a future elevated $CO_2$ environment. |
| Gouvea, J.R.F., Sentelhas, P.C., Gazzola, S.T. and Santos, M.C. 2009. Climate changes and technological advances: Impacts on sugarcane productivity in tropical southern Brazil. Scientia Agricola 66: 593-605. | The authors used the agrometeorological model of Doorenbos and Kassam (1994) "to estimate sugarcane yield in tropical southern Brazil, based on future A1B climatic scenarios presented in the fourth Intergovernmental Panel on Climate Change report," first calculating potential productivity, which considers "the possible impacts caused by changes in temperature, precipitation, sunshine hours and $CO_2$ concentration in the atmosphere, as well as technological advances," and then actual productivity, which additionally accounts for the yield-reducing effects of water stress. Gouvea *et* |

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| | *al.* calculate that "potential productivity will increase by 15% in relation to the present condition in 2020, by 33% in 2050 and by 47% in 2080," and that "actual productivity will increase by 12% in relation to the present condition in 2020, by 32% in 2050 and by 47% in 2080." Of these productivity gains, they further indicate that the portions due to expected technological advances, including the development of new varieties and best management practices, will account for 35% of the yield gains in 2020, 51% in 2050, and 61% in 2080. |
| Stocklin, J., Kuss, P. and Pluess, A.R. 2009. Genetic diversity, phenotypic variation and local adaptation in the alpine landscape: case studies with alpine plant species. Botanica Helvetica 119: 125-133. | "The evolutionary potential to respond to global change is mostly intact in alpine plants, even at high altitude." |
| Wyckoff, P.H. and Bowers, R. 2010. Response of the prairie-forest border to climate change: impacts of increasing drought may be mitigated by increasing $CO_2$. Journal of Ecology 98: 197-208. | "The sensitivity of annual growth rates to drought has steadily declined over time as evidenced by increasing growth residuals and higher growth rates for a given PDSI [Palmer Drought Severity Index] value after 1950 [when the atmosphere's $CO_2$ concentration rose by 57 ppm from 1950 to 2000] compared with the first half of the century [when the $CO_2$ increase was only 10 ppm]." Declining sensitivity of growth to drought translates into lower predicted mortality rates at all sites," and that "at one site, declining moisture sensitivity yields a 49% lower predicted mortality from a severe drought." Hence, "the decreasing drought sensitivity of established trees may act as a buffer and delay the movement of the prairie-forest ecotone for many decades even in the face of climate change." |
| Gunderson, C.A., O'Hara, K.H., Campion, C.M., Walker, A.V. and Edwards, N.T. 2010. Thermal plasticity of photosynthesis: the role of acclimation in forest responses to a warming climate. Global Change Biology 16: 2272-2286. | "[W]arming treatments resulted in a shift in the temperature response curves for $CO_2$ assimilation, such that leaves in warmer treatments had higher temperature optima." This adjustment in photosynthetic response was typically accomplished over a period of as little as two days. The strong acclimation potential observed in this investigation suggests that seedling physiology is not as sensitive to warming per se as predicted by original algorithms." Concluding the high degree of homeostasis observed indicates that direct impacts of climatic warming on forest productivity, species survival, and range limits may be less than predicted by existing models." |
| Frei, E., Bodin, J. and Walther, G.-R. 2010. Plant species' range shifts in mountainous areas -- all uphill from here? *Botanica* | Although there is indeed a general tendency for plant species to move upward in elevation at their *cold*-limited range boundary in |

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| *Helvetica* **120**: 117-128. | response to rising temperatures, some remain stationary and some even move in the opposite direction, while at their *heat*-limited range boundary, many do not move at all. |
| Olmstead, A.L. and Rhode, P.W. 2011. Adapting North American wheat production to climatic challenges, 1839-2009.*Proceedings of the National Academy of Sciences USA* **108**: 480-485. | Modern agronomic research will enable us to meet any challenges posed by future climate change. |
| Baily, J.K., Genung, M.A., Ware, I., Gorman, C., Nuland, M.V., Long, H. and Schweitzer, J.A. 2014. Indirect genetic effects: an evolutionary mechanism linking feedbacks, genotypic diversity and coadaptation in a climate change context. Functional Ecology 28: 87-95. | Noting that “rapid evolution is common” and that “genetic divergence occurs along a variety of gradients, including those affected by global change,” Bailey opines that “this body of work heralds a new direction in climate change research and broadens our perspectives on the consequences of gradients to eco-evolutionary dynamics in a changing world.” |
| Kell, D.B. 2011. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany* **108**: 407-418. | Benefits to be reaped from the breeding of crops that produce deeper and more “bushy” root systems than they do currently include much greater steady-state trapping of carbon, and also of nutrients and water, leading to improved drought and flooding tolerance, greater biomass yields, and better soil structure and steady-state carbon sequestration. |
| Hudson, J.M.G. and Henry, G.H.R. 2010. High Arctic plant community resists 15 years of experimental warming. Journal of Ecology 98: 1035-1041. | This evergreen-shrub heath continues to exhibit community-level resistance to long-term experimental warming.” Other plant communities have also “exhibited strong resistance to simulated climate change manipulations, where resistance is defined as the ability of a community to maintain its composition and structure in the face of environmental change.” |
| Izaurralde, R.C., Thomson, A.M., Morgan, J.A., Fay, P.A., Polley, H.W. and Hatfield, J.L. 2011. Climate impacts on agriculture: Implications for forage and rangeland production. *Agronomy Journal* **103**: 371-381. | “Diversified crop-livestock production systems would provide increased resilience to conditions of higher $CO_2$, higher temperatures, and uncertain precipitation changes, and therefore help ensure pasture and rangeland production under future climates.” |
| Goufo, P., Pereira, J., Moutinho-Pereira, J., Correia, C.M., Figueiredo, N., Carranca, C., Rosa, E.A.S. and Trindade, H. 2014. Rice (*Oryza sativa* L.) phenolic compounds under elevated carbon dioxide ($CO_2$) concentration. *Environmental and Experimental Botany* **99**: 28-37. | “Phenolic compounds are emerging as important defense compounds in rice,” Several flavonoids “have also been found to exhibit antibiotic activities against the soil-borne pathogenic fungi *Rhizoctonia solani* and *Fusarium oxysporum*,” which they say are “the causal agents of rice seedling rot disease,” again citing Kong *et al.* (2004), as well as Olofsdotter *et al.* (2002). Data indicate the rise in the air’s $CO_2$ concentration may well “increase plant resistance to specific weeds, pests and pathogens.” |

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| Afkhami, M.E., McIntyre, P.J. and Strauss, S.Y. 2014. Mutualist-mediated effects on species' range limits across large geographic scales. *Ecology Letters* **17**: 1265-1273. | "Understanding the processes determining species range limits is central to predicting species distributions under climate change." Without a proper understanding and incorporation of these important biotic interactions, projections of species range reductions -- such as those anticipated by the IPCC -- as a result of future climate change should be reassessed. |
| dos Santos, D.L. and Sentelhas, P.C. 2014. Climate change scenarios and their impact on water balance and sugarcane yield in Southern Brazil. *Sugar Tech* **16**: 356-365. | The study "assesses the impacts of different climate change scenarios on water balance and on potential and attainable yields of four sugarcane production regions in the state of São Paulo." The results of this exercise indicated that "even with the huge impact of climate change on the water balance of all locations, the potential and actual yields may increase substantially as a function of the combination of higher air temperatures, higher $CO_2$ concentration and also better management practices in the future scenarios." |
| Hart, J.L., Oswalt, C.M. and Turberville, C.M. 2014. Population dynamics of sugar maple through the southern portion of its range: implications for range migration. *Botany* **92**: 563-569. | One of the major concerns of projected future $CO_2$-induced global warming is that temperatures might rise so fast and furiously that many plant species will be driven to extinction, being unable to migrate fast enough toward cooler regions of the planet to keep pace with the projected warming. The results of study indicate that (1) "over the past 20 years, the southern range boundary of sugar maple has neither contracted nor expanded," and that (2) "when accounting for documented northern range boundary shifts, these results indicate an expansion of the geographic distribution for sugar maple at this time attributed to the relatively stable southern range boundary." |
| Teixeira, J.E.C., Weldekidan, T., de Leon, N., Flint-Garcia, S., Holland, J.B., Lauter, N., Murray, S.C., Xu, W., Hessel, D.A., Kleintop, A.E., Hawk, J.A., Hallauer, A. and Wisser, R.J. 2015. Hallauer's Tuson: a decade of selection for tropical-to-temperate phonological adaptation in maize. *Heredity* **114**: 229-240 | Crop species, in particular maize, exhibit an astounding capacity for environmental adaptation. |
| Bothwell, L.D., Selmants, P.C., Giardina, C.P. and Litton, C.M. 2014. Leaf litter decomposition rates increase with rising mean annual temperature in Hawaiian tropical montane wet forests. *PeerJ* **2**: 10.7717/peerj.685. | "An increase in rates of nutrient release from decaying leaf litter with climate warming, as suggested by our results, could delay or even prevent the onset of progressive nutrient limitation of ecosystem carbon sequestration." |

| **V. Humans Would Flourish In A Moderately Warmer Climate, and Adaptation Will Increase the Benefits Even More** | |
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| Bennett, C.M., Dear, K.B.G. and McMichael, A.J. 2014. Shifts in the seasonal distribution of deaths in Australia, 1968-2007. *International Journal of Biometeorology* **58**: 835-8428. | Ratio of mortality in summer months versus winter months has risen since 1968, driven by fewer deaths in winters (which have been milder). Moreover the rate at which winters warm is greater than the rate at which summers warm, suggesting that temperature-related mortality may net decrease as climate warms. |
| Petkova, E.P., Gasparrini, A. and Kinney, P.L. 2014. Heat and mortality in New York City since the beginning of the 20th century. *Epidemiology* **25**: 554-560. | Humans adapt to rising temperatures; greater standard of living permits better adaptation. |
| Wiltshire, A., Gornall, J., Booth, B., Dennis, E., Falloon, P., Kay, G., McNeall, D., McSweeney, C. and Betts, R. 2013. The importance of population, climate change and $CO_2$ plant physiological forcing in determining future global water stress. Global Environmental Change 23: 1083-1097. | Wiltshire *et al.* conclude that population growth will cause water stress, regardless of warming, and state in relevant part that "the effect of $CO_2$ on plant water use efficiency is likely to have a direct effect on run-off causing increased water availability." Further, "the effect of rising $CO_2$ is to increase available water and to reduce the number of people living in high water stress by around 200 million compared to climate only projections." |
| Lindeboom, W., Alam, N., Begum, D. and Streatfield, P.K. 2012. The association of meteorological factors and mortality in rural Bangladesh, 1983-2009. *Global Health Action* **5**: 61-73. | While Bangladesh has experienced a generally rising mortality rate, that increase is markedly higher for temperatures below mean, and smaller for temperatures above mean, suggesting that warmer weather leads to a slower rise in mortality. |
| Mrema, S., Shamte, A., Selemani, M. and Masanja, H. 2012. The influence of weather on mortality in rural Tanzania: a time-series analysis 1999-2010. *Global Health Action* **5**: 33-43. | Relative cold--in this case 7 C below mean--results in dramatically higher mortality rates than relative heat does. |
| Egondi, T., Kyobutungi, C., Kovats, S., Muindi, K., Ettarh, R. and Rocklov, J. 2012. Time-series analysis of weather and mortality patterns in Nairobi's informal settlements. *Global Health Action* **5**: 23-31. | Even in warm regions such as Kenya, mortality tends to rise as climate cools, not as it warms. |
| Jackson, M.C., Johansen, L., Furlong, C., Colson, A. and Sellers, K.F. 2010. Modelling the effect of climate change on prevalence of malaria in western Africa. *Statistica Neerlandica* **64**: 388-400. | Very little correlation exists between rates of malaria prevalence and climate indicators in western Africa. |
| Kampen, H. and Werner, D. 2010. Three years of bluetongue disease in central Europe with special reference to Germany: what lessons can be learned? *Wiener Klinische Wochenschrift* **122** (Suppl. 3): 31-39. | It is due to continuing globalization rather than to climate change that even central and northern Europe are at risk of new pathogens as well as vectors of disease entering and establishing. |
| Ooi, E.-E. and Gubler, D.J. 2009. Global spread of epidemic dengue: the influence of environmental change. *Future Virology* **4**: 571- | "There is no good evidence to suggest that the current geographic expansion of the dengue virus and its vectors has been or will |

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| 580. | be due to global warming." |
| Ibelings, B.W., Gsel, A.S., Mooij, W.M., van Donk, E., van den Wyngaert, S. and Domis, L.N. de S. 2011. Chytrid infections and diatom spring blooms: paradoxical effects of climate warming on fungal epidemics in lakes. *Freshwater Biology* **56**: 754-766. | Climate warming is not invariably linked with disease emergence and may actually reduce fungal epidemics. |
| Toro, K., Bartholy, J., Pongracz, R., Kis, Z., Keller, E. and Dunay, G. 2010. Evaluation of meteorological factors on sudden cardiovascular death. *Journal of Forensic and Legal Medicine* **17**: 236-242. | Sudden cardiovascular deaths are inversely related to air temperature in Budapest. |
| Haque, U., Hashizume, M., Glass, G.E., Dewan, A.M., Overgaard, H.J. and Yamamoto, T. 2010. The role of climate variability in the spread of malaria in Bangladeshi highlands. *PLoS ONE* **5**: 10.1371/journal.pone.0014341. | There is no evidence for any association between the number of malaria cases in Bangladesh and temperature, rainfall and humidity. |
| Nkurunziza, H. and Pilz, J. 2011. Impact of increased temperature on malaria transmission in Burundi. *International Journal of Global Warming* **3**: 77-87. | Increased temperatures in Burundi may reduce mosquito survival and, therefore, reduce malaria. |
| Reiter, P. 2008. Global warming and malaria: knowing the horse before hitching the cart. *Malaria Journal* **7**(Supplement 1): 10.1186/1475-2875-7-S1-S3. | The principal determinants of malaria are linked to ecological and societal change, politics and economics, rather than climate change. |
| Yang, X., Hou, Y. and Chen, B. 2011. Observed surface warming induced by urbanization in east China. *Journal of Geophysical Research* **116**: 10.1029/2010JD015452. | Urban heat island effects are real and contribute significantly to warming and are ignored by the current focus on greenhouse gas reductions. |
| Hulden, L. and Hulden, L. 2009. The decline of malaria in Finland -- the impact of the vector and social variables. *Malaria Journal* **8**: 10.1186/1475-2875-8-94. | Malaria in Finland was a sociological disease and malaria trends were strongly linked to changes in the human household size and housing standard. |
| Grundstein, A. and Dowd, J. 2011. Trends in extreme apparent temperatures over the United States, 1949-2010.*Journal of Applied Meteorology and Climatology* **50**: 1650-1653. | Heat-related mortality in major metropolitan areas declined over the 1961-1998 period. |
| Matzarakis, A., Muthers, S. and Koch, E. 2011. Human biometeorological evaluation of heat-related mortality in Vienna. *Theoretical and Applied Climatology* **105**: 1-10. | Researchers found a significant relationship between heat stress and mortality in Vienna, but noted some significant decreases of the sensitivity to the stresses. |
| Zhang, D.D., Lee, H.F., Wang, C., Li, B., Pei, Q., Zhang, J. and An, Y. 2011a. The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences USA*: 10.1073/pnas.1104268108. | Cooling was the ultimate cause, and cooling-driven economic downturn was the direct cause, of large-scale human crises in pre-industrial Europe and the Northern Hemisphere. |
| Kysely, J., Plavcova, E., Davidkovova, H. and Kyncl, J. 2011. Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. *Climate Research* **49**: 113-129. | In the context of climate change, substantial reductions in cold-related mortality are very likely in mid-latitudinal regions, particularly if the increasing adaptability of societies to weather is taken into account. It is probable that reductions in cold-related mortality will be more important than possible increases in |

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| | heat-related mortality. |
| Wichmann, J., Anderson, Z.J., Ketzel, M., Ellermann, T. and Loft, S. 2011. Apparent temperature and cause-specific mortality in Copenhagen, Denmark: A case-crossover analysis. *International Journal of Environmental Research and Public Health* **8**: 3712-3727. | Warm weather in Copenhagen corresponded with reduced deaths due to cardiovascular disease and was not associated with death from cerebrovascular disease and respiratory disease. During the cold months, all three associations were inverse or protective. |
| Nabi, S.A. and Qader, S.S. 2009. Is global warming likely to cause an increased incidence of malaria? Libyan Journal of Medicine 4: 18-22. | The two researchers conclude that "global warming alone will not be of a great significance in the upsurge of malaria unless it is accompanied by a deterioration in other parameters like public health facilities, resistance to anti-malarial drugs, decreased mosquito control measures." Hence, they say that "no accurate prediction about malaria can truly be made," since "it is very difficult to estimate what the other factors will be like in the future." |
| Young, T.K. and Kakinen, T.M. 2010. The health of Arctic populations: Does cold matter? American Journal of Human Biology 22: 129-133. | The two researchers report that mean January temperature correlated negatively with several health outcomes, including infant mortality rate, age-standardized mortality rates (all causes, respiratory, cancer, injuries), perinatal mortality rate and tuberculosis incidence rate, but that it correlated positively with life expectancy. That is to say, as mean January temperature rose, the desirable metric of life expectancy at birth rose right along with it, while all of the undesirable health metrics (such as mortality and disease incidence) declined. For example, they report that "for every 10°C increase in mean January temperature, the life expectancy at birth among males increased by about six years," while "infant mortality rate decreased by about four deaths per thousand live births." |
| Roger Bezdek, Robert Hirsch, Robert Wendling, *The Impending World Energy Mess*, Toronto, Canada: Apogee Prime Press, 2010. | The authors find more energy is required to heat a structure than to cool it, and relatively cold temperatures require large quantities of energy to ensure survivability and livability. Transportation – by vehicle, train, boat, or airplane – in a colder climate is more difficult and energy intensive than transportation in a warmer climate. One of the primary hazards during a cold winter is the loss of electrical power and access to energy. |
| Bayentin, L., El Adlouni, S., Ouarda, T.B.M.J., Gosselin, P., Doyon, B. and Chebana, F. 2010. Spatial variability of climate effects on ischemic heart disease hospitalization rates for the period 1989-2006 in Quebec, Canada. International Journal of Health Geographics 9:10.1186/1476-072X-9-5. | Bayentin *et al.* find that "a decline in the effects of meteorological variables on IHD daily admission rates was observed over the period of 1989-2006," which observation, in their words, "can partly be explained by the changes in surface air temperature," which they describe as warming "over the last few decades," as is further described by Bonsal |

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| | *et al.* (2001) and Zhang *et al.* (2000) for the 20th-century portion of the study's duration. In addition, they note that "winters have been steadily warmer," while "summers have yet to become hotter for most regions," which is another beneficial characteristic of the warming that was experienced over most of the planet throughout the latter part of the 20th century (Easterling *et al.*, 1997). |
| Reiter, P. 2010. West Nile virus in Europe: understanding the present to gauge the future. Eurosurveillance 15: eurosurveillance.org/ViewArticle.aspx ?Articleid=19508. | Reiter states that "one point is clear: the importation and establishment of vector-borne pathogens that have a relatively low profile in their current habitat is a serious danger to Europe and throughout the world," which state of affairs, in his view, "is a direct result of the revolution of transport technologies and increasing global trade that has taken place in the past three decades." And he further concludes that in view of what his review reveals, "globalization is potentially a far greater challenge to public health in Europe than any future changes in climate (Tatem *et al.*, 2006)." |
| Fernandez-Raga, M., Tomas, C. and Fraile, R. 2010. Human mortality seasonality in Castile-Leon, Spain, between 1980 and 1998: the influence of temperature, pressure and humidity. International Journal of Biometeorology 54: 379-392. | For all three of the disease types studied, Fernandez-Raga *et al.* found that "the death rate is about 15% higher on a winter's day than on a summer's day," which they describe as "a result often found in previous studies," citing the work of Fleming *et al.* (2000), Verlato *et al.* (2002), Grech *et al.* (2002), Law *et al.* (2002) and Eccles (2002). |
| Gething, P.W., Smith, D.L., Patil, A.P., Tatem, A.J., Snow, R.W. and Hay, S.I. 2010. Climate change and the global malaria recession. Nature 465: 342-345. | "[C]laims that rising mean temperatures have already led to increases in worldwide malaria morbidity and mortality are largely at odds with observed decreasing global trends in both." In fact, they report that "the combined natural and anthropogenic forces acting on the disease throughout the twentieth century have resulted in the great majority of locations undergoing a net reduction in transmission between one and three orders of magnitude larger than the maximum future increases proposed under temperature-based climate change scenarios." |
| Zhang, Z., Tian, H., Cazelles, B., Kausrud, K.L., Brauning, A. Guo, F. and Stenseth, N.C. 2010. Periodic climate cooling enhanced natural disasters and wars in China during AD 10-1900. Proceedings of the Royal Society B 277: 10.1098/rspb.2010.0890. | "[F]ood production during the last two millennia has been more unstable during cooler periods, resulting in more social conflicts." "It is very probable that cool temperature may be the driving force in causing high frequencies of meteorological, agricultural disasters and then man-made disasters (wars) in ancient China," noting that "cool temperature could not only reduce agricultural and livestock production directly, |

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| | but also reduce agricultural production by producing more droughts, floods and locust plagues," while stating that the subsequent "collapses of agricultural and livestock production would cause wars within or among different societies." |
| Christidis, N., Donaldson, G.C. and Stott, P.A. 2010. Causes for the recent changes in cold- and heat-related mortality in England and Wales. Climatic Change 102: 539-553. | When adaptation was included in the analysis, as was the case in the data they analyzed, they found there were only 0.7 death per million people per year due to warming in the hottest part of the year, but a decrease of fully 85 deaths per million people per year due to warming in the coldest part of the year, for a lives-saved to life-lost ratio of 121.4. |
| Dunn, R.R., Davies, T.J., Harris, N.C. and Gavin, M.C. 2010. Global drivers of human pathogen richness and prevalence. Proceedings of the Royal Society B 277: 2587-2595. | "[P]athogen richness (number of kinds) is largely explained by the number of birds and mammal species in a region," "[T]he most diverse countries with respect to birds and mammals are also the most diverse with respect to pathogens." "We are unlikely to be able to change patterns of pathogen richness dramatically," In fact, "pathogen prevalence is much more sensitive to variation in health spending among regions," and "importantly, for human health, the prevalence of key human pathogens is strongly influenced by disease control efforts." |
| Johansson, M.A., Cummings, D.A.T. and Glass, G.E. 2009. Multiyear climate variability and dengue-El Niño Southern Oscillation, weather and dengue incidence in Puerto Rico, Mexico, and Thailand: A longitudinal data analysis. PLoS Medicine 6: e1000168. | The three researchers report that they "did not find evidence of a strong, consistent relationship in any of the study areas" between weather and dengue, while Rohani (2009), who wrote a Perspective piece on their study, states that the three researchers found "no systematic association between multi-annual dengue outbreaks and El Niño Southern Oscillation." Thus, as stated in the "Editors' Summary" of Johansson *et al.*'s paper, their findings "provide little evidence for any relationship between ENSO, climate, and dengue incidence." |
| Williams, C.R., Mincham, G., Ritchie, S.A., Viennet, E. and Harley, D. 2014. Bionomic response of *Aedes aegypti* to two future climate change scenarios in far north Queensland, Australia: implications for dengue outbreaks. *Parasites & Vectors* **7**: 10.1186/1756-3305-7-447. | Williams *et al.* say "it is therefore unclear whether dengue risk would increase or decrease in tropical Australia with climate change." And they thus conclude that their findings "challenge the prevailing view that a future, warmer climate will lead to larger mosquito populations and a definite increase in dengue transmission." |
| Coates, L., Haynes, K., O'Brien, J., McAneney, J. and Dimer de Oliveira, F. 2014. Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844-2010. *Environmental Science & Policy* **42**: 33-4. | "Both deaths and death rates (per unit of population) fluctuate widely but show an overall decrease with time." This drop in death rate has occurred, as they describe it, in spite of the fact that "the elderly are significantly more vulnerable to the risk of heat-associated death than the general |

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| | population, and this vulnerability increases with age." Nevertheless, they clearly state that "death rates amongst seniors also show a decrease with time." |
| Zhou, X., Zhao, A., Meng, X., Chen, R., Kuang, X., Duan, X. and Kan, H. 2014. Acute effects of diurnal temperature range on mortality in 8 Chinese cities. *Science of the Total Environment* **493**: 92-97. | An *increase* in diurnal temperature range (DTR) has been found to lead to an *increase* in daily mortality in several Chinese cities. As a result of "the largest epidemiologic study to date in China to examine the association of DTR with daily mortality" indicates that the global warming of Earth's recent past was characterized by daily minimum temperatures rising three times more than daily maximum temperatures, thereby significantly reducing the DTR and saving a significant number of lives worldwide. |
| Bobb, J.F., Peng, R.D., Bell, M.L. and Dominici, F. 2014. Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives* **122**: 811-816. | One of the concerns expressed by the IPCC with respect to the potential impacts of $CO_2$-induced global warming is an increase in the number of heat related deaths, which they predict should be rising in response to enhanced summertime temperature variability and more extreme heat waves, particularly among the elderly. "Increasing temperatures are anticipated to have profound health impacts," but "little is known about the extent to which the population may be adapting." Data show the U.S. population has "become more resilient to heat over time." |
| Cheng, J., Xu, Z., Zhu, R., Wang, X., Jin, L., Song, J. and Su, H. 2014. Impact of diurnal temperature range on human health: a systematic review. *International Journal of Biometeorology* **58**: 2011-2024. | A review of the findings of 25 different studies,, 11 of which investigated the relationship between Diurnal Temperature Range (DTR) and *mortality* (death), and 14 of which examined the impact of DTR on *morbidity* (hospitalization). Both found that a decrease in DTR - such as typically occurs when Earth's climate is in a warming mode - leads to decreases in both morbidity and mortality. |
| Son, J.-Y, Bell, M.L. and Lee, J.-T. 2014. The impact of heat, cold, and heat waves on hospital admissions in eight cities in Korea. *International Journal of Biometeorology* **58**: 1893-1903. | "Cold effects generally appear higher than heat effects in most cities." In other words, although the cardiovascular hospitalization rate slightly increased as the temperature rose in general, temperature extremes from heat waves had no discernible impact. On the other hand, with respect to the effect of cold weather, they authors report there were very significant increases in hospitalizations when comparing the admissions at 2°C with those at 15°C, which increases amounted to 50.5%, 43.6 % and 53.6% for allergic diseases, asthma, and selected respiratory diseases, respectively. |
| Zhang, Y., Peng, L., Kan, H., Xu, J., Chen, R., Liu, Y. and Wang, W. 2014. Effects of | "There is limited evidence for the impacts of meteorological changes on asthma hospital |

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| meteorological factors on daily hospital admissions for asthma in adults: A time-series analysis. *PLOS ONE* **9**: e102475. | admissions in adults." After controlling for secular and seasonal trends, weather, air pollution and other confounding factors there was a significant negative correlation between asthma hospitalizations and daily mean temperature (DMT), "with lower temperatures associated with a higher risk of hospital admission for asthma," wherein "the cold effect appeared to be relatively acute, with duration lasting several weeks, while the hot effect was short-term." "Warmer temperatures were not associated with asthma hospital admissions." |
| Yu, L., Kong, F., Shi, X., Yang, Z., Zhang, M. and Yu, Y. 2015. Effects of elevated $CO_2$ on dynamics of microcystin-producing and non-microcystin-producing strains during Microcystis blooms. *Journal of Environmental Sciences* **27**: 251-258 | Warming causes an increase in the prevalence of non-mycrocystin-(a class of toxins)-producing bacteria in freshwater lakes which results in healthier drinking water. |
| Liu, Y., Guo, Y., Wang, C., Li, W., Lu,J., Shen, S., Xia, H., He, J., and Oiu, X. 2015. Association between temperature change and outpatient visits for respiratory tract infections amoung chidlren in Guangzhou, China. *International Journal of Environmental Research and Public Health***12** :439-454 | Large temperature decreases are associated with significantly increased risk of pediatric respiratory tract infections. |
| Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B. and McMichael, A.J. 2014. Comparative assessment of the effects of climate change heat- and cold-related mortality in the United Kingdom and Australia. *Environmental Health Perspectives* **122**: 1285-1292 | Cold-related mortaility is expected decrease due to global warming from 61 to approximately 42 deaths per 100,000 population per year in the UK. |
| Shen, X., Liu, B., Li, G., Wu, Z., Jin, Y., Yu, P. and Zhou, D. 2014. Spatiotemporal change of diurnal temperature range and its relationship with sunshine duration and precipitation in China. *Journal of Geophysical Research: Atmospheres***119**: 13,163-13,179. | In a study of diurnal temperature range conducted for the entirety of China based on data collected from 479 weather stations for the period 1962 to 2011, researchers found that the country-wide diurnal temperature range declined at a mean rate of 0.157°C/decade. This shows that cold temperature extremes are responsible for far more deaths around the world than are warm temperature extremes, suggesting that if the Earth warms there should be a significant decresae in temperature-related human mortality. |
| Huang, C., Chu, C., Wang, X. and Barnett, A.G. 2015. Unusually cold and dry winters increase mortality in Australia.*Environmental Research* **136**: 1-7. | In a study involving five major cities in Australia, researchers considered "how unseasonal patterns in temperature and humidity in winter and summer were associated with unseasonal patterns in death." The researchers found that there were "far more deaths in winter," such that "death rates were 20-30% higher in a winter than a summer." This demonstrates that warming of the globe actually leads to fewer |

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| | deaths from all causes combined than does maintaining the thermal status quo. |
| Oliveira, F.M., Macario, K.D., Simonassi, J.C., Gomes, P.R.S., Anjos, R.M., Carvalho, C., Linares, R., Alves, E.Q., Castro, M.D., Souza, R.C.C.L. and Marques Jr., A.N. 2014. Evidence of strong storm events possibly related to the Little Ice Age in sediments on the southern coast of Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology* **415**: 233-239. | Scientists conducted research regarding increasing atmospheric temperature's implications on global cooling. Their work consisted of collecting sediment and mollusk species' remains to investigate changes over the "Little Ice Age." The research adds further proof to the argument that increasing temperatures may be integral to combating a global Ice Age. |
| Wei, Z., Fang, X. and Su, Y. 2014. Climate change and fiscal balance in China over the past two millennia. *The Holocene* **24**: 1771-1784. | Researchers conducted an anthropological and sociological study over Chinese economic history over a 2130 year period. Their study concluded that "fiscal crisis was more likely to occur in cold-dry climatic scenarios," with heavy implications for climate change on society. This research would prove that "both temperature and precipitation displayed more significant effects on the fiscal fluctuation within the long term, particularly for temperature." |
| | Temperature extremes can be dangerous to the elderly, who are particularly susceptible to hypothermia (cold stress or low body temperatures), a condition that can cause illness or death.[1] |

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| **VI. The Evidence Does Not Support Asserted Ecosystem Harms from Moderate Warming** | |
| ***A. Moderate Warming Will Not Harm Terrestrial Ecosystems, and Will Benefit Them Due to "Greening"*** | |
| Barton, B.T. and Ives, A.R. 2014. Direct and indirect effects of warming on aphids, their predators, and ant mutualists. *Ecology* **95**: 1479-1484. | Analysis of warming effects on a system of aphids (corn/grass pest), aphid predators, and aphid-tending ants showed warming unexpectedly led to decrease in aphid population by altering ant-aphid mutualism. Warming may therefore remove a threat to food crops like corn. |
| Sanchez-de-Leon, Y., Lugo-Perez, J., Wise, D.H., Jastrow, J.D. and Gonzalez-Meler, M.A. 2014. Aggregate formation and carbon sequestration by earthworms in soil from a temperate forest exposed to elevated atmospheric $CO_2$: A microcosm experiment. Soil Biology & Biochemistry 68: 223-230. | Sanchez-de-Leon *et al.* conclude from their findings that "earthworms at the ORNL-FACE site directly contribute to the formation of soil aggregates and could be an important factor contributing to the soil stabilization of increased recent carbon inputs resulting from atmospheric $CO_2$ enrichment." |

[1] U.S. Department of Health and Human Services, "Tips for Health and Safety," available at www.acf.hhs.gov/programs/ocs/liheap/consumer_info/health.html.

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| Bartomeus, I., Park, M.G., Gibbs, J., Danforth, B.N., Lakso, A.N. and Winfree, R. 2013. Biodiversity ensures plant-pollinator phenological synchrony against climate change. Ecology Letters 16: 1331-1338. | Researchers found support for the biodiversity insurance hypothesis, or "the idea that biodiversity can buffer ecosystem functioning against the loss of individual species." The study concludes that "overall, our results suggest that pollination systems, especially for generalized species such as apple, may be buffered against climate change," while adding that their study also "supports the biodiversity insurance hypothesis" and saying that it "adds to several recent lines of evidence indicating that high levels of biodiversity are needed to sustain ecosystem function in real-world ecosystems." |
| Wurzburger, N. and Miniat, C.F. 2014. Drought enhances symbiotic dinitrogen fixation and competitive ability of a temperate forest tree. *Oecologia* **174**: 1117-1126. | Drought conditions improved the growth of nitrogen-fixing species, which alleviated nitrogen depletion in symbionts. |
| Auad, A.M., Fonseca, M.G., Resende, T.T. and Maddalena, I.S.CP. 2012. Effect of climate change on longevity and reproduction of *Sipha flava* (Hemiptera: Aphididae). *Florida Entomologist* **95**: 433-444. | Increased $CO_2$ and temperature caused key pest (sugarcane aphid) to reproduce less and live shorter life span. |
| Baffoe, K., Dalin, P., Nordlander, G. and Stenberg, J.A. 2012. Importance of temperature for the performance and biocontrol efficiency of the parasitoid *Perilitus brevicollis* (Hymenoptera: Braconidae) on *Salix*. *BioControl* **57**: 611-618. | Natural pest control (benign parasites that infect beetles that eat trees) will become stronger and more effective at higher temperatures. |
| Hamilton, J., Zangerl, A.R., Berenbaum, M.R., Sparks, J.P., Elich, L., Eisenstein, A. and DeLucia, E.H. 2012. Elevated atmospheric $CO_2$ alters the arthropod community in a forest understory. *Acta Oecologica* **43**: 80-85. | Enriched $CO_2$ environment resulted in fewer herbivorous arthropods and more predaceous arthropods--ultimately acting to the benefit of the trees. |
| Garruña-Hernandez, R., Canto, A., Mijangos-Cortes, J.O., Islas, I., Pinzon, L. and Orellana, R. 2012. Changes in flowering and fruiting of Habanero pepper in response to higher temperature and $CO_2$. *Journal of Food, Agriculture & Environment* **10**: 802-808. | Habañero pepper grows better under high-$CO_2$ conditions, including a larger number of seeds. Moreover, the robustness offsets the weakening effects of growing at higher temperatures. |
| Khumairoh, U., Groot, J.C.J. and Lantinga, E.A. 2012. Complex agro-ecosystems for food security in a changing climate. *Ecology and Evolution* **2**: 1696-1704. | Intentional cultivation of full ecosystems can boost yield of rice and make it more resilient to climatic changes. |
| Rao, M.S., Srinivas, K., Vanaja, M., Rao, G.G.S.N., Venkateswarlu, B. and Ramakrishna, Y.S. 2009. Host plant (Ricinus communis Linn.) mediated effects of elevated $CO_2$ on growth performance of two insect folivores. Current Science 97: 1047-1054. | Castor "is an important non-edible oilseed crop grown in many parts of the arid and semi-arid regions of India," Larvae fed on ambient $CO_2$ foliage, exhibited greater consumption." However, they say that the efficiency of conversion into larval biomass "decreased in the case of larvae grown on 700 and 550 ppm $CO_2$ foliage," so that they "grew slower and took longer time to pupation," which latter phenomenon would allow significantly more time (~13%) for them to be preyed upon by still |

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| | higher orders of creatures. |
| Qian, H., Wang, S., Li, Y. and Wang, X. 2009. Breeding bird diversity in relation to environmental gradients in China. Acta Oecologica 35: 819-823. | "Of all environmental variables examined, normalized difference vegetation index [NDVI], a measure of plant productivity, is the best variable to explain the variance in breeding bird richness." |
| Morgan, E.R. and Wall, R. 2009. Climate change and parasitic disease: farmer mitigation? Trends in Parasitology 25: 308-313. | The two UK researchers indicate that "several biological mechanisms (including increased parasite mortality and more rapid acquisition of immunity), in tandem with changes in husbandry practices (including reproduction, housing, nutrition, breed selection, grazing patterns and other management interventions), might act to mitigate increased parasite development rates, preventing dramatic rises in overall levels of diseases." However, because "optimum mitigation strategies will be highly system specific and depend on detailed understanding of interactions between climate, parasite abundance, host availability and the cues for and economics of farmer intervention," "there is a need for research that considers likely effects of climate change and mitigation strategies in terms of the whole host-parasite system, including anthropogenic responses, and not just in terms of parasite population dynamics." |
| Mahecha, M.D., Reichstein, M., Varvalhais, N., Lasslop, G., Lange, H., Seneviratne, S.I., Vargas, R., Ammann, C., Arain, M.A., Cescatti, A., Janssens, I.A., Migliavacca, M., Montagnani, L. and Richardson, A.D. 2010. Global convergence in the temperature sensitivity of respiration at ecosystem level. Science 329: 838-840. | "[C]ontrary to previous findings," as they describe it, they say their results "suggest that Q10 is independent of mean annual temperature, " Perhaps the most significant consequence of the new assessment of the issue writes that their new work "reduces fears that respiration fluxes may increase strongly with temperature, accelerating climate change." |
| Hillstrom, M.L., Vigue, L.M., Coyle, D.R., Raffa, K.F. and Lindroth, R.L. 2010. Performance of the invasive weevil Polydrusus sericeus is influenced by atmospheric $CO_2$ and host species. Agricultural and Forest Entomology 12: 285-292. | The five researchers, all from the University of Wisconsin's Department of Entomology, report that feeding the weevils with foliage produced on trees in the $CO_2$-enriched FACE plots had no affect on male longevity, but that it reduced female longevity by 19%. And they state that "Polydrusus sericeus egg production rate declined by 23% and total egg production declined by 29% for females fed foliage produced under elevated $CO_2$ compared with ambient $CO_2$." In light of their several findings, as well as the continued upward trend in the air's $CO_2$ content, Hillstrom *et al.* conclude that "concentrations of elevated $CO_2$ above 500 ppm have the potential to decrease P. sericeus populations by reducing female longevity and fecundity." |
| Compant, S., van der Heijden, M.G.A. and Sessitsch, A. 2010. Climate change effects on beneficial plant-microorganism interactions. FEMS Microbiology Ecology 73: 197-214. | The researchers find that "in most cases, plant-associated microorganisms had a beneficial effect on plants under elevated $CO_2$." In addition, they report that "numerous studies |

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| | indicated that plant growth-promoting microorganisms (both bacteria and fungi) positively affected plants subjected to drought stress." |
| Yin, J., Sun, Y. and Ge, F. 2014. Reduced plant nutrition under elevated $CO_2$ depresses the immunocompetence of cotton bollworm against its endoparasite. *Scientific Reports* **14**: 10.1038/srep04538. | Lower nutritive value of certain plants under elevated levels of $CO_2$ will have an adverse effect on plant-predator species (e.g., cotton bollworm), which will make them more susceptible to their predators--resulting in a net-beneficial effect on plants. |
| Stiling, P., Moon, D., Rossi, A., Forkner, R., Hungate, B.A., Day, F.P., Schroeder, R.E. and Drake, B. 2013. Direct and legacy effects of long-term elevated $CO_2$ on fine root growth and plant-insect interactions. New Phytologist 200: 788-795. | Stiling *et al.* report that "elevated $CO_2$ reduced the densities of all herbivore-damaged leaves, which included damage produced by leaf miners, leaf tiers, leaf chewers and leaf gallers, on all host plant species, including the nitrogen-fixing legume, Galactia." These results "are similar to those of other studies, most of which have also found reductions in insect herbivory under elevated $CO_2$ (reviewed in Lincoln *et al.*, 1993; Watt *et al.*, 1995; Bezemer and Jones, 1998; Hunter, 2001; Whittaker, 2001; Stiling and Cornelissen, 2007; Lindroth, 2010; Robinson *et al.*, 2012)." |
| Hamilton, J., Zangerl, A.R., Berenbaum, M.R., Sparks, J.P., Elich, L., Eisenstein, A. and DeLucia, E.H. 2012. Elevated atmospheric $CO_2$ alters the arthropod community in a forest understory. Acta Oecologica 43: 80-85. | Elevated levels of $CO_2$ may protect plants by decreasing the population of herbivorous arthropods and increasing their predators. |
| Reef, R. and Lovelock, C.E. 2014. Historical analysis of mangrove leaf traits throughout the 19th and 20th centuries reveals differential responses to increases in atmospheric $CO_2$. *Global Ecology and Biogeography* **23**: 1209-1214. | Specific leaf area or SLA - which is the ratio of leaf area to weight - is "a key indicator of $CO_2$-induced changes in photosynthetic activity and growth." The study of two species of mangrove found that while one did not show much change as a result of $CO_2$ increases during the last century, the other, common in Australia and the U.S. showed increased productivity with increased $CO_2$ levels, and that the increases have been linear, and did not appear to show a saturation level for the benefits. |
| Meehan, T.D., Couture, J.J., Bennett, A.E. and Lindroth, R.L. 2014. Herbivore-mediated material fluxes in a northern deciduous forest under elevated carbon dioxide and ozone concentrations. *New Phytologist* **204**: 397-407. | Anthropogenic $CO_2$ enrichment is "known to alter tree physiology and growth," but the "cascading effects on herbivore communities and herbivore-mediated nutrient cycling are poorly understood." The data show that the outwardly-negative activity of insect herbivores eating tree leaves may have a number of hidden (below-ground) positive consequences, which become even more positive as the air's $CO_2$ content continues its temporal upward trajectory. |
| Vogel, N., Fabricius, K.E., Strahl, J., Noonan, S.H.C., Wild, C. and Uthicke, S. 2015. Calcareous green alga *Halimeda*tolerates ocean acidification conditions at tropical carbon seeps. *Limnology and Oceanography* **60**: 263-275 | Organisms living near natural volcanic steeps are often acclimatized – and in some cases adapted – to elevated $CO_2$ environments. |

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| Bonachela, J.A., Pringle, R.M., Sheffer, E., Coverdale, T.C., Guyton, J.A., Caylor, K.K., Levin, S.A. and Tarnita, C.E. 2015. Termite mounds can increase the robustness of dryland ecosystems to climatic change. *Science* **347**: 651-655 | "Termites and other ecosystem engineers may buffer the effects of anthropogenic global change in some of the world's most environmentally and socioeconomically sensitive regions." |
| ***B. Animals Will Adapt to Moderate Warming*** | |
| Li, Y., Cohen, J.M. and Rohr, J.R. 2013. Review and synthesis of the effects of climate change on amphibians. *Integrative Zoology* **8**: 145-161. | Literature review on impact of climate change on amphibians shows no clear link. There is a lack of evidence on many subjects (morphology, tolerance, etc.), and what evidence there is shows that climate change is not "acutely lethal" to amphibians. |
| Caruso, N.M., Sears, M.W., Adams, D.C. and Lips, K.R. 2014. Widespread rapid reductions in body size of adult salamanders in response to climate change. *Global Change Biology* **20**: 1751-1759. | Salamanders (sensitive to warming because they rely on skin respiration) show rapid adaptation to warming conditions. |
| Lindstrom, T., Brown, G.P., Sisson, S.A., Phillips, B.L. and Shine, R. 2013. Rapid shifts in dispersal behavior on an expanding range edge. Proceedings of the National Academy of Sciences USA 110: 13,452-13,456. | Previous studies of Australian cane toads underestimated their ability to "expand into newly available habitat under climate change." |
| Scheffers, B.R., Edwards, D.P., Diesmos, A., Williams, S.E. and Evans, T.A. 2014. Microhabitats reduce animal's exposure to climate extremes. Global Change Biology 20: 495-503. | Scheffers *et al.* write that "assuming uniform increases of 6°C, microhabitats decreased the vulnerability of communities by up to 32-fold, whereas under non-uniform increases of 0.66 to 3.96°C, microhabitats decreased the vulnerability of communities by up to 108-fold." They conclude that their data suggest that "consideration of microhabitats provides a more realistic assessment of exposure within rainforests, possibly reducing exposure to extreme events by an order of 22," and that "inclusion of microhabitat buffering within models is therefore fundamental to making accurate assessments of vulnerability under future conditions." |
| Lopez-Alcaide, S., Nakamura, M., Macip-Rios, R. and Martinez-Meyer, E. 2014. Does behavioral thermoregulation help pregnant *Sceloporus adleri* lizards in dealing with fast environmental temperature rise? *Herpetological Journal* **24**: 41-47. | Pregnant lizards successfully adapt to increased temperatures through behavioral changes, without negative impacts on offspring. |
| Schilthuizen, M. and Kellermann, V. 2014. Contemporary climate change and terrestrial invertebrates: evolutionary versus plastic changes. *Evolutionary Applications* **7**: 56-67. | Terrestrial invertebrates show adaptive responses to climate change both evolutionarily and in terms of phenotypic plasticity. |
| Varner, J. and Dearing, M.D. 2014. Dietary plasticity in pikas as a strategy for atypical resource landscapes. *Journal of Mammalogy* **95**: 72-81. | Animals successfully adapt to changes in climate by shifting diet patterns. |
| Urban, M.C., Richardson, J.L. and Freidenfelds, N.A. 2013. Plasticity and genetic | Meta-analysis shows multiple studies demonstrating both plastic and evolutionary |

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| adaptation mediate amphibian and reptile responses to climate change. *Evolutionary Applications* **7**: 88-103. | responses in amphibians and reptiles that allow adaptation to climate change. |
| Kovach, R.P., Gharrett, A.J. and Tallmon, D.A. 2012. Genetic change for earlier migration timing in a pink salmon population. *Proceedings of the Royal Society B* **279**: 3870-3878. | Alaskan pink salmon showed rapid micro-evolution at a genetic level in responses to warming conditions, beginning migration at an earlier time point in the year. |
| Leal, M. and Gunderson, A.R. 2012. Rapid change in the thermal tolerance of a tropical lizard. *The American Naturalist* **180**: 815-822. | When a tropical lizard indigenous to Puerto Rico was found in an area of Miami with colder minimum temperatures, researchers examined how it adapted. They found that the lizard's critical thermal minimum temperature |
| Stoner, A.W., Ottmar, M.L. and Copeman, L.A. 2010. Temperature effects on the molting, growth, and lipid composition of newly-settled red king crab. *Journal of Experimental Marine Biology and Ecology* **393**: 138-147. | A study of red king crab in Alaska found that temperature had no significant effect on their survival rates. |
| Nyamukondiwa, C. and Terblanche, J.S. 2010. Within-generation variation of critical thermal limits in adult Mediterranean and Natal fruit flies *Ceratitis capitata* and *Ceratitis rosa*: thermal history affects short-term responses to temperature. *Physiological Entomology* **35**: 255-264. | Fruit flies, and several other insect species, are capable of adjusting their thermal tolerance within a single generation. |
| Maraldo, K., Krogh, P.H., van der Linden, L., Christensen, B., Mikkelsen, T.N., Beier, C. and Holmstrup, M. 2010. The counteracting effects of atmospheric $CO_2$ concentrations and drought episodes: Studies of enchytraeid communities in a dry heathland. *Soil Biology & Biochemistry* **42**: 1958-1966. | Experimentally-imposed warming had no significant impact on small oligochaete worms. |
| Lowe, S.J., Patterson, B.R. and Schaefer, J.A. 2010. Lack of behavioral responses of moose (*Alces alces*) to high ambient temperatures near the southern Periphery of their range. *Canadian Journal of Zoology* **88**: 1032-1041. | Higher temperatures do not impact the habitat use of moose. |
| Matthysen, E., Adriaensen, F. and Dhondt, A.A. 2011. Multiple responses to increasing spring temperatures in the breeding cycle of blue and great tits (*Cyanistes caeruleus, Parus major*). *Global Change Biology* **17**: 1-16. | Warming does not impact the breeding cycle of blue and great tits. |
| Rodder, D., Hawlitschek, O. and Glaw, F. 2010. Environmental niche plasticity of the endemic gecko *Phelsuma parkeri* Loveridge 1941 from Pemba Island, Tanzania: a case study of extinction risk on flat islands by climate change. *Tropical Zoology* **23**: 35-49. | Tanzanian geckos are likely not threatened by climate change. |
| Catenazzi, A., Lehr, E., Rodriguez, L.O. and Vredenburg, V.T. 2010. *Batrachochytrium dendrobatidis* and the collapse of anuran species richness and abundance in the Upper Manu National Park, southeastern Peru. *Conservation Biology* **25**: 382-391. | Climate change has not caused the reduction in the frog population in Southeastern Peru. |
| Suggitt, A.J., Gillingham, P.K., Hill, J.K., | In response to temperature changes, certain |

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| Huntley, B., Kunin, W.E., Roy D.B. and Thomas, C.D. 2011. Habitat microclimates drive fine-scale variation in extreme temperatures. *Oikos* **120**: 1-8. | populations may shift microhabitats. |
| Karell, P., Ahola, K., Karstinen, T., Valkama, J. and Brommer, J.E. 2011. Climate change drives microevolution in a wild bird. *Nature Communications*: 10.1038/ncomms1213. | Tawny owls in Finland have successfully evolved to respond to climate-driven change. |
| Dias, M.P., Granadeiro, J.P., Phillips, R.A., Alonso, H. and Catry, P. 2011. Breaking the routine: individual Cory's shearwaters shift winter destinations between hemispheres and across ocean basins. *Proceedings of the Royal Society B* **278**: 1786-1793. | Observations of Cory's shearwaters' migration habits reveals their ability to change winter destinations and adapt to changing climates. |
| Barnagaud, J.-Y., Crochet, P.A., Magnani, Y., Laurent, A.B., Menoni, E., Novoa, C. and Gimenez, O. 2011. Short-term response to the North Atlantic Oscillation but no long-term effects of climate change on the reproductive success of an alpine bird. *Journal of Ornithology* **152**: 631-641. | Black Grouse have been able to track climatic trends and appear to be more threatened by declines in the availability of suitable habitats. |
| Zivanovic, G. and Mestres, F. 2011. Changes in chromosomal polymorphism and global warming: The case of *Drosophila subobscura* from Apatin (Serbia). *Genetics and Molecular Biology* **34**: 489-495. | A study of fruit flies determined there was a significant increase in the frequency of certain chromosomal arrangements characteristic of southern latitudes, which they describe as "warm adapted," and a significant decrease in the frequency of such arrangements characteristic of northern latitudes, which they describe as "cold adapted." It would appear that many forms of animal life may be well equipped to evolve with sufficient rapidity to survive the challenges of any rapid warming. |
| Vatka, E., Orell, M. and Rytkonen, S. 2011. Warming climate advances breeding and improves synchrony of food demand and food availability in a boreal passerine. *Global Change Biology* **17**: 3002-3009. | There was no evidence that warming would lead to mismatches between the times when birds of temperate and boreal regions require an abundance of food to feed their new hatchlings and the times when that food is available in its greatest abundance, and actually indications the matching improved. |
| Chen, I.-C., Hill, J.K., Ohlemuller, R., Roy, D.B. and Thomas, C.D. 2011. Rapid range shifts of species associated with high levels of climate warming. *Science* **333**: 1024-1026. | Demonstrating an ability to adapt, species have responded to warming by shifting to higher elevations and to higher latitudes. |
| Orizaola, G. and Laurila, A. 2009. Microgeographic variation in temperature-induced plasticity in an isolated amphibian metapopulation. Evolutionary Ecology 23: 979-991. | The two Swedish researchers report that (1) "in general, larvae exposed to warmer temperature experienced higher survival and metamorphosed faster," that (2) there "were differences among the populations in both trait mean values and in the plastic responses," and that (3) "among-family variation within populations was found in growth rate and time to metamorphosis, as well as in plasticity suggesting that these traits have a capacity to evolve." |
| Hockey, P.A.R. and Midgley, G.F. 2009. Avian | The two researchers report that the bird |

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| range changes and climate change: a cautionary tale from the Cape Peninsula. Ostrich 80: 29-34. | colonization events may be better explained by "direct anthropogenic changes to the landscape than by the indirect effects of climate change." And they add that "no a priori predictions relating to climate change, such as colonizers being small and/or originating in nearby arid shrub-lands, were upheld." |
| Popy, S., Bordignon, L. and Prodon, R. 2010. A weak upward elevational shift in the distributions of breeding birds in the Italian Alps. Journal of Biogeography 37: 57-67. | "[A]t the European scale, no overall expansion or contraction of the distributions of the studied species was detected." In light of their findings, as well as those of others they cite, Popy *et al.* conclude that "until a better understanding of the underlying mechanisms is achieved, predictions based only on 'climate envelope' models should be either validated or considered cautiously." |
| Erwin, D.H. 2009. Climate as a driver of evolutionary change. Current Biology 19: R575-R583. | "[T]here is an intriguing possibility that diversity does not track climate, but rather builds up during warm intervals but without falling by proportional amounts when climates turn cooler," with the result that "warmer climates may serve as an evolutionary diversification pump with higher diversity persisting [throughout following cooler periods], at least for a time." |
| Garroway, C.J., Bowman, J., Cascaden, T.J., Holloway, G.L., Mahan, C.G., Malcolm, J.R., Steele, M.A., Turner, G. and Wilson, P.J. 2010. Climate change induced hybridization in flying squirrels. Global Change Biology 16: 113-121. | It had already been determined by Bowman *et al.* (2005) that G. volans had expanded its range from the south beginning in the mid-1990s in concert with a series of warm winters; and now the nine Canadian and U.S. researchers' new findings indicate that "the expansion of G. volans north into the G. sabrinus range in Ontario has resulted in the formation of a new hybrid zone." In addition, their analyses suggest that "the hybridization was recent, coinciding with the recent increase in sympatry." Thus, they go on to state that -- to their knowledge -- "this is the first report of hybrid zone formation following a range expansion induced by contemporary climate change." |
| Thomas, D.W., Bourgault, P., Shipley, B., Perret, P. and Blondel, J. 2010. Context-dependent changes in the weighting of environmental cues that initiate breeding in a temperate passerine, the Corsican Blue Tit (Cyanistes caeruleus). The Auk 127: 129-139. | Thomas *et al.* acknowledge that "if a single environmental feature [such as temperature] were responsible for the timing of breeding, climate change could cause a severe decline in breeding success, with negative demographic consequences." However, they say they "have not detected any consistent mismatch between Blue Tit breeding dates and caterpillar peak [abundance] dates over the 14 and 21 years for which they have data for Muro and Pirio [two sites in northern Corsica], respectively." |
| Conte, A., Gilbert, M. and Goffredo, M. 2009. Eight years of entomological surveillance in Italy show no evidence of Culicoides imicola geographical range expansion. Journal of | Addressing a midge which transmits the bluetongue virus, the researchers say their results indicated there had been "no detectable range expansion of C. imicola population in |

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| Applied Ecology 46: 1332-1339. | Italy over the past six years." In fact, they report that "a weak, but significant reduction was observed in the transition zone." Conte *et al.* conclude that their data "support the hypothesis that the spread of BTV in Italy is not because of the geographical expansion of its main vector, but to a modification of the interaction between the virus, the vector and the environment, as may also have been the case in northern Europe." |
| Millar, C.I. and Westfall, R.D. 2010. Distribution and climatic relationships of the American Pika (Ochotona princeps) in the Sierra Nevada and Western Great Basin, U.S.A.; periglacial landforms as refugia in warming climates. Arctic, Antarctic, and Alpine Research 42: 76-88. | The two U.S. Forest Service researchers report that "whereas concern exists for diminishing range of pikas relative to early surveys, the distribution and extent in our study, pertinent to four subspecies and the Pacific southwest lineage of pikas, resemble the diversity range conditions described in early 20th-century pika records (e.g., Grinnell and Storer, 1924)." Millar and Westfall say their results suggest that "pika populations in the Sierra Nevada and southwestern Great Basin are thriving, persist in a wide range of thermal environments, and show little evidence of extirpation or decline." |
| Anchukaitis, K.J. and Evans, M.N. 2010. Tropical cloud forest climate variability and the demise of the Monteverde golden toad. Proceedings of the National Academy of Sciences, USA 107: 5036-5040. | The two researchers report that "contrary to interpretations of the short instrumental record (Pounds *et al.*, 1999), no long-term trend in dry season hydroclimatology can be inferred from our δ18O time series at Monteverde (1900-2002)." Instead, they find that "variability at the interannual scale dominates the isotope signal, particularly during the period of increased ENSO variance since the late 1960s," and they add, in this regard, that "there is no evidence of a trend associated with global warming." |
| Checa, M.F., Barragan, A., Rodriguez, J. and Christman, M. 2009. Temporal abundance patterns of butterfly communities (Lepidoptera: Nymphalidae) in the Ecuadorian Amazonia and their relationship with climate. Annales de la Société Entomologique de France (NS) 45: 470-486. | Checa *et al.* captured a total of 9,236 individual Nymphalidae butterflies representing 208 different species, two of which species had not previously been found in Ecuador, and two of which were determined to actually be "new" species that had not previously been found anywhere. In further analyzing their data, they discovered there was "a constant replacement of species throughout the year," and that "these communities had the highest species richness and abundance during the months with high temperatures." What was especially noteworthy about this finding was the fact that the mean temperature of their study area, as they describe it, "only varies over one degree during the whole year." |
| Bustamante, H.M., Livo, L.J. and Carey, C. 2010. Effects of temperature and hydric environment on survival of the Panamanian Golden Frog infected with a pathogenic chytrid fungus. Integrative Zoology 5: 143-153. | The three researchers report that (1) "frogs exposed to a dosage of 100 Bd [pathogenic] zoospores survived significantly longer than those that had been exposed to 104 or 106 zoospores," that (2) "exposed frogs housed at 23°C survived significantly longer than those |

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| | that were housed at 17°C," and that (3) "exposed frogs held in dry conditions survived significantly longer than those in wet conditions." The data "do not support the contention that rising global temperatures are necessary to cause the death of amphibians infected with this pathogen, because the pathogen was equally lethal at 17 as at 23°C, and frogs at the warmer temperature lived significantly longer than those at the cooler one." |
| McCaffery R.M. and Maxell, B.A. 2010. Decreased winter severity increases viability of a montane frog population. Proceedings of the National Academy of Sciences USA 107: 8644-8649. | "[P]arameters that describe winter severity were negatively correlated with survival, transition, and breeding probabilities in this high-elevation R. luteiventris population," and that there was "an increase in survival and breeding probability as severity of winter decreased." "Contrary to much of what has been discussed in the literature," "these results suggest that under certain circumstances, a warming climate may be helpful to some amphibian populations, particularly those that live in harsh conditions at the edge of their thermal tolerances." Their results "unambiguously demonstrate that earlier ending winters with lower snowpack in this system lead to higher survival rates, higher probabilities of breeding, and higher population viability." |
| Bell, R.C., Parra, J.L., Tonione, M., Hoskin, C.J., Mackenzie, J.B., Williams, S.E. and Moritz, C. 2010. Patterns of persistence and isolation indicate resilience to climate change in montane rainforest lizards. Molecular Ecology 19: 2531-2544. | The evidence demonstrates "persistence and isolation" of most populations of the montane species "throughout the strong climate oscillations of the late Pleistocene, and likely extending back to the Pliocene." These observations "support the general hypothesis that isolated tropical montane regions harbor high levels of narrow-range taxa because of their resilience to past climate change." "At first sight, species such as L. robertsi would seem especially prone to local extinction and loss of considerable genetic diversity with any further warming; but have evidently persisted through past warming events." |
| Rosset, V., Lehmann, A. and Oertli, B. 2010. Warmer and richer? Predicting the impact of climate warming on species richness in small temperate waterbodies. Global Change Biology 16: 2376-2387. | "Temperature rise could significantly increase pond species richness," and that "in presently species-poor high altitude ponds, the potential increase would be particularly marked, with a proportional increase (+150%; from 14-35 species) almost double that in lowland areas" and that "long-term monitoring of vegetation plots in terrestrial environments indicates an increase in local species richness (Pauli *et al.*, 2007; Vittoz *et al.*, 2009). |
| Westwood, A.B. and Blair, D. 2010. Effect of regional climate warming on the phenology of butterflies in boreal forests in Manitoba, | The two Canadian researchers report that spring and summer temperatures were little changed over the course of the research period |

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| Canada. Environmental Entomology 39: 1122-1133. | and, consequently, that "adult butterfly response was variable for spring and summer months." However, autumn temperatures warmed significantly; and they observed that "13 of 19 species showed a significant increase in flight period extending longer into the autumn," when "flight period extensions increased by 31.5 ± 13.9 days over the study period." And in this regard, they note that "two species, Junonia coenia and Euphydryas phaeton, increased their northerly ranges by ~ 150 and 70 km, respectively." Quoting Westwood and Blair, "warmer autumns and winters may be providing opportunities for range extensions of more southerly butterfly species held at bay by past climatic conditions." |
| Scherrer, D. and Korner, C. 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. Global Change Biology 16: 2602-2613. | Scherrer and Korner say their findings are "important in the context of climate change," because they show that "species do not necessarily need to climb several hundred meters in elevation to escape the warmth." Quite often, in fact, they say that a "few meters of horizontal shift will do," so that for plants "unable or too slow to adapt to a warmer climate, thermal microhabitat mosaics offer both refuge habitats as well as stepping stones as atmospheric temperatures. The data "challenge the stereotype of particularly sensitive and vulnerable alpine biota with respect to climatic warming," noting that "high elevation terrain may in fact be more suitable to protect biodiversity under changing climatic conditions than most other, lower elevation types of landscapes." |
| Harsch, M.A. and Lambers, J.H.R. 2014. Species distributions shift downward across western North America. *Global Change Biology* 10.1111/gcb.12697. | Harsch and Lambers (2014) write that "in general, documented and projected [species] distribution shifts are toward the poles or higher elevations." These findings, as they continue, are "consistent with downward distribution shifts being mediated by moisture stress, with declining snow at upper distribution limits increasing moisture stress (leading to a distribution expansion downward) while increasing precipitation decreases moisture stress at lower distribution limits," also "leading to a distribution expansion downward." The data "highlight the likelihood that continued winter warming and snowfall decline will limit further elevational distribution shifts both in North America and at mid- to high-latitude mountain distributions globally." |
| Logan, M.L., Cox, R.M. and Calsbeek, R. 2014. Natural selection on thermal performance in a novel thermal environment. *Proceedings of the National Academy of Sciences* **111**: 14,165- | Tropical organisms may mitigate the detrimental effects of warming through evolutionary change in thermal physiology. "When we simulated a rapid change in the |

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| 14,169. | thermal environment by transplanting a population of lizards to a warmer and more thermally variable habitat, we observed strong natural selection on thermal physiology." "Rapid climate change may result in directional selection on thermal physiology, even in species whose thermoregulatory behaviors are thought to shelter them from natural selection." |
| Malinowska, A.H., van Strien, A.J., Verboom, J., WallisdeVries, M.F. and Opdam, P. 2014. No evidence of the effect of extreme weather events on annual occurrence of four groups of ectothermic species. PLOS ONE **9**: e110219. | Observations of delicate species such as butterflies show no significant effects from extreme weather, leading the researchers to conclude that "weather extremes might not be ecologically relevant for the majority of species." |
| Polgar, G., Khang, T.F., Chua, T. and Marshall, D.J. 2015. Gross mismatch between thermal tolerances and environmental temperatures in a tropical freshwater snail: Climate warming and evolutionary implications. *Journal of Thermal Biology* **47**: 99-108 | Freshwater snails' "thermal safety margin" is broad which suggests they are not particularly vulnerable to warming. |
| Bertelsmeier, C., Luque, G.M., Hoffmann, B.D. and Courchamp, F. 2015. Worldwide ant invasions under climate change. *Biodiversity Conservation* **24**: 117-128 | "Contrary to general expectations, climate change will not result in range expansion for most [ant] species." |
| Du, W.-G. and Shine, R. 2015. The behavioural and physiological strategies of bird and reptile embryos in response to unpredictable variation in nest temperature. *Biological Reviews* **90**: 19-30 | "Like free-living stages of the life cycle, embryos exhibit behavioral and physiological plasticity that enables them to deal with unpredictable abiotic challenges," among which is global warming. |
| Coker, D.J., Nowicki, J.P. and Pratchett, M.S. 2015. Body condition of the coral-dwelling fish *Dascyllus aruanus*(Linnaeus 1758) following host colony bleaching. *Environmental Biology of Fishes* **98**: 691-695. | Certain coral-dwelling fish show the ability to maintain their fecundity during a mild coral bleaching event. |
| Thyrring, J., Rysgaard, S., Blicher, M.E. and Sejr, M.K. 2015. Metabolic cold adaptation and aerobic performance of blue mussels (*Mytilus edulis*) along a temperature gradient into the High Arctic region. *Marine Biology* **162**: 235-243. | Blue mussels adapt to temperature change along a latitudinal gradient. |
| Bennett, N.L., Severns, P.M., Parmesan, C. and Singer, M.C. 2015. Geographic mosaics of phenology, host preference, adult size and microhabitat choice predict butterfly resilience to climate warming. *Oikos* **124**: 41-53. | The climate-sensitive butterfly *Euphydryas editha* exhibits resiliance to climate change. |
| Cross, E.L., Peck, L.S. and Harper, E.M. 2015. Ocean acidification does not impact shell growth or repair of the Antarctic brachiopod *Liothyrella uva* (Broderip, 1833). *Journal of Experimental Marine Biology and Ecology* **462**: 29-35. | Working with Antarctic brachiopods, researchers examined the effects of projected environmental conditions in 2050 and 2100 on the growth rate and ability to repair their shells. The researchers report that shell repair rate "was not affected by either acidified conditions or temperature." In the case of shell growth rate, it was actually increased by elevated temperature. |
| Barrows, C.W. and Fisher, M. 2014. Past, | Lizards with low population dispersion--thought |

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| present and future distributions of a local assemblage of congeneric lizards in southern California. Biological Conservation **180**: 97-107. | to be sensitive to habitat challenges--have developed behavioral responses to warming that enabled them to survive both colder and hotter periods. |
| Ruiz-Aravena, M., Gonzalez-Mendez, A., Estay, S.A., Gaitan-Espitia, J.D., Barria-Oyarzo, I., Bartheld, J.L. and Bacigalupe, L.D. 2014. Impact of global warming at the range margins: phenotypic plasticity and behavioral thermoregulation will buffer an endemic amphibian. *Ecology and Evolution* **4**: 4467-4475. | Scientists conducted research on amphibian species' ability to acclimate to rising temperatures, concluding that they "will be able to endure the worst projected scenario of climate warming." This conclusion resulted from their findings on the species' ability to regulate behavioral body temperature and thermal performance. |
| Shi, H., Paull, D., Wen, Z. and Broome, L. 2014. Thermal buffering effect of alpine boulder field microhabitats in Australia: Implications for habitat management and conservation. *Biological Conservation* **180**: 278-287. | Scientists conducted research over how well species can acclimate to increasing atmospheric temperatures. Their study concluded that as regions become less suitable, there still remains many microhabitats of tree hollows, roost cavities, and tropical boulder fields would continue to provide sufficient den and nest sites for a range of animal species. |
| ***C. Moderately Warming Seas Result in Flourishing Ocean Vegetation, Which Acts as a Carbon Sink*** | |
| Raitsos, D.E., Pradhan, Y., Lavender, S.J., Hoteit, I., McQuatters-Gollop, A., Reid, P.C. and Richardson, A.J. 2014. From silk to satellite: half a century of ocean color anomalies in the Northeast Atlantic. *Global Change Biology* **20**: 2117-2123. | Using new datasets coupled with satellite images, researchers showed phytoplankton biomass increasing substantially in North Atlantic and North Sea. Oscillations in growth parallel oscillations in temperature. |
| Lohbeck, K.T., Riebesell, U. and Reusch, T.B.H. 2014. Gene expression changes in the coccolithophore *Emiliania huxleyi* after 500 generations of selection to ocean acidification. *Proceedings of the Royal Society B* **281**: 10.1098/rspb.2014.0003. | Key phytoplankton species exposed to $CO_2$/acidification acutely (short-term physiological response) and chronically (long-term adaptive response). After 500 generations of adaptive response, genes crucial to pH regulation and carbon-transport were up-regulated--the phytoplankton evolved to cope with acid conditions. |
| Kennedy, H., Beggins, J., Duarte, C.M., Fourqurean, J.W., Holmer, M., Marba, N. and Middelburg, J.J. 2010. Seagrass sediments as a global carbon sink: Isotopic constraints. *Global Biogeochemical Cycles* **24**: 10.1029/2010GB003848. | "Seagrass meadows are natural hot spots for carbon sequestration." |
| Tokoro, T., Hosokawa, S., Miyoshi, E., Tada, K., Watanabe, K., Montani, S., Kayanne, H. and Kuwae, T. 2014. Net uptake of atmospheric $CO_2$ by coastal submerged aquatic vegetation. *Global Change Biology* **20**: 1873-1884. | Unexpectedly, coastal vegetation (seagrass) is a $CO_2$ sink rather than producer. A significant amount of carbon is captured by marine organisms ("blue carbon"). |
| Clark, J.S., Poore, A.G.B., Ralph, P.J. and Doblin, M.A. 2013. Potential for adaptation in response to thermal stress in an intertidal macroalga. Journal of Phycology 49: 630-639. | "[F]inding of genetic variation in thermal tolerance of H. banksii embryos suggests resilience to thermal stresses." |
| McMinn, A., Muller, M.N., Martin, A. and Ryan, | McMinn *et al.* state that "brine channel and |

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| K.G. 2014. The response of Antarctic sea ice algae to changes in pH and $CO_2$. PLOS ONE 9: e86984. | surface communities have only limited access to the underlying water column and consequently their $CO_2$ supply becomes severely restricted," such that "under these circumstances, restricted $CO_2$supply limits microalgae growth (McMinn *et al.*, 1999)," so that "unlike planktonic ecosystems where $CO_2$ is rarely in short supply, in sea ice brine systems the shortage is often acute." And, therefore, they opine that "the addition of $CO_2$as a result of ocean acidification may partially alleviate this stress." The researchers conclude that "elevated $pCO_2$ positively affected the growth rate of the brine algal community." |
| Johnson, M.D., Moriarty, V.W. and Carpenter, R.C. 2014. Acclimatization of the crustose coralline alga Porolithon onkodes to variable $pCO_2$. PLOS ONE 9: e87678. | Johnson *et al.* write that "the significance of the original habitat of the coralline calcification response to variable, high $pCO_2$ indicates that individuals existing in dynamic $pCO_2$ habitats may be acclimatized to ocean acidification within the scope of in situ variability." And they thus end their paper by saying that "given the potential dire consequences of ocean acidification for coastal ecosystems, it is important to consider how acclimatization may facilitate the survival of marine organisms in the near future." |
| Zou, D. and Gao, K. 2014. Temperature response of photosynthetic light- and carbon-use characteristics in the red seaweed *Gracilariopsis lemaneiformis* (Gracilariales, Rhodophyta). *Journal of Phycology* **50**: 366-375. | Higher temperatures had a clearly positive effect for commonly used seaweed species. |
| Suarez-Alvarez, S., Gomez-Pinchetti, J.L. and Garcia-Reina, G. 2012. Effects of increased $CO_2$ levels on growth, photosynthesis, ammonium uptake and cell composition in the macroalga *Hypnea spinella* (Gigartinales, Rhodophyta). *Journal of Applied Phycology* **24**: 815-823. | Enriched $CO_2$ environment spurred growth and activity of microalgae used for bioremediation of water pollution. |
| Koch, M, Bowes, G., Ross, C. and Zhang, X.-H. 2013. Climate change and ocean acidification effects on seagrasses and marine macroalgae. *Global Change Biology* **19**: 103-132. | Seagrasses and marine microalgae respond positively to elevated $CO_2$ and acidification. Photosynthesis is not saturated at current levels of dissolved inorganic carbon. |
| Aeby, G.S., Williams, G.J., Franklin, E.C., Haapkyla, J., Harvell, C.D., Neale, S., Page, C.A., Raymundo, L., Vargas-Angel, B., Willis, B.L., Work, T.M. and Davy, S.K. 2011. Growth anomalies on the coral genera *Acropora* and *Porites* are strongly associated with host density and human population size across the Indo-Pacific. *PLoS ONE* **6**: 10.1371/journal.pone.0016887. | Host abundance and human population size were the optimal predictors for variations in the prevalence of growth anomalies in the Indo-Pacific. Sea surface temperature anomalies have no association. |
| Osborne, K., Dolman, A.M., Burgess, S.C. and Johns, K.A. 2011. Disturbance and the | The Great Barrier Reef has maintained a stable presence over the totality of its expanse based |

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| dynamics of coral cover on the Great Barrier Reef (1995-2009). *PLoS ONE* **6**: 10.1371/journal.pone.0017516. | on evaluation of overall regional coral cover. |
| Bauman, A.G., Baird, A.H. and Cavalcante, G.H. 2011. Coral reproduction in the world's warmest reefs: southern Persian Gulf (Dubai, United Arab Emirates). *Coral Reefs* **30**: 405-413. | Corals are capable of reproductive activities under extreme environmental conditions and can therefore survive and proliferate. |
| Beaufort, L., Probert, I., de Garidel-Thoron, T., Bendif, E.M., Ruiz-Pino, D., Metzl, N., Goyet, C., Buchet, N., Coupel, P., Grelaud, M., Rost, B., Rickaby, R.E.M. and de Vargas, C. 2011. Sensitivity of coccolithophores to carbonate chemistry and ocean acidification. *Nature* **476**: 80-83. | Rising atmospheric $CO_2$ concentrations will very likely *not* bring a halt, or even a significant reduction, to coccolithophere calcification in either the decades or centuries to come. |
| Tremblay, J.-E., Belanger, S., Barber, D.G., Asplin, M., Martin, J., Darnis, G.;, Fortier, L., Gratton, Y., Link, H., Archambault, P., Sallon, A., Michel, C., Williams, W.J., Philippe, B. and Gosselin, M. 2011. Climate forcing multiplies biological productivity in the coastal Arctic Ocean. *Geophysical Research Letters* **38**: 10.1029/2011GL048825. | Repeated instances of ice ablation in the Coastal Arctic Ocean and upwelling during fall 2007 and summer 2008 multiplied the production of ice algae, phytoplankton, zooplankton and benthos by 2 to 6 fold. |
| Renaudie, J., Danelian, T. Saint Martin, S., Le Callonnec, L. and Tribovillard, N. 2010. Siliceous phytoplankton response to a Middle Eocene warming event recorded in the tropical Atlantic (Demerara Rise, ODP Site 1260A). Palaeogeography, Palaeoclimatology, Palaeoecology 286: 121-134. | "[P]re-warming flora, dominated by cosmopolitan species of the diatom genus Triceratium, was replaced during the warming interval by a new and more diverse assemblage, dominated by Paralia sulcata (an indicator of high productivity) and two endemic tropical species." In addition, they state that "the critical warming interval was characterized by a steady increase in tropical species." In addition, they state that "the microflora preserved above the critical interval was once again of low diversity and dominated by various species of the diatom genus Hemiaulus." |
| Xu, Z., Zou, D. and Gao, K. 2010. Effects of elevated $CO_2$ and phosphorus supply on growth, photosynthesis and nutrient uptake in the marine macroalga Gracilaria lemaneiformis (Rhodophyta). Botanica Marina 53: 123-129. | In the case of growth rate or biomass production, the elevated $CO_2$ treatment exhibited a 48% increase in the natural Pi treatment,. The three Chinese researchers say that "elevated levels of $CO_2$ in seawater increase the growth rate of many seaweed species despite the variety of ways in which carbon is utilized in these algae," noting that "some species, are capable of using $HCO_3$-, but are limited by the current ambient carbon concentration in seawater," and that "enrichment of $CO_2$ relieves this limitation and enhances growth." |
| Pedersen, O., Malik, A. and Colmer, T.D. 2010. Submergence tolerance in Hordeum marinum: dissolved $CO_2$ determines underwater photosynthesis and growth. Functional Plant Biology 37: 524-531. | The three researchers report that "plants submerged for 7 days in water at air equilibrium (18 μM $CO_2$) suffered loss of biomass, whereas those with 200 μM $CO_2$ continued to grow," and in this regard, they say that "higher underwater net photosynthesis at 200 μM $CO_2$ increased by 2.7- to 3.2-fold sugar |

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| | concentrations in roots of submerged plants, compared with at air equilibrium $CO_2$." And they say that this phenomenon "is likely to have contributed to the greater root growth in submerged plants with the higher $CO_2$ supply." In addition, they note that the latter $CO_2$-enriched plants "tillered similarly to plants with shoots in air." |
| ***D. Moderate Warming Will Not Harm Oceanic Ecosystems, And May Benefit Them*** | |
| Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., Forrest, R.E., Gehrke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson, R. and Richardson, A.J. 2010. Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. Global Change Biology 16: 1194-1212. | Under the IPCC's "plausible climate change scenario, primary production will increase around Australia" with "overall positive linear responses of functional groups to primary production change," and that "generally this benefits fisheries catch and value and leads to increased biomass of threatened marine animals such as turtles and sharks," adding that the calculated responses "are robust to the ecosystem type and the complexity of the model used." In the concluding sentence of their paper, Brown *et al.* state that the primary production increases suggested by their work to result from future IPCC-envisioned greenhouse gas emissions and their calculated impacts on climate "will provide opportunities to recover overfished fisheries, increase profitability of fisheries and conserve threatened biodiversity." |
| Woodroffe, C.D., Brooke, B.P., Linklater, M., Kennedy, D.M., Jones, B.G., Buchanan, C., Mleczko, R., Hua, Q. and Zhao, J.-X. 2010. Response of coral reefs to climate change: Expansion and demise of the southernmost Pacific coral reef. *Geophysical Research Letters* **37**: 10.1029/2010GL044067. | Coral reefs were much more extensive 9000 years ago than they are today in mid-latitudes which indicates relic reefs could become a substrate for reef expansion in response to anticipated warmer temperatures. |
| Munday, P.L., Cheal, A.J., Dixson, D.L., Rummer, J.L. and Fabricius, K.E. 2014. Behavioral impairment in reef fishes caused by ocean acidification at $CO_2$ seeps. *Nature Climate Change* **4**: 487-492. | Study compared naturally high-acid ocean area (near volcanic seep) with nearby reef and found little difference in biodiversity or community. |
| Pinceel, T., Vanschoenwinkel, B., Waterkeyn, A., Vanhove, M.P.M., Pinder, A., Timms, B.V. and Brendonck, L. 2013. Fairy shrimps in distress: a molecular taxonomic review of the diverse fairy shrimp genus *Branchinella* (Anostraca: Thamnocephalidae) in Australia in the light of ongoing environmental change. *Hydrobiologia* **700**: 313-327. | Fairy shrimp under various anthropogenic environmental pressures (including climate change as well as mining, river regulation, and other challenges) have been able to develop "at least three new cryptic species" as a mechanism for adapting to challenging conditions. |
| Zapata, F.A., Rodriguez-Ramirez, A., Caro-Zambrano, C. and Garzon-Ferreira, J. 2010. Mid-term coral-algal dynamics and conservation status of a Gorgona Island (Tropical Eastern Pacific) coral reef. | Despite recurrent natural disturbances, the La Azufrada reef at Gorgona Island is just as flourishing as it was in 1982. |

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| *International Journal of Tropical Biology and Conservation* **58** (Suppl. 1): 81-94. | |
| Yakob, L. and Mumby, P.J. 2011. Climate change induces demographic resistance to disease in novel coral assemblages. *Proceedings of the National Academy of Sciences USA* **108**: 1967-1969. | "High population turnover within novel ecosystems enhances coral resistance to epizootics," and, therefore, "disease could become a less important driver of change in the future." "Projecting the future of a novel ecosystem from trends in the recent past may have misleading results." |
| Dalpadado, P., Arrigo, K.R., Hjollo, S.S., Rey, F., Ingvaldsen, R.B., Sperfeld, E., van Dijken, G.L., Stige, L.C., Olsen, A. and Ottersen, G. 2014. Productivity in the Barents Sea - Response to recent climate variability. *PLOS ONE* **9**: e95273. | Moderate localized warming in Barents Sea showed broad positive effects on ecosystem. |
| Kelmo, F., Bell, J.J., Moraes, S.S., Gomes, R.C.T., Mariano-Neto, E. and Attrill, M.J. 2014. Differential responses of emergent intertidal coral reef fauna to a large-scale El-Niño Southern Oscillation Event: Sponge and coral resilience. *PLOS ONE* **9**: e93209. | Coral reefs relatively resilient to 1997-98 ENSO effects. Changes due to climate change likely to alter mix of species, but no widespread mortality predicted. |
| Barott, K.L., Williams, G.J., Vermeij, M.J.A., Harris, J., Smith, J.E., Rohwer, F.L. and Sandin, S.A. 2012. Natural history of coral-algae competition across a gradient of human activity in the Line Islands. *Marine Ecology Progress Series* **460**: 1-12. | Coral and algae ordinarily compete in reef systems, with corals holding the upper hand. But around populated islands, algae won out, suggesting that human impacts play a more decisive role in coral competitive capacity, rather than acidification or $CO_2$ concentration. |
| Manzello, D.P., Enochs, I.C., Melo, N., Gledhill, D.K. and Johns, E.M. 2012. Ocean acidification refugia of the Florida Reef Tract. *PLoS ONE* **7**: e41715. | Seagrass--which had greater reproduction and biomass in response to higher $CO_2$ levels--also provided a refuge for coral from acidification due to $CO_2$ uptake. |
| Johnson, V.R., Russell, B.D., Fabricius, K.A.E., Brownlee, C. and Hall-Spencer, J.M. 2012. Temperate and tropical brown macroalgae thrive, despite decalcification, along natural $CO_2$ gradients. *Global Change Biology* **18**: 2792-2803. | Increased levels of $CO_2$ resulted in proliferation of algae due to reduction in numbers of herbivorous sea urchins in the area--without harm to the calcifying properties of the algae. |
| Aberle, N., Bauer, B., Lewandowska, A., Gaedke, U. and Sommer, U. 2012. Warming induces shifts in microzooplankton phenology and reduces time-lags between phytoplankton and protozoan production. *Marine Biology* **159**: 2441-2453. | Warmer temperatures correlated with stronger match between grazers and fodder in terms of populations, suggesting a stronger ecosystem overall. |
| Hargrave, C.W., Gary, K.P. and Rosado, S.K. 2009. Potential effects of elevated atmospheric carbon dioxide on benthic autotrophs and consumers in stream ecosystems: a test using experimental stream mesocosms. Global Change Biology 15: 2779-2790. | The authors "used free air $CO_2$ enrichment to compare effects of relative to ambient $CO_2$ on several ecosystem properties and functions in large, outdoor, experimental mesocosms that mimicked shallow sand-bottom prairie streams." "e$CO_2$ decreased water-column pH," but the three U.S. scientists discovered that the all-important primary productivity of benthic algae "was about 1.6, 1.9, 2.5 and 1.3 times greater in the e$CO_2$ treatment on days 30, 45, 60 and 75, respectively." Thus, e$CO_2$ "had positive effects on benthic invertebrates, |



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| | significantly increasing chironomid density, biomass, and average size." |
| Borges, A.V. and Gypens, N. 2010. Carbonate chemistry in the coastal zone responds more strongly to eutrophication than to ocean acidification. Limnology and Oceanography 55: 346-353. | The findings of the two researchers indicate that "the increase of primary production due to eutrophication could counter the effects of ocean acidification on surface water carbonate chemistry in coastal environments," and that "changes in river nutrient delivery due to management regulation policies can lead to stronger changes in carbonate chemistry than ocean acidification," as well as changes that are "faster than those related solely to ocean acidification." They add that "the response of carbonate chemistry to changes of nutrient delivery to the coastal zone is stronger than ocean acidification." |
| Kiessling, W. 2009. Geologic and biologic controls on the evolution of reefs. Annual Review of Ecological and Evolutionary Systems 40: 173-192. | "[O]n geologic timescales, there is little evidence for climate change affecting reefs in a linear fashion. "[C]hanges in mean global temperature as reconstructed from stable oxygen isotopes and the distribution of non-reef climate-sensitive sediments do not correspond to changes in reef abundance or latitudinal distribution." "[R]eports linking reef expansions and declines to climate change fail to explain why other changes in temperature did not lead to a similar response in reefs and why the reported (fairly modest) temperature changes would have such a dramatic effect." With respect to ocean acidification, "just like temperature," it is currently receiving much attention as "a control of reef development," but that "the boom and bust pattern of reefs and hyper-calcifiers is difficult to explain with inferred long-term changes in the saturation state of ocean water." "Neither climate nor sea-level nor chemical changes in the oceans can elucidate the waxing and waning of reefs" throughout their history on earth. |
| Kim, J.-M., Lee, K., Yang, E.J., Shin, K., Noh, J.H., Park, K.-T., Hyun, B., Jeong, H.-J., Kim, J.-H., Kim, K.Y., Kim, M., Kim, H.-C., Jang, P.-G. and Jang, M.-C. 2010. Enhanced production of oceanic dimethylsulfide resulting from $CO_2$-induced grazing activity in a high $CO_2$ world. Environmental Science & Technology: 10.1021/es102028k. | The data indicate that "in the context of global environmental change, the key implication of our results is that DMS production resulting from $CO_2$-induced grazing activity may increase under future high $CO_2$ conditions," and, therefore, they conclude that "DMS production in the ocean may act to counter the effects of global warming in the future." |
| Garrard, S.L. and Beaumont, N.J. 2014. The effect of ocean acidification on carbon storage and sequestration in seagrass beds: a global and UK context. *Marine Pollution Bulletin* **86**: 138-146. | Based on projections of future anthropogenic $CO_2$ emissions and their impacts on the above- and below-ground growth of seagrass, over the remainder of this century, the global standing stock of seagrass "is expected to increase by 94%, whilst the standing stock in the UK is expected to increase by 82%." The associated *value* of this increase in both *above*- and *below*-ground carbon sequestration capacity is |

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| | - when summed over the entire world - approximately 500 and 600 billion pounds sterling ($765-918 billion USD), respectively, between 2010 and 2100. |
| Hendriks, I.E., Duarte, C.M., Olsen, Y.S., Steckbauer, A., Ramajo, L., Moore, T.S., Trotter, J.A. and McCulloch, M. 2015. Biological mechanisms supporting adaptation to ocean acidification in coastal ecosystems. *Estuarine, Coastal and Shelf Science* **152**: A1-A8 | Acidification forced by increased atmospheric carbon dioxide may not uniformly affect all marine environments and, in some instances, calcifers may potentially benefit from changes to ambient seawater pH. |
| Eidens, C., Bayraktarov, E., Hauffe, T., Pizarro, V., Wilke, T. and Wild, C. 2014. Benthic primary production in an upwelling-influenced coral reef, Colombian Caribbean. *PeerJ* **2**: 10.7717/peerj.554 | "Stable benthic productivity in coral reefs suggests a relatively high resilience of local benthic communities against natural environmental fluctuations and anthropogenic disturbances," which includes climate change. |
| Macreadie, P.I., York, P.H., Sherman, C.D.H., Keough, M.J., Ross, D.J., Ricart, A.M. and Smith, T.M. 2014. No detectable impact of small-scale disturbances on 'blue carbon' within seagrass beds. *Marine Biology* **161**: 2939-2944. | Researchers challenged "a common assumption in the field of 'blue carbon' research that loss of seagrass habitat causes release of stored organic carbon" after several of their experiments in seagrass habitat disruptions proved "disturbance had no detectable effect on C org levels within seagrass sediments, even for high-intensity disturbance treatments." The significance of this research disproves one of the key tenants of the "positive feedback" thesis, demonstrating that climate change does not trigger further climate change through ecosystem disruption. |
| ***E. Studies of Impacts of Acidification and Warming on Ocean Life Show Adaptability and Resilience*** | |
| Miranda, R.J., Cruz, I.C.S. and Leao, Z.M.A.N. 2013. Coral bleaching in the Caramuanas reef (Todos os Santos Bay, Brazil) during the 2010 El Niño event. Latin American Journal of Aquatic Research 41: 351-360. | "[C]orals have an adaptive capacity or resistance to seasonal changes in environmental conditions," which was suggested by previous studies. |
| Yamano, H., Sugihara, K. and Nomura, K. 2011. Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters* **38**: 10.1029/2010GL046474. | Increases in sea-surface temperature have resulted in the poleward range expansion of modern corals. |
| Wu, Y., Gao, K. and Riebesell, U. 2010. $CO_2$-induced seawater acidification affects physiological performance of the marine diatom *Phaeodactylum tricornutum*. *Biogeosciences* **7**: 2915-2923. | $CO_2$-induced seawater acidification increases growth in marine diatom and would brake the rate-of-rise of the atmosphere's $CO_2$ concentration. |
| Felis, T., McGregor, H.V., Linsley, B.K., Tudhope, A.W., Gagan, M.K., Suzuki, A., Inoue, M., Thomas, A.L., Esat, T.M., Thompson, W.G., Tiwari, M., Potts, D.C., Mudelsee, M., Yokoyama, Y. and Webster, J.M. 2014. Intensification of the meridional temperature gradient in the Great Barrier Reef following the Last Glacial Maximum. *Nature* | Corals managed to flourish even when historical sea surface temperature gradients were steeper than they are now. |

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| *Communications* **5**: 10.1038/ncomms5102. | |
| Kapsenberg, L. and Hofmann, G.E. 2014. Signals of resilience to ocean change: high thermal tolerance of early stage Antarctic sea urchins (*Sterechinus neumayeri*) reared under present-day and future $pCO_2$ and temperature. *Polar Biology* **37**: 967-980. | Antarctic sea urchins not only survived at higher levels of temperature and acidity than expected, but those traits seemed to be heritable. |
| Moulin, L., Grosjean, P., Leblud, J., Batigny, A. and Dubois, P. 2014. Impact of elevated $pCO_2$ on acid-base regulation of the sea urchin *Echinometra mathaei* and its relation to resistance to ocean acidification: A study in Mesocosms. *Journal of Experimental Marine Biology and Ecology* **457**: 97-104. | This study of coral reef sea urchins under acidified conditions and high $CO_2$ concentrations showed that they could regulate their own pH and maintain respiratory metabolism. |
| Morris, M.R.J., Richard, R., Leder, E.H., Rowan, D.H., Barrett, N. A.-H. and Robers S.M. 2014. Gene expression plasticity evolves in response to colonization of freshwater lakes in threespine stickleback. *Molecular Ecology* **23**: 3226-3240. | Fish in novel environment showed greater phenotypic plasticity--allowing for more rapid adaptation. |
| Spungin, D., Berman-Frank, I. and Levitan, O. 2014. *Trichodesmium's* strategies to alleviate phosphorus limitation in the future acidified oceans. *Environmental Microbiology* **16**: 1935-1947. | An oceanic cyanobacterium is shown to become markedly more robust at higher $CO_2$ levels, and also maintains its role in fixing nitrogen, even in areas of low phosphorus. |
| Eichner, M., Rost, B. and Kranz, S.A. 2014. Diversity of ocean acidification effects on marine $N_2$ fixers. *Journal of Experimental Marine Biology and Ecology* **457**: 199-207. | A study of three oceanic diazotrophic cyanobacteria show a variety of responses to elevated $CO_2$, but the prevalent trend is to become stronger at higher levels, especially for the most productive (nitrogen-fixing) type. |
| Chua, C.-M., Leggat, W., Moya, A. and Baird, A.H. 2013. Near-future reductions in pH will have no consistent ecological effects on the early life-history stages of reef corals. *Marine Ecology Progress Series***486**: 143-151. | Even though young coral is expected to be vulnerable to ocean acidification, study shows "no direct ecological effects of ocean acidification on the early life-history stages of reef corals ...." This is important because corals play a role in oceanic uptake of $CO_2$. |
| Gibbin, E.M. and Davy, S.K. 2014. The photo-physiological response of a model cnidarian-dinoflagellate symbiosis to $CO_2$-induced acidification at the cellular level. *Journal of Experimental Marine Biology and Ecology* **457**: 1-7. | Sea anemones and their symbiont dinoflagellates not only survive but flourish under more acid conditions. |
| Gabay, Y., Fine, M., Barkay, Z. and Benayahu, Y. 2014. Octocoral tissue provides protection from declining oceanic pH. *PLOS ONE* **9**: e91553. | Under conditions of increased acidification, octocorals showed resilience to lower pH levels when in colony (but not when structural components were isolated from the colony). |
| García-Gómez, C., Gordillo, F.J.L., Palma, A., Lorenzo, M.R. and Segovia, M. 2014. Elevated $CO_2$ alleviates high PAR and UV stress in the unicellular chlorophyte *Dunaliella tertiolecta*. *Photochemical & Photobiological Sciences* **13**: 1347-1358. | $CO_2$ alleviated the stress experienced by phytoplankton associated with light exposure. |
| Rodriguez, A.B., Fodrie, F.J., Ridge, J.T., Lindquist, N.L., Theuerkauf, E.J., Coleman, S.E., Grabowski, J.H., Brodeur, M.C., Gittman, | Oysters seeking refuge in intertidal areas may be vulnerable to sea level rise if they cannot build reefs quickly enough. This study shows |

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| R.K., Keller, D.A. and Kenworthy, M.D. 2014. Oyster reefs can outpace sea-level rise. *Nature Climate Change* **4**: 493-497. | previous estimates were more than an order of magnitude (10x) too slow. Oysters should have no problem keeping pace with sea level rises, and may benefit. |
| Cole, A.J., Lawton, R.J., Pisapia, C. and Pratchett, M.S. 2014. The effects of coral bleaching on settlement preferences and growth of juvenile butterflyfishes. *Marine Environmental Research* **98**: 106-110. | Sub-fatal coral bleaching does not affect coral-dependent fish as much as expected: no change in growth or health, nor was there a preference for unbleached versus bleached coral. |
| Gericke, R.L., Heck Jr., K.L. and Fodrie, F.J. 2014. Interactions between northern-shifting tropical species and native species in the northern Gulf of Mexico. *Estuaries and Coasts* **37**: 952-961. | Even as climate changes causes species to move (generally polar), this study showed range expansions of potential competitor species (snapper) had no effect on target species (pinfish). (Caveat: GOM was a busy place summer/fall 2010.) |
| Smith, T.B., Glynn, P.W., Mate, J.L., Toth, L.T. and Gyory, J. 2014. A depth refugium from catastrophic coral bleaching prevents regional extinction. *Ecology* **95**: 1663-1673. | Both recent and archaeological records confirm that corals can survive thermal stress and bleaching by seeking refuge in deeper waters. |
| Breckels, R.D. and Neff, B.D. 2014. Rapid evolution of sperm length in response to increased temperature in an ectothermic fish. *Evolution and Ecology* **28**: 521-533. | Guppies showed rapid evolutionary response to elevated temperatures that compensated for any diminishment. |
| Cornwall, C.E., Boyd, P.W., McGraw, C.M., Hepburn, C.D., Pilditch, C.A., Morris, J.N., Smith, A.M. and Hurd, C.L. 2014. Diffusion boundary layers ameliorate the negative effects of ocean acidification on the temperate coralline macroalga *Arthrocardia corymbosa*. *PLOS ONE* **9**: e97235. | Acidified conditions still permitted growth of calciferous coral/algae when water moved slowly, permitting a buffer layer, creating potential refuge from acidification. |
| Murray, C.S., Malvezzi, A., Gobler, C.J. and Baumann, H. 2014. Offspring sensitivity to ocean acidification changes seasonally in a coastal marine fish. *Marine Ecology Progress Series* **504**: 1-11. | Coastal fish already experience wide changes in pH and $CO_2$ levels. Studies across generations show parents in high $CO_2$ levels gave birth to offspring adapted to high $CO_2$ levels. This shows transgenerational plasticity: adaptation over multiple generations without changing DNA. |
| Palumbi, S.R., Barshis, D.J., Traylor-Knowles, N. and Bay, R.A. 2014. Mechanisms of reef coral resistance to future climate change. *Science* **344**: 895-898. | Acclimating corals to warmer temperatures accomplishes similar adaptation (to temperature as well as acidification) in two years that would ordinarily take generations. Current models do not take account of this phenomenon. |
| Precht, W.F., Deslarzes, K.J.P., Hickerson, E.L., Schmahl, G.P., Nuttall, M.F. and Aronson, R.B. 2014. Back to the future: The history of acroporid corals at the Flower Garden Banks, Gulf of Mexico, USA. *Marine Geology***349**: 152-161. | Changes in species ranges for GOM corals is more “a return to conditions of times past” than a novel effect of warming, suggesting that corals can deal with warming better than expected. |
| Movilla, J., Gori, A., Calvo, E., Orejas, C., Lopez-Sanz, A., Dominguez-Carrio, C., Grinyo, J. and Pelejero, C. 2014. Resistance of two Mediterranean cold-water coral species to low-pH conditions. *Water* **6**: 59-67. | Certain species of coral showed no effect from acidification despite being from zones that were expected to be sensitive to acidification. |
| Moustafa, M.Z., Moustafa, M.S., Moustafa, | Study of coral in inhospitable environment in |

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| Z.D. and Moustafa, S.E. 2014. Survival of high latitude fringing corals in extreme temperatures: Red Sea oceanography. *Journal of Sea Research* **88**: 144-151. | Suez canal (large temperature swings, little new water inputs) survive and thrive despite exceeding ordinary bleaching thresholds. |
| Allan, B.J.M., Miller, G.M., McCormick, M.I., Domenici, P. and Munday, P.L. 2014. Parental effects improve escape performance of juvenile reef fish in a high-$CO_2$ world. *Proceedings of the Royal Society B* **281**: 20132179. | Fish in high $CO_2$ conditions raised by parents acclimated to high $CO_2$ showed better escape responses than high-$CO_2$ fish not reared by parents acclimated to high $CO_2$ levels. Transgenerational adaptation mitigates effects of $CO_2$ on behavior. |
| Kerfahi, D., Hall-Spencer, J.M., Tripathi, B.M., Milazzo, M., Lee, J. and Adams, J.M. 2014. Shallow water marine sediment bacterial community shifts along a natural $CO_2$ gradient in the Mediterranean Sea off Vulcano, Italy. *Microbial Ecology* **67**: 819-828. | Bacterial diversity not only did not suffer but increased along with the $CO_2$ gradient. |
| Mondal, T., Raghunathan, C. and Venkataraman, K. 2013. Bleaching: The driving force of scleractinian new recruitment at Little Andaman Island, Andaman and Nicobar Islands. Proceedings of the National Academy of Sciences, India, Section B Biological Sciences 83: 585-592. | After studying reef bleaching in the Andaman Sea, the study concludes that bleaching can lead to settlement and diversification within a coral reef. |
| Schoepf, V., Grottoli, A.G., Warner, M.E., Cai, W-J., Melman, T.F., Hoadley, K.D., Pettay, D.T., Hu, X., Li, Q., Xu, H., Wang, Y., Matsui, Y. and Baumann, J.H. 2013. Coral energy reserves and calcification in a high-$CO_2$ world at two temperatures. PLOS ONE 8: e75049. | The study concludes that "some corals could be more resistant to combined ocean acidification and warming expected by the end of this century than previously thought," such that "the immediate effects of rising seawater temperature and ocean acidification may be tolerable for some species." |
| Ho, M.A., Price, C., King, C.K., Virtue, P. and Byrne, M. 2013. Effects of ocean warming and acidification on fertilization in the Antarctic echinoid Sterechinus neumayeri across a range of sperm concentrations. Marine Environmental Research 90: 136-141. | The study concludes that "decreased pH did not affect fertilization" of a species of Antarctic sea urchin but that "warming enhanced fertilization ... likely through stimulation of sperm motility and reduced water viscosity." As such, "fertilization in S. neumayeri, even at low sperm levels potentially found in nature, is resilient to near-future ocean warming and acidification." |
| Pratchett, M.S., McCowan, D., Maynard, J.A. and Heron, S.F. 2013. Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. PLOS ONE 8: e70443. | Four types of reef-building coral demonstrate both resilience and adaptation in the face of warming and acidification. |
| Sanders, M.B., Bean, T.P., Hutchinson, T.H. and Le Quesne, W.J.F. 2013. Juvenile king scallop, Pecten maximus, is potentially tolerant to low levels of ocean acidification when food is unrestricted. PLOS ONE 8: e74118. | The study determined that for ocean scallops "none of the exposure levels were found to have significant effects on the clearance rates, respiration rates, condition index or cellular turnover (RNA: DNA) of individuals" and "where food is in abundance, bivalves like juvenile P. maximus may display a tolerance to limited changes in seawater chemistry." |
| Jantzen, C., Haussermann, V., Forsterra, G., Laudien, J., Ardelan, M., Maier, S. and Richter, C. 2013. Marine Biology160: 2597-2607. | This study replicated the conclusion of recent studies that found "a higher acclimatization potential of cold-water corals to ocean |

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| | acidification." |
| Ragazzola, F., Foster, L.C., Form, A.U., Buscher, J., Hansteen, T.H. and Fietzke, J. 2013. Phenotypic plasticity of a coralline algae in a high $CO_2$ world. Ecology and Evolution 3: 3436-3446. | The study concludes that "the ability to change the energy allocation between cell growth and structural support is a clear adaptive response of the organism," which they say "is likely to increase its ability to survive in a high $CO_2$ world." |
| Couce, E., Ridgwell, A. and Hendy, E.J. 2013. Future habitat suitability for coral reef ecosystems under global warming and ocean acidification. Global Change Biology 19: 3592-3606. | Couce *et al.* conclude that "contrary to expectations, the combined impact of ocean surface temperature rise and acidification leads to little, if any, degradation in future habitat suitability across much of the Atlantic and areas currently considered 'marginal' for tropical corals, such as the eastern Equatorial Pacific." And they note, in this regard, that "these results are consistent with fossil evidence of range expansions during past warm periods." |
| Lewis, C.N., Brown, K.A., Edwards, L.A., Cooper, G. and Findlay, H.S. 2013. Sensitivity to ocean acidification parallels natural $pCO_2$ gradients experienced by Arctic copepods under winter sea ice. Proceedings of the National Academy of Sciences USA 110: 10.1073/pnas.131516210. | Lewis *et al.*, after mixed findings, concluded that "the natural range of $pCO_2$ experienced by an organism determines its sensitivity to future OA," and that, "certainly, ubiquitous species in their adult form, living across a range of physicochemical conditions, are likely capable of surviving change." |
| Chan, V.B.S., Thiyagarajan, V., Lu, X.W., Zhang, T. and Shih, K. 2013. Temperature dependent effects of elevated $CO_2$ on shell composition and mechanical properties of Hydroides elegans: Insights from a multiple stressor experiment. PLOS ONE 8: e78945. | Chan *et al.* concluded that their "results from the analyses of tube mineralogy, ultrastructure and mechanical properties showed that predicted coastal warming may not hinder H. elegans ability to build normal tubes even in the face of projected near-future decreases in pH or salinity." |
| Mayfield, A.B., Fan, T.-Y. and Chen, C.-S. 2013. Physiological acclimation to elevated temperature in a reef-building coral from an upwelling environment. Coral Reefs 32: 909-921. | Mayfield *et al.* stated that "upon nine months of exposure to nearly 30°C, all colony (mortality and surface area), polyp (Symbiodinium density and chlorophyll a content), tissue (total thickness), and molecular (gene expression and molecular composition)-level parameters were documented at similar levels between experimental corals and controls incubated at 26.5°C, suggesting that this species can readily acclimate to elevated temperatures." Citing other studies, they continue to say "there is now a growing body of evidence to support the notion that corals inhabiting more thermally unstable habitats outperform conspecifics from reefs characterized by more stable temperatures when exposed to elevated temperatures." |
| Pedersen, S.A., Hansen, B.H., Altin, D. and Olsen, A.J. 2013. Medium-term exposure of the North Atlantic copepod Calanus finmarchicus (Gunnerus, 1770) to $CO_2$-acidified seawater: effects on survival and development. Biogeosciences10: 7481-7491. | Pedersen *et al.* studied "the impact of medium-term exposure to $CO_2$ acidified seawater on survival, growth and development was investigated in the North Atlantic copepod Calanus finmarchicus," where using a custom-developed experimental system, "fertilized eggs and subsequent development stages |

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| | were exposed to normal seawater (390 ppm $CO_2$) or one of three different levels of $CO_2$-induced acidification (3300, 7300, 9700 ppm $CO_2$)." They conclude that "the absence of any apparent reduction in the overall survival during the present medium-term exposure to 3300 ppm $CO_2$, indicates that survival of Calanus eggs and nauplii may be robust against the direct effects of the worst-case $CO_2$ scenario predicted for year 2300." |
| Mukherjee, J., Wong, K.K.W., Chandramouli, K.H., Qian, P.-Y., Leung, P.T.Y., Wu, R.S.S. and Thiyagarajan, V. 2013. Proteomic response of marine invertebrate larvae to ocean acidification and hypoxia during metamorphosis and calcification. The Journal of Experimental Biology 216: 4580-4589. | Mukherjee *et al.* concluded that "the aragonite tube-forming tubeworm larvae have a high tolerance to hypoxia and may possess the capacity to acclimate over time, even in the phase of ocean acidification." |
| Crook, E.D., Cooper, H., Potts, D.C., Lambert, T. and Paytan, A. 2013. Impacts of food availability and $pCO_2$ on planulation, juvenile survival, and calcification of the azooxanthellate scleractinian coral Balanophyllia elegans. Biogeosciences 10: 7599-7608. | In the final sentence of their paper, the five U.S. researchers conclude that "as long as food availability remains high, B. elegans may be able to largely compensate for the extra energy required for calcification at low saturations, even if calcification occurs at slightly lower rates than at modern $pCO_2$." "[W]e conclude that food abundance is critical for azooxanthellate coral calcification, and that B. elegans may be partially protected from adverse consequences of ocean acidification in habitats with abundant heterotrophic food." |
| Styf, H.J.K., Skold, H.N. and Eriksson, S.P. 2013. Embryonic response to long-term exposure of the marine crustacean Nephrops norvegicus to ocean acidification and elevated temperature. Ecology and Evolution 3: 5055-5065. | "[T]his species would benefit from global warming and be able to withstand the predicted decrease in ocean pH in the next century during their earliest life stages." |
| Byrne, M., Lamare, M., Winter, D., Dworjanyn, S.A. and Uthicke, S. 2014. The stunting effect of a high $CO_2$ ocean on calcification and development in sea urchin larvae, a synthesis from the tropics to the poles. Philosophical Transactions of the Royal Society B 368: 10.1098/rstb.2012.0439. | Byrne *et al.* write that "adaptation through natural selection over coming decades may also facilitate persistence in a changing ocean, especially for species from warmer latitudes that have a comparatively shorter generation time compared with polar species." In addition, they note that "recent quantitative genetics and genomic studies with echinoids indicate the presence of traits to facilitate resilience and adaptation (genetic) to ocean acidification (Pespini *et al.*, 2012; Kelly *et al.*, 2013; Sunday *et al.*, 2011; Schlegel, *et al.*, 2012), as well as to ocean warming and to both stressors combined (Foo *et al.*, 2012)." |
| Benner, I., Diner, R.E., Lefebvre, S.C., Li, D., Komada, T., Carpenter, E.J. and Stillman, J.H. 2014. Emiliania huxleyi increases calcification but not expression of calcification-related genes in long-term exposure to elevated temperature and $pCO_2$. Philosophical Transactions of the Royal Society B 368: | Benner *et al.* report that "in contrast to findings from short-term experiments, our results suggest that long-term acclimation or adaptation could change, or even reverse, negative calcification responses in E. huxleyi and its feedback to the global carbon cycle." |

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| 10.1098/rstb.2013.0049. | |
| Calosi, P., Rastrick, S.P.S., Lombardi, C., de Guzman, H.J., Davidson, L., Jahnke, M., Giangrande, A., Hardege, J.D., Schulze, A., Spicer, J.I. and Ganbi, M.-C. 2014. Adaptation and acclimatization to ocean acidification in marine ectotherms: an in situ transplant experiment with polychaetes at a shallow $CO_2$ vent system. Philosophical Transactions of the Royal Society B 368: 10.1098/rstb.2012.0444. | Noting that previous studies have shown that "unicellular organisms can adapt to elevated $pCO_2$," citing Lohbeck *et al.* (2012), Benner *et al.* (2013) and Tatters *et al.* (2013), the eleven scientists say their study (1) "provides evidence that a marine ectotherm (Platynereis dumerilii) has been able to genetically and physiologically adapt to chronic and elevated levels of $pCO_2$," and that it (2) "supports those studies that have indicated the potential of marine metazoans [animals with differentiated tissues, including nerves and muscles] to adapt to elevated $pCO_2$," citing the work of Pespeni *et al.* (2013), Pistevos *et al.* (2011), Sunday *et al.* (2011), Foo *et al.* (2012), Schlegel *et al.* (2012), Padilla-Gamiño *et al.* (2013) and Kelly *et al.* (2013). |
| Ivanina, A.V. and Sokolova, I.M. 2013. Interactive effects of pH and metals on mitochondrial functions of intertidal bivalves Crassostrea virginica and Mercenaria mercenaria. Aquatic Toxicology 144-145: 303-309. | Ivanina and Sokolova conclude that "moderate acidosis (such as occurs during exposure to air, extreme salinities or elevated $CO_2$ levels in the intertidal zone) may have a beneficial side-effect of protecting mitochondria against toxicity of metals," in that "reduced intracellular pH caused by exposure to elevated $CO_2$ levels abolished the metal-induced generation of reactive oxygen species in isolated clam cells (Ivanina *et al.*, 2013) consistent with a mitochondrial mechanism of the cytoprotective effects of moderate acidification," while noting that a similar mechanism had been "experimentally demonstrated for the surface proteins of unicellular algae" in the studies of Niyogi and Wood (2004), Wilde *et al.* (2006) and Esbaugh *et al.* (2013). |
| Sett, S., Bach, L.T., Schulz, K.G., Koch-Klavsen, S., Lebrato, M. and Riebesell, U. 2014. Temperature modulates coccolithophorid sensitivity of growth, photosynthesis and calcification to increasing seawater $pCO_2$. PLOS ONE 9: e88308. | The six scientists determined that increased temperature generally (1) enhanced the growth and production rates of both species and (2) modified the responses of their primary metabolic processes (photosynthesis, growth and calcification) to increasing $CO_2$, such that the optima of the three processes occurred at higher $CO_2$ concentrations as temperatures rose from intermediate to high values. |
| Pansch, C., Schaub, I., Havenhand, J. and Wahl, M. 2014. Habitat traits and food availability determine the response of marine invertebrates to ocean acidification. Global Change Biology 20: 765-777. | In discussing their findings, Pansch *et al.* say they indicate that "populations from fluctuating $pCO_2$ environments are more tolerant to elevated $pCO_2$ than populations from more stable $pCO_2$ habitats." And so they conclude that "considering the high tolerance of Kiel specimens and the possibility to adapt over many generations, near future OA alone does not seem to present a major threat for A. improvisus." |
| Amaral, V., Cabral, H.N. and Bishop, M.J. 2014. Prior exposure influences the behavioral | Amaral *et al.* suggest that "both the migration of gastropods out of acidified waters and |

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| avoidance by an intertidal gastropod, Bembicium aurantum, of acidified waters. Estuarine, Coastal and Shelf Science 136: 82-90. | retraction into their shells serves to reduce exposure time to acidified waters and may reduce the impact of this stressor on their populations," while "the stronger response to acidification of gastropods from populations previously exposed to this stressor suggests that the response may be learned, inherited or induced over multiple exposures." And so they conclude that their study "adds to growing evidence that estuarine organisms may exhibit considerable physiological and behavior adaptive capacity to acidification." |
| Ern, R., Huong, D.T.T., Phuong, N.T., Wang, T. and Bayley, M. 2014. Oxygen delivery does not limit thermal tolerance in a tropical eurythermal crustacean. The Journal of Experimental Biology 217: 809-814. | In concluding the report of their study, Ern *et al.* write that "in the giant freshwater shrimp the current worst-case scenario predicting a 3°C increase in tropical water temperature by the end of this century does not cause a negative effect on its growth performance." |
| Palumbi, S.R., Barshis, D.J., Traylor-Knowles, N. and Bay, R.A. 2014. Mechanisms of reef coral resistance to future climate change. *Science* **344**: 895-898. | Searching for the mechanisms of adaptation to warmer waters, scientists found that adaptation to warmer temperatures could occur within two years, rather than multiple generations of natural selection. Acclimation was reflected in gene expression, so coral showed short-term acclimation and longer-term adaptive responses. |
| Nguyen, H.D. and Byrne, M. 2014. Early benthic juvenile *Parvulastra exigua* (Asteroidea) are tolerant to extreme acidification and warming in its intertidal habitat. *Journal of Experimental Marine Biology and Ecology* **453**: 36-42. | Sea-stars resilient to higher degrees of warming than expected, and rapidly form adaptive responses that would mitigate near-term negative outcomes. |
| Jarrold, M.D., Calosi, P., Verberk, W.C.E.P., Rastrick, S.P.S., Atfield, A. and Spicer, J.I. 2013. Physiological plasticity preserves the metabolic relationship of the intertidal non-calcifying anthozoan-*Symbiodinium*symbiosis under ocean acidification. *Journal of Experimental Marine Biology and Ecology* **449**: 200-206. | Sea anemones show high levels of physiological plasticity in acidified waters, preserving photosynthetic capacity. |
| McClanahan, T.R. and Muthiga, N.A. 2014. Community change and evidence for variable warm-water temperature adaptation of corals in Northern Male Atoll, Maldives. *Marine Pollution Bulletin* **80**: 107-113. | Seven years after massive coral bleaching event in Maldives in 1998, researchers found many varieties of coral, and noted that some bleached less than predicted in response to a thermal event in 2005. They also note that "selective breeding and transplanting" of corals can alleviate problems further. |
| Hildebrandt, N., Niehoff, B. and Sartoris, F.J. 2014. Long-term effects of elevated $CO_2$ and temperature on the Arctic calanoid copepods *Calanus glacialis* and *C. hyperboreus*. *Marine Pollution Bulletin* **80**: 59-70. | Arctic zooplankton can tolerate much higher concentrations of $CO_2$ than expected, and even when negative effects appear they are sub-fatal. |
| Bates, A.E., Barrett, N.S., Stuart-Smith, R.D., Holbrook, N.J., Thompson, P.A. and Edgar, G.J. 2014. Resilience and signatures of | Human-made ecological reserve habitats can offset species stresses from warming. |

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| tropicalization in protected reef fish communities. *Nature Climate Change* **4**: 62-67. | |
| Comeau, S., Edmunds, P.J., Spindel, N.B. and Carpenter, R.C. 2014. Diel $pCO_2$ oscillations modulate the response of the coral *Acropora hyacinthus* to ocean acidification. *Marine Ecology Progress Series* **501**: 99-111. | Oscillations in $CO_2$ levels produced corals strongly resistant to acidification compared to those treated with steady levels of $CO_2$. |
| Haynert, K., Schonfeld, J., Schiebel, R., Wilson, B. and Thomsen, J. 2014. Response of benthic foraminifera to ocean acidification in their natural sediment environment: a long-term culturing experiment. *Biogeosciences***11**: 1581-1597. | Species expected to be susceptible to ocean acidification was exposed to moderate and high levels of $CO_2$ concentrations. It proved to be hardy even at the higher levels of exposure. |
| Stoks, R., Geerts, A.N. and De Meester, L. 2014. Evolutionary and plastic responses of freshwater invertebrates to climate change: realized patterns and future potential. *Evolutionary Applications* **7**: 42-55. | Warming causes rapid adaptive changes both genetically and in terms of phenotypic plasticity. |
| Crozier, L.G. and Hutchings, J.A. 2014. Plastic and evolutionary responses to climate change in fish. *Evolutionary Applications* **7**: 68-87. | Wild fish populations adapted to climate change with both evolutionary and plastic responses. |
| Collins, S., Rost, B. and Rynearson, T.A. 2014. Evolutionary potential of marine phytoplankton under ocean acidification. *Evolutionary Applications* **7**: 140-155. | Marine phytoplankton adapts to increased acidification both through "sorting standing variation in fitness and by using *de novo* mutation," which result in rapid evolution. |
| Yu, K., Zhao, J., Roff, G., Lybolt, M., Feng, Y., Clark, T. and Li, S. 2012. High-precision U-series ages of transported coral blocks on Heron Reef (southern Great Barrier Reef) and storm activity during the past century. *Palaeogeography, Palaeoclimatology, Palaeoecology* **337-338**: 23-36. | Corals in South Barrier Reefs have been exposed to major storm activity for most of the 20th century and are not as delicate as presumed. |
| Wu, Z., Zeng, B., Li, R. and Song, L. 2012. Combined effects of carbon and phosphorus levels on the invasive cyanobacterium, *Cylindrospermopsis raciborskii*. *Phycologia* **51**: 144-150. | Increasingly $CO_2$-enriched environments resulted in increased photosynthesis, biomass, and nitrogen fixation of cyanobacteria. |
| Fernandez-Reiriz, M.J., Range, P., Alvarez-Saldago, X.A., Espinosa, J. and Labarta, U. 2012. Tolerance of juvenile *Mytilus galloprovincialis* to experimental seawater acidification. *Marine Ecology Progress Series* **454**: 65-74. | Mussels common to Spain proved resistant to acidified seawater conditions. |
| Vogel, N. and Uthicke, S. 2012. Calcification and photobiology in symbiont-bearing benthic foraminifera and responses to a high $CO_2$ environment. *Journal of Experimental Marine Biology and Ecology* **424-425**: 15-24. | Corals showed ability to maintain calciferous growth through $CO_2$ concentrations projected through 2100, and in one case even showed an enhanced growth rate. |
| Range, P., Pilo, D., Ben-Hamadou, R., Chicharo, M.A., Matias, D., Joaquim, S., Oliveira, A.P. and Chicharo, L. 2012. Seawater acidification by $CO_2$ in a coastal lagoon environment: Effects on life history traits of juvenile mussels *Mytilus galloprovincialis*. *Journal of Experimental Marine Biology and* | Study of mussels under acid conditions showed little adverse effect. While calcification was reduced, growth was not, which indicates that the reduction was post-deposition. Mortality was no different from control. "[T]here is no evidence of $CO_2$-related mortalities of juvenile or adult bivalves in natural habitats, |

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| *Ecology* **424-425**: 89-98. | even under conditions that far exceed the worst-case scenarios for future ocean acidification (Tunnicliffe *et al.*, 2009)." |
| Teira, E., Fernandez, A., Alvarez-Salgado, X.A., Garcia-Martin, E.E., Serret, P. and Sobrino, C. 2012. Response of two marine bacterial isolates to high $CO_2$ concentration. *Marine Ecology Progress Series* **453**: 27-36. | Two species of bacteria not only showed no negative effects from higher $CO_2$ and acidification but even showed some negative feedback, acting to raise the pH (less acid). |
| McCulloch, M., Falter, J., Trotter, J. and Montagna, P. 2012. Coral resilience to ocean acidification and global warming through pH up-regulation. *Nature Climate Change* **2**: 623-627. | Some corals can up-regulate calcification at sites of pH changes, resisting acidification. Moreover, this effect is enhanced in higher water temperatures, so warming may offset the threat from acidification. |
| Weydmann, A., Soreide, J.E., Kwasniewski, S. and Widdicombe, S. 2012. Influence of $CO_2$-induced acidification on the reproduction of a key Arctic copepod *Calanus glacialis*. *Journal of Experimental Marine Biology and Ecology* **428**: 39-42. | Key arctic copepod showed no negative effects from $CO_2$-acidified water. |
| Foo, S.A., Dworjanyn, S.A., Poore, A.G.B. and Byrne, M. 2012. Adaptive capacity of the habitat modifying sea urchin *Centrostephanus rodgersii* to ocean warming and ocean acidification: Performance of early embryos. *PLoS ONE* **7**: e42497. | "[E]cologically important species" of sea urchin shows resilience to increased acidification and temperature, and no trade-off between the two. |
| Suggett, D.J., Hall-Spencer, J.M., Rodolfo-Metalpa, R., Boatman, T.G., Payton, R., Pettay, D.T., Johnson, V.R., Warner, M.E. and Lawson, T. 2012. Sea anemones may thrive in a high $CO_2$ world. *Global Change Biology* **18**: 3015-3025. | Far from being threatened, sea anemones seemed to thrive in a high-$CO_2$ environment, studied near a cold vent system near Sicily. |
| Cubillos, J.C., Henderiks, J., Beaufort, L., Howard, W.R. and Hallegraeff, G.M. 2012. Reconstructing calcification in ancient coccolithophores: Individual coccolith weight and morphology of *Coccolithus pelagicus* (sensu lato). *Marine Micropaleontology* **92-93**: 29-39. | Despite rising $CO_2$ and acidification, marine calcifiers (coccoliths) showed more calcification than fossilized counterparts. |
| Ravaux, J., Leger, N., Rabet, N., Morini, M., Zbinden, M., Thatje, S. and Shillito, B. 2012. Adaptation to thermally variable environments: capacity for acclimation of thermal limit and heat shock response in the shrimp *Palaemonetes varians*. *Journal of Comparative Physiology B* **182**: 899-907. | French shrimp can expand thermal capacity upwards (acclimation), suggesting they may not even need to migrate in order to sustain existing habitat. |
| Hannisdal, B., Henderiks, J. and Liow, L.H. 2012. Long-term evolutionary and ecological responses of calcifying phytoplankton to changes in atmospheric $CO_2$. *Global Change Biology* **18**: 3504-3516. | Fossil records show coccolithophores (calcifying algae, protists, and phytoplankton key to moving organic matter from ocean surface to depths) were more prominent, larger, and more calcified during previous high-$CO_2$ period in history. They thus appear to be not only resistant to acidification, but show a longstanding evolutionary response. |
| Galbraith, H.S., Blakeslee, C.J. and Lellis, W.A. | Critical thermal maximum (CTM)--the |

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| 2012. Recent thermal history influences thermal tolerance in freshwater mussel species (Bivalvia: Unionoida). *Freshwater Science* **31**: 83-92. | temperature at which an organism loses function sufficient to prevent its escape--shown to be moveable in mussel species. In general, mussels acclimated to higher temperatures displayed a significantly higher CTM than those not so acclimated. |
| Lachapelle, J. and Bell, G. 2012. Evolutionary rescue of sexual and asexual populations in a deteriorating environment. *Evolution* **66**: 3508-3518. | "[M]ajor shifts in ways of life can arise within short time frames through the action of natural selection in sexual populations," essentially a form of "evolutionary rescue" for sea organisms in danger from a changed environment (here, changing from fresh to salt water). |
| Miller, G.M., Watson, S.-A., Donelson, J.M., McCormick, M.I. and Munday, P.L. 2012. Parental environment mediates impacts of increased carbon dioxide on a coral reef fish. *Nature Climate Change* **2**: 858-861. | Juvenile anemonefish experience negative reactions to higher levels of $CO_2$, but if parents are acclimated to $CO_2$, the negative effects are "absent or reversed." The mechanism is non-genetic, suggesting rapid (single-generation) adaptation is possible in addition to multi-generational genetic effects. |
| Seebacher, F., Holmes, S., Roosen, N.J., Nouvian, M., Wilson, R.S. and Ward, A.J.W. 2012. Capacity for thermal acclimation differs between populations and phylogenetic lineages within a species. *Functional Ecology* **26**: 1418-1428. | Analyzing the ability to adapt to climate change on a species-wide scale is too coarse; individual populations within a species may have stronger capacity to adapt than others, preventing extinctions. Different genetic lineages of mosquitofish showed different capacity for thermal adaptation. |
| Thiyagarajan, V. and Ko, G.W.K. 2012. Larval growth response of the Portuguese oyster (*Crassostrea angulata*) to multiple climate change stressors. *Aquaculture* **370-371**: 90-95. | Researchers examined impacts on oyster larvae of changes in salinity, temperature, and pH. They found that salinity and temperature had a much greater effect on growth, and pH had little to none. Higher temperatures and lower salinity--the projected effects of climate change--resulted in stronger growth. |
| Vehmaa, A., Brutemark, A. and Engstrom-Ost, J. 2012. Maternal effects may act as an adaptation mechanism for copepods facing pH and temperature changes. *PLOS ONE* **7**: e48538. | Researchers found a strong maternal effect in copepods, allowing offspring to survive challenging conditions if the mother had acclimated to similar conditions. |
| Joint, I., Doney, S.C. and Karl, D.M. 2011. Will ocean acidification affect marine microbes? *The ISME Journal* **5**: 1-7. | Evidence indicates that certain marine and freshwater phytoplankton can adapt to pH changes. |
| Martin, S., Richier, S., Pedrotti, M.-L., Dupont, S., Castejon, C., Gerakis, Y., Kerros, M.-E., Oberhansli, F., Teyssie, J.-L., Jeffree, R. and Gattuso, J.-P. 2011. Early development and molecular plasticity in the Mediterranean sea urchin *Paracentrotus lividus* exposed to $CO_2$-driven acidification. *The Journal of Experimental Biology* **214**: 1357-1368. | Mediterranean sea urchins are extremely resistant to low pH. |
| Byrne, M., Soars, N.A., Ho, M.A., Wong, E., McElroy, D., Selvakumaraswamy, P., Dworjanyn, S.A. and Davis A.R. 2010. Fertilization in a suite of coastal marine invertebrates from SE Australia is robust to near-future ocean warming and acidification. | Warming has no significant effect on fertilization of certain shallow subtidal echinoids, an asteroid and an abalone. |

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| *Marine Biology* **157**: 2061-2069. | |
| Berge, T., Daugbjerg, N., Andersen, B.B. and Hansen, P.J. 2010. Effect of lowered pH on marine phytoplankton growth rates. *Marine Ecology Progress Series* **416**: 10.3354/meps08780. | "Marine phytoplankton in general are resistant to climate change in terms of ocean acidification, and do not increase or decrease their growth rates according to ecological relevant ranges of pH and free $CO_2$." |
| Small, D., Calosi, P., White, D., Spicer, J.I. and Widdicombe, S. 2010. Impact of medium-term exposure to $CO_2$ enriched seawater on the physiological functions of the velvet swimming crab *Necora puber*. *Aquatic Biology* **10**: 11-21. | Most physiological functions in velvet swimming crabs are resistant to low pH levels. |
| Parker, L.M., Ross, P.M. and O'Connor, W.A. 2011. Populations of the Sydney rock oyster, *Saccostrea glomerata*, vary in response to ocean acidification. *Marine Biology* **158**: 689-697. | Selective breeding of Sydney Rock Oysters may be a solution to impacts of ocean acidification. This also indicates an innate ability to adapt to ocean acidification. |
| Byrne, M., Selvakumaraswamy, P., Ho, M.A., Woolsey, E. and Nguyen, H.D. 2011. Sea urchin development in a global change hotspot, potential for southerly migration of thermotolerant propagules. *Deep-Sea Research II* **58**: 712-719. | Ocean warming may be advantageous to sea urchin development in Southeast Australia. |
| Bilyk, K.T. and DeVries, A.L. 2011. Heat tolerance and its plasticity in Antarctic fishes. *Comparative Biochemistry and Physiology, Part A* **158**: 382-390. | Antarctic fish have significant thermal plasticity and can, therefore, tolerate warming temperatures. |
| Ericson, J.A., Lamare, M.D., Morley, S.A. and Barker, M.F. 2010. The response of two ecologically important Antarctic invertebrates (*Sterechinus neumayeri* and *Parborlasia corrugatus*) to reduced seawater pH: effects on fertilization and embryonic development. *Marine Biology* **157**: 2689-2702. | Certain Antarctic invertebrates are not more affected by lowered pH compared to tropical and temperate counterparts. |
| Eme, J., Dabruzzi, T.F. and Bennett, W.A. 2011. Thermal responses of juvenile squaretail mullet (*Liza vaigiensis*) and juvenile crescent terapon (*Terapon jarbua*) acclimated at near-lethal temperatures, and the implications for climate change. *Journal of Experimental Marine Biology and Ecology* **399**: 35-38. | "Tropical marine fishes inhabiting fringing nursery environments may have the upper thermal tolerance necessary to endure substantial increases in sea temperatures." |
| Morrongiello, J.R., Crook, D.A., King, A.J., Ramsey, D.S. and Brown, P. 2011. Impacts of drought and predicted effects of climate change on fish growth in temperate Australian lakes. *Global Change Biology* **17**: 745-755. | Increased growing season, which results from warming, may actually increase fish growth. |
| Range, P., Chicharo, M.A., Ben-Hamadou, R., Pilo, D., Matias, D., Joaquim, S., Oliveira, A.P. and Chicharo, L. 2011. Calcification, growth and mortality of juvenile clams *Ruditapes decussatus* under increased $pCO_2$ and reduced pH: Variable responses to ocean acidification at local scales? *Journal of Experimental Marine Biology and Ecology* **396**: 177-184. | Low pH seawater reduced mortality in juvenile clams. |
| Seo H., Kudo, H. and Kaeriyama, M. 2011. Long-term climate-related changes in somatic | Juvenile Hokkaido Chum Salmon grew at an increased rate in their first year of life in areas |

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| growth and population dynamics of Hokkaido chum salmon. *Environmental Biology of Fishes* **90**: 131-142. | with warmer sea surface temperatures. |
| Bechmann, R.K., Taban, I.C., Westerlund, S., Godal, B.F., Arnberg, M., Vingen, S., Ingvarsdottir, A. and Baussant, T. 2011. Effects of ocean acidification on early life stages of Shrimp (*Pandalus borealis*) and mussel (*Mytilus edulis*). *Journal of Toxicology and Environmental Health, Part A* **74**: 424-438. | Low pH levels did not reduce the survival of shrimp larvae. |
| Yu, P.C., Matson, P.G., Martz, T.R. and Hofmann, G.E. 2011. The ocean acidification seascape and its relationship to the performance of calcifying marine invertebrates: Laboratory experiments on the development of urchin larvae framed by environmentally-relevant $pCO_2$/pH. *Journal of Experimental Marine Biology and Ecology* **400**: 288-295. | Developmental progression and survival of sea urchin larvae was within the norm at low pH levels. |
| Denny, M.W., Dowd, W.W., Bilir, L., and Mach, K.J. 2011. Spreading the risk: Small-scale body temperature variation among intertidal organisms and its implications for species persistence. *Journal of Experimental Marine Biology and Ecology* **400**: 175-190. | Based on research at an intertidal site, researchers found that within-site variation in extreme temperatures rivaled variation among sites along fourteen degrees of latitude. |
| Poloczanska, E.S., Smith, S., Fauconnet, L., Healy, J., Tibbetts, I.R., Burrows, M.T. and Richardson, A.J. 2011. Little change in the distribution of rocky shore faunal communities on the Australian east coast after 50 years of rapid warming. *Journal of Experimental Marine Biology and Ecology* **400**: 145-154. | Of 37 examined species of Australian marine fauna, only six showed negative poleward shifts. |
| Seabra, R., Wethey, D.S., Santos, A.M. and Lima, F.P. 2011. Side matters: Microhabitat influence on intertidal heat stress over a large geographical scale. *Journal of Experimental Marine Biology and Ecology* **400**: 200-208. | Thermal heterogeneity within habitats must be fully understood in order to interpret patterns of biogeographic response to climate change. |
| Munday, P.L., Hernaman, V., Dixson, D.L. and Thorrold, S.R. 2011b. Effect of ocean acidification on otolith development in larvae of a tropical marine fish. *Biogeosciences* **8**: 1631-1641. | Larval clownfish can survive ocean chemistry changes that may occur in the next 50-100 years. |
| Wood, H.L., Spicer, J.I., Lowe, D.M. and Widdicombe, S. 2010. Interaction of ocean acidification and temperature; the high cost of survival in the brittlestar *Ophiura ophiura*. *Marine Biology* **157**: 2001-2013. | Serpent starfish should be able to successfully cope with the physiological changes brought about by any modest temperature increase and/or pH decline likely to occur in the future. |
| Moulin, L., Catarino, A.I., Claessens, T. and Dubois, P. 2011. Effects of seawater acidification on early development of the intertidal sea urchin *Paracentrotus lividus* (Lamarck 1816). *Marine Pollution Bulletin* **62**: 48-54. | Sea urchins inhabiting stressful intertidal environments produce offspring that may better resist future ocean acidification. |
| Boelen, P., van de Poll, W.H., van der Strate, H.J., Neven, I.A., Beardall, J. and Buma, A.G.J. 2011. Neither elevated nor reduced $CO_2$ affects | Elevated $CO_2$ had no significant effect on the Antarctic diatom *Chaetoceros brevis.* |

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| the photophysiological performance of the marine Antarctic diatom *Chaetoceros brevis*. *Journal of Experimental Marine Biology and Ecology* **406**: 38-45. | |
| Sunday, J.M., Crim, R.N., Harley, C.D.G. and Hart, M.W. 2011. Quantifying rates of evolutionary adaptation in response to ocean acidification. *PLoS ONE* **6**: e22881. | Sea urchin species may have faster evolutionary responses within 50 years of the onset of predicted year-2100 $CO_2$ conditions despite having lower population turnover rates. |
| Hurd, C.L., Cornwall, C.E., Currie, K., Hepburn, C.D., McGraw, C.M., Hunter, K.A. and Boyd, P.W. 2011. Metabolically induced pH fluctuations by some coastal calcifiers exceed projected 22nd century ocean acidification: a mechanism for differential susceptibility? *Global Change Biology* **17**: 3254-3262. | Coralline seaweeds encounter a wide range of pH values and are able to withstand periods of low pH. Further, sea urchins and abalone readily survive very low pH. |
| van Woesik, R., Sakai, K., Ganase, A. and Loya, Y. 2011. Revisiting the winners and the losers a decade after coral bleaching. *Marine Ecology Progress Series* **434**: 67-76. | The southeastern coral reef of Sesoko Island was able to absorb localized thermal stress events without undergoing change to a less desirable state. |
| Anlauf, H., D'Croz, L. and O'Dea, A. 2011. A corrosive concoction: The combined effects of ocean warming and acidification on the early growth of a stony coral are multiplicative. *Journal of Experimental Marine Biology and Ecology***397**: 13-20. | "The resilience of planulae to predicted climatic conditions suggests that healthy coral reefs should be able to regenerate naturally after catastrophic events (such as ENSO-induced coral bleaching), if source populations can provide planulae in sufficient quantity and local stressors such as over-fishing, pollution and habitat destruction are controlled." |
| Grelaud, M., Schimmelmann, A. and Beaufort, L. 2009. Coccolithophore response to climate and surface hydrography in Santa Barbara Basin, California, AD 1917-2004. Biogeosciences 6: 2025-2039. | The three researchers report that "morphometric parameters measured on E. Huxleyi, G. muellerae and G. oceanica indicate increasing coccolithophore shell carbonate mass from ~1917 until 2004 concomitant with rising $pCO_2$ and sea surface temperature in the region of the SBB." More specifically, they say that "a >33% increase in mean coccolith weight was determined for the order Isochrysidales over 87 years from ~1917 until 2004." |
| Scopelitis, J., Andrefouet, S., Phinn, S., Chabanet, P., Naim, O., Tourrand, C. and Done, T. 2009. Changes of coral communities over 35 years: Integrating in situ and remote-sensing data on Saint-Leu Reef (la Reunion, Indian Ocean). Estuarine, Coastal and Shelf Science 84: 342-352. | "Despite the multiple disturbance events," in the words of the six scientists, "the coral community distribution and composition in 2006 on Saint-Leu Reef did not display major differences compared to 1973." This pattern of recurrent recovery suggests "a high degree of coral resilience at the site, led by rapid recovery of compact branching corals." |
| Meyer, E., Davies, S., Wang, S., Willis, B.L., Abrego, D., Juenger, T.E. and Matz, M.V. 2009. Genetic variation in responses to a settlement cue and elevated temperature in the reef-building coral Acropora millepora. Marine Ecology Progress Series 392: 81-92. | The U.S., Canadian, and Australian researchers confirmed the existence of phenotypic variance for several pertinent thermal and dispersive factors among the families of coral they studied, which finding, in their words, "suggests the existence of considerable heritable variation in natural coral populations," which in turn supports "the possibility of effective adaptive responses to climate change." |

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| McClanahan, T.R., Muthiga, N.A., Maina, J., Kamukuru, A.T. and Yahya, S.A.S. 2009. Changes in northern Tanzania coral reefs during a period of increased fisheries management and climatic disturbance. Aquatic Conservation: Marine and Freshwater Ecosystems 19: 758-771. | The Kenyan, Swedish, Tanzanian, and US researchers report that their repeated surveys "indicate general stability of these reefs over time," and they state that "in the context of the high bleaching and mortality of western Indian Ocean reefs after 1998 (Goreau *et al.*, 2000; McClanahan *et al.*, 2007), the general stability and improvement of these reefs six to seven years after the largest ENSO in recent history (McPhaden, 1999) indicates reefs with considerable resilience to climate change." |
| Hendriks, I.E., Duarte, C.M. and Alvarez, M. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. Estuarine, Coastal and Shelf Science 86: 157-164. | Hendriks *et al.* write that the world's marine biota are "more resistant to ocean acidification than suggested by pessimistic predictions identifying ocean acidification as a major threat to marine biodiversity." |
| Suwa, R., Nakamura, M., Morita, M., Shimada, K., Iguchi, A., Sakai, K. and Suzuki, A. 2010. Effects of acidified seawater on early life stages of scleractinian corals (Genus Acropora). Fisheries Science 76: 93-99. | Suwa *et al.* report that "A. digitifera larval survival rate did not differ significantly among pH treatments," and the graphs of their data indicate that survivorship in A. tenuis was actually about 18.5% greater in the lowest pH (highest $CO_2$) treatment than in the ambient seawater treatment. At the end of the subsequent ten-day study, however, polyp size was reduced in the lowest pH treatment, but by only about 14%, which is not too bad for an atmospheric $CO_2$ concentration in the range of 2115-3585 ppm. And in the A. tenuis coral, this reduction in individual size was more than compensated by the even greater percentage increase in survivorship. In addition, after only four days of being exposed to the zooxanthellae derived from giant clams, all polyps in all treatments had acquired a full complement of the symbiotic zooxanthella. In discussing their findings, the seven scientists say they indicate that "the survival of coral larvae may not be strongly affected by pH change," or "in other words," as they continue, "coral larvae may be able to tolerate ambient pH decreases of at least 0.7 pH units." |
| Havenhand, J.N. and Schlegel, P. 2009. Near-future levels of ocean acidification do not affect sperm motility and fertilization kinetics in the oyster Crassostrea gigas. Biogeosciences 6: 3009-3015. | In water of pH 8.15, mean sperm swimming speeds were 92.1±4.8μm/s, while in water of pH 7.8 they were actually slightly higher at 94.3±5.5μm/s, although the difference was not statistically significant. Likewise, mean fertilization success in water of pH 8.15 was 63.4%, while in water of pH 7.8 it was also slightly higher at 64.1%; although this difference, too, was not statistically significant. The Swedish scientists state that "the absence of significant overall effects of pH on sperm swimming behavior and fertilization success is remarkable," emphasizing that their study "showed clearly that these results were not due to inadequate statistical power," and adding |

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| | that "the absence of significant effect is likely a true reflection of the responses of Crassostrea gigas gametes and zygotes from the Swedish west coast to levels of $CO_2$-induced acidification expected by the end of this century." |
| Lombard, F., da Rocha, R.E., Bijma, J. and Gattuso, J.-P. 2010. Effect of carbonate ion concentration and irradiance on calcification in planktonic foraminifera. Biogeosciences 7: 247-255. | The four researchers report that "under the IS92a 'business as usual' scenario as defined by the Intergovernmental Panel on Climate Change and projected for the year 2100," their results suggest that "the future increase in temperature [predicted by the IPCC] could increase the production of calcite by foraminifera, counteracting the negative impact of ocean acidification," which could well reduce the expected decline in calcification to virtually nothing. |
| Rodolfo-Metalpa, R., Martin, S., Ferrier-Pages, C. and Gattuso, J.-P. 2010. Response of the temperate coral Cladocora caespitosa to mid- and long-term exposure to $pCO_2$ and temperature levels projected for the year 2100 AD. Biogeosciences 7: 289-300. | The four researchers say that for the Mediterranean zooxanthellate coral, "an increase in $CO_2$, in the range predicted for 2100, does not reduce its calcification rate," and that "an increase in $CO_2$, alone or in combination with elevated temperature, had no significant effect on photosynthesis, photosynthetic efficiency and calcification." However, they report that a 3°C rise in temperature in winter resulted in a 72% increase in gross photosynthesis, as well as a significant increase in daytime calcification rate. |
| Mydlarz, L.D., Holthouse, S.F., Peters, E.C. and Harvell, C.D. 2008. Cellular responses in sea fan corals: Granular amoebocytes react to pathogen and climate stressors. PLoS ONE 3: 10.1371/journal.pone.0001811. | According to Mydlarz *et al.*, "taken together, these studies suggest an unexpected degree of resilience under adverse environmental conditions." Indeed, they say "it is clear from the data presented in this paper that the sea fan aggressively combats infection in the gorgonian-Aspergillus pathosystem and exhibits the capability for resilience against multiple challenges." |
| Lacoue-Labarthe, T., Martin, S., Oberhansli, F., Teyssie, J.-L., Markich, S., Ross, J. and Bustamante, P. 2009. Effects of increased $pCO_2$ and temperature on trace element (Ag, Cd and Zn) bioaccumulation in the eggs of the common cuttlefish, Sepia officinalis. Biogeosciences 6: 2561-2573. | The seven scientists conclude that "decreasing pH until 7.85" "should lead to some possibly beneficial effects, such as a larger egg and presumably hatchling size and a better incorporation of the essential element[s] such as Zn in the embryonic tissue," which phenomena, in their words, "may improve the survival [of] the newly hatched juveniles." What is more, they add that Gutowska *et al.* (2008) have demonstrated that "calcification was enhanced in sub-adult cuttlefish reared at 6,000 ppm $CO_2$." |
| Byrne, M., Soars, N., Selvakumaraswamy, P., Dworjanyn, S.A. and Davis, A.R. 2010. Sea urchin fertilization in a warm, acidified and high $pCO_2$ ocean across a range of sperm densities. Marine Environmental Research 69: 234-239. | "[A]cross all treatments there was a highly significant effect of sperm density, but no significant effect of temperature or interaction between factors." In fact, "low pH did not reduce the percentage of fertilization even at |

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| | the lowest sperm densities used, and increased temperature did not enhance fertilization at any sperm density." In addition, they remark that "a number of ecotoxicology and climate change studies, where pH was manipulated with $CO_2$ gas, show that sea urchin fertilization is robust to a broad pH range with impairment only at extreme levels well below projections for ocean acidification by 2100. Neither seawater warming nor seawater acidification had either a positive or a negative effect of sea urchin fertilization, suggesting that "sea urchin fertilization is robust to climate change stressors." |
| Kuroyanagi, A., Kawahata, H., Suzuki, A., Fujita, K. and Irie, T. 2009. Impacts of ocean acidification on large benthic foraminifers: Results from laboratory experiments. Marine Micropaleontology 73: 190-195. | In declining from the control pH of 8.2 to a pH of 7.9, the mean maximum shell diameter of the large foraminifer actually rose by 8.6%, while its mean shell weight rose by a much smaller and insignificant 0.7%. As the seawater's pH declined all the way to 7.7, however, the organism's mean maximum shell diameter fell by 12.1%, while its mean shell weight fell by 49.3%. |
| Miller, A.W., Reynolds, A.C., Sobrino, C. and Riedel, G.F. 2009. Shellfish face uncertain future in high $CO_2$ world: Influence of acidification on oyster larvae calcification and growth in estuaries. PLoS ONE 4: 10.1371/journal.pone.0005661. | When the larvae of both species were cultured continuously from 96 hours post fertilization for 26 to 28 days while exposed to elevated $CO_2$ concentrations, they "appeared to grow, calcify and develop normally with no obvious morphological deformities, despite conditions of significant aragonite undersaturation," stating that these findings "run counter to expectations that aragonite shelled larvae should be especially prone to dissolution at high $pCO_2$." "[B]oth oyster species generated larval shells that were of similar mean thickness, regardless of $pCO_2$, Oarag [aragonite compensation point] or shell area," remarking that they "interpret the pattern of similar shell thickness as further evidence of normal larval shell development." |
| Breitbarth, E., Bellerby, R.J., Neill, C.C., Ardelan, M.V., Meyerhofer, M., Zollner, E., Croot, P.L. and Riebesell, U. 2010. Ocean acidification affects iron speciation during a coastal seawater mesocosm experiment. Biogeosciences 7: 1065-1073. | $CO_2$ perturbation and phytoplanktonic bloom development resulted in pH value ranges of 7.67-7.97, 7.82-8.06 and 8.13-8.26 at 1050, 700 and 350 ppm $CO_2$, respectively, and that under these conditions there were significantly higher dFe concentrations in the high $CO_2$ treatment compared to the mid and low $CO_2$ treatments. "[O]cean acidification may lead to enhanced Fe-bioavailability due to an increased fraction of dFe and elevated Fe(II) concentrations in coastal systems ... due to pH induced changes in organic iron complexation and Fe(II) oxidation rates," and these phenomena "will result in increased turnover of Fe in surface seawater, potentially maintaining iron bioavailability given a sufficient supply of |

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| | total Fe, since equilibrium partitioning eventually restores the biolabile Fe pools that have been depleted by biological uptake.” |
| Carricart-Ganivet, J.P. and Gonzalez-Diaz, P. 2009. Growth characteristics of skeletons of Montastraea annularis (Cnidaria: Scleractinia) from the northwest coast of Cuba. Ciencias Marinas 35: 237-243. | Working at two reef sites on the northwest coast of Cuba, the authors measured yearly coral extension rates and densities of the dominant Caribbean reef-building coral Montastraea annularis for the period 1991 to 2003, from which data they calculated annual coral calcification rates. The researchers found that the dominant reef-building corals of the tropical Atlantic Ocean seem not only to do fine, but actually to do better, whenever the waters within which they grow periodically warm. |
| Winans, A.K. and Purcell, J.E. 2010. Effects of pH on asexual reproduction and statolith formation of the scyphozoan, Aurelia labiata. Hydrobiologia 645: 39-52. | “[P]olyp survival was 100% after 122 days in seawater in all six temperature and pH combinations;” and few polyps strobilated at 9°C and “temperature effects on budding were consistent with published results.” At 15°C, there were also no significant effects of pH on the numbers of ephyrae or buds produced per polyp or on the numbers of statoliths per statocyst.” However, they state that “statolith size was significantly smaller in ephyrae released from polyps reared at low pH.” “A. labiata polyps are quite tolerant of low pH, surviving and reproducing asexually even at the lowest tested pH.” |
| Cohen, A.L. and Holcomb, M. 2009. Why corals care about ocean acidification: Uncovering the mechanism. Oceanography 22: 118-127. | Cohen and Holcomb state that “naturally elevated levels of inorganic nutrients and, consequently, high levels of primary and secondary production, may already be facilitating high coral calcification rates in regions with naturally high dissolved $CO_2$ levels.” |
| Jury, C.P., Whitehead, R.F. and Szmant, A.M. 2010. Effects of variations in carbonate chemistry on the calcification rates of Madracis auretenra (= Madracis mirabilis sensu Wells, 1973): bicarbonate concentrations best predict calcification rates. Global Change Biology 16: 1632-1644/. | “Coral responses to ocean acidification are more diverse than currently thought,” and “the reliability of using carbonate concentration or aragonite saturation state as the sole predictor of the effects of ocean acidification on coral calcification,” as many current models do, is put into question. “[I]f we truly wish to decipher the response of coral calcification to ocean acidification, a firmer grasp of the biological component of biomineralization is paramount.” |
| Holcomb, M., McCorkle, D.C. and Cohen, A.L. 2010. Long-term effects of nutrient and $CO_2$ enrichment on the temperate coral Astrangia poculata (Ellis and Solander, 1786). Journal of Experimental Marine Biology and Ecology 386: 27-33. | Relative to ambient conditions, calcification rates were reduced by the $CO_2$ treatment to approximately 33% of the ambient rate, but with the addition of nutrients bounced partway back to 62% of the ambient rate. These effects led the researchers to conclude that “nutritionally replete corals should be able to compensate for reduced saturation state under elevated $pCO_2$ conditions.” As $pCO_2$ increases and seawater saturation state declines, the |

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| | "availability of DIC to the zooxanthellae will increase, potentially allowing increased photosynthesis which provides both alkalinity and energy to help drive calcification." Consequently, if corals are experiencing carbon limitation, they say that "elevated $pCO_2$ could even positively impact calcification." |
| Dupont, S., Lundve, B. and Thorndyke, M. 2010. Near future ocean acidification increases growth rate of the lecithotrophic larvae and juveniles of the sea star Crossaster papposus. Journal of Experimental Zoology (Molecular and Developmental Evolution) 314B: 382-389. | Echinoderm larvae and juveniles were "positively impacted by ocean acidification." "[L]arvae and juveniles raised at low pH grow and develop faster, with no negative effect on survival or skeletogenesis within the time frame of the experiment (38 days)." The sea stars' growth rates were "two times higher" in the acidified seawater; and they remark that "C. papposus seem to be not only more than simply resistant to ocean acidification, but are also performing better." |
| Ries, J.B., Cohen, A.L. and McCorkle, D.C. 2010. A nonlinear calcification response to $CO_2$-induced ocean acidification by the coral Oculina arbuscula. Coral Reefs 29: 661-674. | "[F]ollowing the initial acclimation phase, survivorship in each experimental treatment was 100%," while last of all, in regard to the corals' rates of calcification and linear extension, they say that "no significant difference was detected relative to the control treatment (ΩA = 2.6) for corals reared under ΩA of 2.3 and 1.6," which latter values correspond to pH reductions from current conditions of 0.08 and 0.26, respectively. The 0.26 pH reduction is approximately twice the maximum reduction that would likely result from the burning of all fossil fuels in the crust of the earth, "pointing to the apparent insensitivity of calcification and linear extension within O. arbuscula to reductions in ΩA from 2.6 to 1.6 [which] reflects the corals' ability to manipulate the carbonate chemistry at their site of calcification." |
| Krief, S., Hendy, E.J., Fine, M., Yam, R., Meibom, A., Foster, G.L. and Shemesh, A. 2010. Physiological and isotopic responses of scleractinian corals to ocean acidification. Geochimica et Cosmochimica Acta 74: 4988-5001. | "[T]he inverse response of skeleton deposition and tissue biomass to changing $CO_2$ conditions is consistent with the hypothesis that calcification stimulates zooxanthellae photosynthesis by enhancing $CO_2$ concentration within the coelenteron," and "since calcification is an energy-consuming process ... a coral polyp that spends less energy on skeletal growth can instead allocate the energy to tissue biomass." "[T]he physiological response to higher $CO_2$/lower pH conditions was significant, but less extreme than reported in previous experiments," suggesting that "scleractinian coral species will be able to acclimate to a high $CO_2$ ocean even if changes in seawater pH are faster and more dramatic than predicted." |
| Grimsditch, G., Mwaura, J.M., Kilonzo, J. and Amiyo, N. 2010. The effects of habitat on coral | "During the 2007 bleaching season, corals in the shallow lagoons of Kanamai and Vipingo |

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| bleaching responses in Kenya. Ambio 39: 295-3-4. | were more resistant to bleaching stress than corals in the deeper lagoons of Mombasa Marine Park and Nyali," which suggests, in their words, that "corals in the shallower lagoons have acclimatized and/or adapted to the fluctuating environmental conditions they endure on a daily basis and have become more resistant to bleaching stress," indicating that earth's corals have the ability to evolve in such a way as to successfully adjust to changing environmental conditions. |
| Frommel, A.Y., Stiebens, V., Clemmesen, C. and Havenhand, J. 2010. Effect of ocean acidification on marine fish sperm (Baltic cod: *Gadus morhua*). *Biogeosciences* **7**: 3915-3919. | "Future ocean acidification will probably not pose a problem for sperm behavior, and hence fertilization success, of Baltic cod." |
| Almen, A.-K., Vehmaa, A., Brutemark, A. and Engstrom-Ost, J. 2014. Coping with climate change? Copepods experience drastic variations in their physiochemical environment on a diurnal basis. *Journal of Experimental Marine Biology and Ecology* **460**: 120-128. | "Copepods are the most abundant zooplankton, constituting an important food source for fish in the Baltic Sea." Copepods regularly experience "a change in pH of more than 0.5 units and 5°C change in temperature" in each of their daily migrations; and thus "coastal copepods are experiencing a range of variation in their physicochemical environment that is equal to or larger than the predicted climate change for the year 2100." |
| Bessell-Browne, P., Stat, M., Thomson, D. and Clode, P.L. 2014. Coscinaraea marshae corals that have survived prolonged bleaching exhibit signs of increased heterotrophic feeding. *Coral Reefs* **33**: 795-804. | Bessell-Browne *et al.* say they demonstrate that "high-latitude, mesophotic coral populations can possess the adaptive ability to survive extreme heating events, adding to existing knowledge which indicates that some coral species will be able to adapt to, and survive, the increasing stressors expected with future climate change." |
| Pedersen, S.A., Hakedal, O.J., Salaberria, I., Tagliati, A., Gustavson, L.M., Jenssen, B.M., Olsen, A.J. and Altin, D. 2014. Multigenerational exposure to ocean acidification during food limitation reveals consequences for copepod scope for growth and vital rates. *Environmental Science & Technology* **48**: 12,275-12,284. | "The copepod *Calanus finmarchicus* is a key component of northern Atlantic food webs, linking energy-transfer from phytoplankton to higher trophic levels." The study of the effects of four different $CO_2$-induced ocean acidification (OA) scenarios found "a significant delay in development rate among the parental generation animals exposed to 2080 µatm $CO_2$ but not in the following F1 generation animals under the same conditions." This discovery "suggests that *C. finmarchicus* may have adaptive potential to withstand the direct long-term effects of even the more pessimistic future OA scenarios" - even under conditions of limited food supply. |
| Comeau, S., Carpenter, R.C., Njiri, Y., Putnam, H.M., Sakai, K. and Edmunds, P.J. 2014a. Pacific-wide contrast highlights resistance of reef calcifiers to ocean acidification. *Proceedings of the Royal Society B* **281**: 10.1098/rspb.2014.1339. | In spite of "pessimistic projections forecasting the disappearance of most coral reefs before the end of the current century," a compilation of laboratory studies suggests it is more likely that "coral calcification will decline approximately 10-20% (rather than ceasing) for a doubling of present-day partial pressure of $CO_2$." "More subtle responses to ocean acidification [OA] |

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| | have also been shown in recent studies reporting signs of resistance to OA for some reef calcifiers." Field observations at underwater $CO_2$ vents in Papua New Guinea and sites with high seawater $pCO_2$ in Palau have also shown that some reef calcifiers can persist in naturally acidified conditions." The data showed that for three of the four calcifiers "there was no effect of $pCO_2$ on net calcification" at any of the three locations, which "may represent a constitutive and geographically conserved capacity to resist some of the effects of OA." |
| Yates, K.K., Rogers, C.S., Herlan, J.J., Brooks, G.R., Smiley, N.A. and Larson, R.A. 2014. Diverse coral communities in mangrove habitats suggest a novel refuge from climate change. *Biogeosciences* **11**: 4321-4337. | Studying a previously undocumented refuge for corals, the data showed higher than expected resiliency factors for mangrove-coral habitats providing evidence for adaptation of coastal organisms and ecosystem transition due to recent climate change. |
| Hazan, Y., Wangensteen, O.S. and Fine, M. 2014. Tough as a rock-boring urchin: adult *Echinometra* sp. EE from the Red Sea show high resistance to ocean acidification over long-term exposures. *Marine Biology* **161**: 2532-2545. | Sea urchins native to the Red Sea's Gulf of Aqaba exhibited higher than anticipated resistance to acidification, and differing $CO_2$ environments suggesting "high resistance of adults [of the species] to near future ocean acidification conditions." |
| Kroeker, K.J., Gaylord, B., Hill, T.M., Hosfelt, J.D., Miller, S.H. and Sanford, E. 2014. The role of temperature in determining species' vulnerability to ocean acidification: A case study using *Mytilus galloprovincialis*. *PLOS ONE* **9**: e100353. | "There is considerable concern regarding potential synergistic effects among multiple environmental changes, where the combined effect on a species of two or more drivers is worse than would be expected from a strictly additive influence of the separate factors." However, research has shown that "the presence of a second driver can also offset or lessen the effects of another stressor." Although high $CO_2$ significantly reduced mussel growth at 14°C, this effect gradually lessened with successive warming to 20°C, illustrating how moderate warming can mediate the effects of OA through temperature's effects on both physiology and seawater geochemistry. "The mussels grew thicker shells in warmer conditions independent of $CO_2$ treatment," and that "together, these results highlight the importance of considering the physiological and geochemical interactions between temperature and carbonate chemistry," especially when assessing a species vulnerability to OA. |
| Shama, L.N.S., Strobel, A., Mark, F.C. and Wegner, K.M. 2014. Transgenerational plasticity in marine sticklebacks: maternal effects mediate impacts of a warming ocean. *Functional Ecology* **28**: 1482-1493. | "Empirical evidence is accumulating that marine species might be able to adapt to rapid environmental change if they have sufficient standing variation (the raw material for evolutionary change) and/or phenotypic plasticity to mount fast responses." "TGP can buffer short-term detrimental effects of climate warming and may buy time for genetic |

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| | adaptation to catch up, therefore markedly contributing to the evolutionary potential and persistence of populations under climate change." |
| Meier, K.J.S., Berger, C. and Kinkel, H. 2014a. Increasing coccolith calcification during $CO_2$ rise of the penultimate deglaciation (Termination II). *Marine Micropaleontology* **112**: 1-12. | "In natural assemblages, varying seawater carbonate chemistry and environmental factors can influence both coccolithophore calcification and the composition of the coccolithophore assemblages." The study found that "mean coccolithophore weight "strongly increases during Termination II." At the Florida Strait, in fact, they found that coccolith weight actually *doubled* during Termination II, which they say was "mainly an effect of increasing coccolithophore calcification," which they additionally say "is exactly mirroring the rise in atmospheric $CO_2$." |
| Venti, A., Andersson, A. and Langdon, C. 2014. Multiple driving factors explain spatial and temporal variability in coral calcification rates on the Bermuda platform. *Coral Reefs* **33**: 979-997. | "Negative effects of ocean acidification (OA) on coral calcification rates have been well documented" but the researchers note that these results "are heavily drawn from controlled aquarium and mesocosm studies." The study evaluated correlations between seasonal average coral growth rates and light, temperature, and aragonite saturation rate (ωarag). In doing so, they discovered that the observed seasonal differences in these factors account for approximately 44, 52 and 5%, respectively, of the observed seasonal change in coral calcification rate across three different sites, concluding "the covariance of light and ωarag can lead to the false conclusion that calcification is more sensitive to ωarag than it really is." |
| Oliver, A.E., Newbold, L.K., Whiteley, A.S. and van der Gast, C.J. 2014. Marine bacterial communities are resistant to elevated carbon dioxide levels. Environmental Microbiology Reports **6**: 574-582. | "[M]arine bacterial communities are highly resistant to the elevated $CO_2$ and lower pH conditions, as demonstrated from measures of turnover using taxa-time relationships and distance-decay relationships." Further, the $CO_2$ levels used ion the study were designed to simulate 100 years of rising levels, allowing a huge amount of evolutionary adaptation. |
| Wu, Y., Campbell, D.A., Irwin, A.J., Suggett, D.J. and Finkel, Z.V. 2014. Ocean acidification enhances the growth rate of larger diatoms. Limnology and Oceanography **59**: 1027-1034. | Acidifcation enhances the growth rate of diatoms, which in turn helps transport $CO_2$ from the surface to deep-sea storage, thereby slowing the rate of rise of atmospheric concentrations of $CO_2$. |
| Schluter, L., Lohbeck, K.T., Gutowska, M.A., Groger, J.P., Riebesell, U. and Reusch, T.B.H. 2014. Adaptation of a globally important coccolithophore to ocean warming and acidification. Nature Climate Change **4**: 1024-1030. | Warming and acidification increases the growth rates of phytoplankton. Dramatic evolutionary changes are seen even in asexual species. The researchers conclude that evolutionary effects *must* be accounted for in predicting the impacts of climate change. |
| Moulin, L., Grosjean, P., Leblud, J., Batigny, A., Collard, M. and Dubois, P. 2015. Long-term mesocosms study of the effects of ocean | Sea urchins appear to be resilient to ocean acidification levels expected to occur by 2100. |

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| acidification on growth and physiology of the sea urchin *Echinometra mathaei*. *Marine Environmental Research* **103**: 103-114 | |
| Garrard, S.L., Gambi, M.C., Scipione, M.B., Patti, F.P., Lorenti, M., Zupo, V., Paterson, D.M. and Buia, M.C. 2014. Indirect effects may buffer negative responses of seagrass invertebrate communities to ocean acidification. *Journal of Experimental Marine Biology and Ecology* **461**: 31-38. | Oean acidification (OA) may lead to changes in the "attributes of habitat-forming species (such as seagrasses) and other associated communities (epiphytes), thus affecting food and shelter availability for meso-grazers." |
| Bay, R.A. and Palumbi, S.R. 2014. Multi-locus adaptation associated with heat resistance in reef-building corals. *Current Biology* **24**: 252-2956. | Researchers found that "corals living in naturally high-temperature microclimates are more resistant to bleaching because of both acclimation and fixed effects, including adaptation." The researchers concluded that a natural population of these corals "harbors a reservoir of alleles preadapted to high temperatures, suggesting potential for future evolutionary response to climate change." |
| Baker, A.C. 2014. Climate change: many ways to beat the heat for reef corals. Current Biology **24**: 10.1016/j.cub.2014.11.014. | Reef-building corals have an array of responses to increased temperatures and acidification, including rapid acclimatization, faster evolutionary response, and changing algal symbiont communities. |
| Gaitan-Espitia, J.D., Bacigalupe, L.D., Opitz, T., Lagos, N.A.,Timmermann, T. and Lardies, M.A. 2014. Geographic variation in thermal physiological performance of the intertidal crab Petrolisthes violaceus along a latitudinal gradient. The Journal of Experimental Biology **217**: 4379-4386. | Thermal tolerance in porcelain crabs is shared among different species, even when geographic dispersion has produced physiological differentiation, with the result that even the population most sensitive to heat would tolerate moderate levels of warming, as predicted by the IPCC. |
| Sigwart, J.D. and Carey, N. 2014. Grazing under experimental hypercapnia and elevated temperature does not affect the radula of a chiton (Mollusca, Polyplacophora, Lepidopleurida). *Marine Environmental Research* **102**: 73-77. | Scientists found that a mollusk species maintained the same teeth structure, feeding cusp structure, and shell valves in acidified oceans. This research disproves the central argument that ocean acidification harms ecosystems and that species "may be able to overcome even anthropogenic climate change." |
| Comeau, S., Edmunds, P.J., Spindel, N.B. and Carpenter, R.C. 2013. The responses of eight coral reef calcifiers to increasing partial pressure of $CO_2$ do not exhibit a tipping point. *Limnology and Oceanography* **58**: 388-398. | Scientists studied the implication of oceanic $CO_2$ on coral reefs' calcification responses to determine whether they were in danger of increased acidification. The research concluded that they "did not detect a threshold at which the effect of $pCO_2$ on calcification became nonlinear and intensified," which demonstrates the resiliency of coral reef ecosystems in the backdrop of oceanic $CO_2$. |
| ***F. Any Sea Level Rise Has Been Overstated, Is Not Linked To Warming, And Will Not Pose A Serious Problem*** | |
| Wahl, T., Haigh, I.D., Dangendorf, S. and Jensen, J. 2013. Inter-annual and long-term mean sea level changes along the North Sea coastline. *Journal of Coastal Research* Special | No evidence of (predicted) accelerated sea level rise in North Sea. |

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| Issue No. **65**: 1987-1992. | |
| Jevrejeva, S., Moore, J.C., Grinsted, A., Matthews, A.P. and Spada, G. 2014. Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change 113: 11-22. | The study accomplished improved data coverage over past studies “by using many more stations, particularly in the polar regions, and recently processed historic data series from isolated island stations,” and the five researchers, “the new reconstruction suggests a linear trend of 1.9 ± 0.3 mm/yr during the 20th century” and “1.8 ± 0.5 mm/yr for the period 1970-2008.” |
| Baustian, J.J., Mendelssohn, I.A. and Hester, M.W. 2012. Vegetation’s importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. *Global Change Biology* **18**: 3377-3382. | Coastal grasses can withstand rising sea levels and can protect soil from erosion. |
| Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea level rise around mainland Australia? *Journal of Coastal Research* **27**: 368-377. | Although the four data sets employed in this study all show short-term accelerations in sea level rise around Australia near the end of the 20th century, the century as a whole was one of decelerating sea level rise. |
| Konikow, L.F. 2011. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters* **38**: 10.1029/2011GL048604. | The late 20th-/early 21st-century increase in groundwater depletion has likely been responsible for a good deal of the simultaneous increase in the rate of mean global sea level rise over that period. |
| Webb, A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. Global and Planetary Change 72: 234-246. | “[T]here is no evidence of large-scale reduction in island area despite the upward trend in sea level.”<br>The results of this study “contradict widespread perceptions that all reef islands are eroding in response to recent sea level rise.” Quite to the contrary, they note that “reef islands are geomorphically resilient landforms that thus far have predominantly remained stable or grown in area over the last 20-60 years,” and they say that “given this positive trend, reef islands may not disappear from atoll rims and other coral reefs in the near-future as speculated.” |
| Dawson, J.L. and Smithers, S.G. 2010. Shoreline and beach volume change between 1967 and 2007 at Raine island, Great Barrier Reef, Australia. Global and Planetary Change 72: 141-154. | “[D]etailed quantitative surveys and analyses demonstrate that Raine Island increased in area (~6%) and volume (~4%) between 1967 and 2007.” Contrary to perceptions, Raine Island did not erode but instead modestly accreted during the 40-year study period.” “Perceptions of reef island erosion can arise from large short-term seasonal and storm-derived sediment redistribution from one part of the island to another or to a temporary storage on the adjacent reef flat,” but that these phenomena do not necessarily lead to “a net permanent loss from the island sediment budget.” It can be concluded that the most likely effect of a rising sea level is to actually add to the area and volume of low-lying reef islands. |

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| Silva, T.A., Freitas, M.C., Andrade, C., Taborda, R., Freire, P., Schmidt, S. and Antunes, C. 2013. Geomorphological response of the salt-marshes in the Tagus estuary to sea level rise. *Journal of Coastal Research* **Special Issue No. 65**: 582-587. | "Salt marshes, are important ecosystems due to their role in supporting the aquatic food chain, exporting nutrients to surrounding waters and providing nesting areas for migratory birds." They also act as barriers protecting the shoreline by helping to dissipate wave and current energy. "Sea level rise can place these intertidal zones at risk" The study examined historical sedimentation data retrieved from four salt marsh locations within the Tagus estuary, "the largest and most important estuaries of Western Europe." The results indicate the marshes all "lie under the upper threshold of accretion," meaning there exists room for further sediment deposition in the marshes. Comparisons of historic sedimentation rates with projected rates of sea level rise suggest that the Tagus estuary salt marshes "will not be drowned in the forthcoming decades." |
| Nils-Axel Mörner, "There Is No Alarming Sea Level Rise!" *21st Century Science and Technology*, Winter 2010/2011, pp. 12-22. Nils-Axel Mörner, "Eustatic Changes During the Last 300 Years." *Palaeogeogr. Palaeoclim. Palaeoecol*. 13, 1973, pp. 1-14. | Mörner finds that, at most, global average sea level is rising at a rate equivalent to 2-3 inches per century but, more likely is probably not rising at all. Sea level is measured both by tide gauges and, since 1992, by satellite altimetry, and the raw data from satellite altimetry show no increase in global sea level at all. Two distinct satellite systems, using very different measurement methods, produced raw data reaching identical conclusions: The sea level is barely rising, if at all. The sea level is not rising at all in the Maldives, the Laccadives, Tuvalu, India, Bangladesh, French Guyana, Venice, Cuxhaven, Korsør, Saint Paul Island, Qatar, etc. Modelling is not a suitable method of determining global sea-level changes, since a proper evaluation depends upon detailed research in multiple locations with widely-differing characteristics. Since the sea level is not rising, the chief ground of concern relating to the potential effects of anthropogenic "global warming" – that millions of shore-dwellers the world over may be displaced as the oceans expand – is baseless. |
| Judith Curry, "Slowing Sea Level Rise," Climate Etc., April 24, 2014.http://judithcurry. com/2014/04/ 24/ slowing-sea-level-rise/. | Curry notes that it is clear that natural variability has dominated sea level rise during the 20th century, with changes in ocean heat content and changes in precipitation patterns. She concludes that "Once again, the emerging best explanations for the 'pause' in global surface temperatures and the slowdown in sea level rise bring into question the explanations for the rise in both in the last quarter of the 20th century. And makes the 21st century of sea level rise projections seem like unjustified arm waving." |

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| Nils-Axel Mörner, "Sea Level Is Not Rising," Science and Public Policy Institute, December 6, 2012. | This study finds that the differences between the IPCC sea level rise models and the observational data are large and growing. The IPCC's combination of selected tide-gauge records are compared to corrected satellite altimetry data. After 1965, the IPCC sea level rise models become increasingly inaccurate forecasting sea level rise, while the empricial data show no sea level rise. The sea-level record from Venice may be used as a test area for global eustasy. Subtracting the subsidence factor, the Venetian record reveals no rise of eustatic origin, no acceleration whatsoever in the last decades; instead, it shows a sea level falling around 1970. The north-west European coasts are interesting because there are sites that are experiencing both uplift and subsidence. The tide gauge at Korsør in the Great Belt (the strait between the main Danish islands of Zeeland and Funen), for example, is located at the hinge between uplift and subsidence for the last 8,000 years. This tide gauge shows no sea-level rise in the last 50-60 years. |
| Nils-Axel Morner, "Estimating Future Sea Level Changes From Past Records," *Global and Planetary Change*, 40 (2004) 49–54. | Morner finds that in the last 5000 years, global mean sea level has been dominated by the redistribution of water masses over the globe. In the<br>last 300 years, sea level has been oscillation close to the present with peak rates in the period 1890–1930. Between 1930 and 1950, sea fell. The late 20th century lack any sign of acceleration. Satellite altimetry indicates virtually no changes in the last decade. Therefore, observationally based predictions of future sea level in the year 2100 will give a value of + 10F10 cm (or +5F15 cm), by this discarding model outputs by IPCC as well as global loading models. This implies that there is no fear of any<br>massive future flooding as claimed in most global warming scenarios. |
| Nils-Axel Mörner, "The Sun Rules Climate. There's No Danger of Global Sea Level Rise," *21st Century Science and Technology*, Fall 2007, 31-34; Nils-Axel Mörner, "Sea Level Changes and Tsunamis: Environmental Stress and Migration over the Seas," *Internationales Asienforum* 38, 2007, pp. 353-374;<br>Nils-Axel Mörner, "The Greatest Lie Ever Told," P&G-print (2nd ed., 2009, 3rd ed., 2010); Nils-Axel Mörner, "Sea Level Changes in Bangladesh: New Observational Facts, *Energy and Environment*, 21:3, 2010, pp. 249-263; Nils-Axel Mörner, "Some Problems in the Reconstruction of Mean Sea Level and Its | These studies conclude that clear observational measurements in the field indicate that the sea level is not rising in the Maldives, Bangladesh, Tuvalu, Vanuatu, and French Guyana. All these are key sites in the sea level debate, where the IPCC and its supporters have predicted terrible flooding. However, the reality is different from what the IPCC claims. |

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| Changes With Time," *Quaternary International,* 221, 2010, pp. 3-8. | |
| N. Gratiot, E.J. Anthony, A. Gardel, C. Gaucherel, C. Proisy, and J.T. Wells, "Significant Contribution Of The 18.6 Year Tidal Cycle To Regional Coastal Changes," *Nature Geoscience* 1, 169-172, doi: 10.1038/ngeo127, 2008 | The authors report that from the coasts of French Guyana and Surinam there is an excellent sea-level record covering multiple 18.6-year tidal cycles. It exhibits variations around a stable zero level over the last 50 years. |
| Anny Cazenave, Habib-Boubacar Dieng, Benoit Meyssignac, Karina von Schuckmann, Bertrand Decharme and Etienne Berthier, "The Rate of Sea Level Rise," *Nature Climate Change*, March 2014. | The authors found that that from 2002-2012 global $CO_2$ emissions increased 32 percent, but "Since the early 1990s, sea level rose at a mean rate of ~3.1 mm yr. However, over the last decade a slowdown of this rate, of about 30 percent, has been recorded." Their analysis was based on sea-level data from the altimetry record of the past 20 years that separates interannual natural variability in sea level from the longer-term change probably related to AGW. Their results confirm the need for quantifying and further removing from the climate records the short-term natural climate variability if one wants to extract the global warming signal. |
| J. M. Gregory, N. J. White, J. A. Church, M. F. P. Bierkens, J. E. Box, M. R. Van Den Broeke,E J. G. Cogley,F X. Fettweis, G E. Hanna, H P. Huybrechts, L. F. Konikow, P. W. Leclercq, B. Marzeion, J. Oerlemans, M. E. Tamisiea, Y. Wada, M. Wake, and R. S. W. Van De Wale, "Twentieth-Century Global-Mean Sea Level Rise: Is the Whole Greater Than the Sum of the Parts?" *Journal of Climate*, 26, May 2014, pp. 4476–4499. | These authors note that confidence in projections of global-mean sea level rise (GMSLR) depends on an ability to account for GMSLR during the twentieth century. Semi-empirical methods for projecting GMSLR depend on the existence of a relationship between global climate change and the rate of GMSLR, but the implication of the authors' research is that such a relationship is weak or absent during the twentieth century. Accordingly, they conclude that "The rate of GMSLR was not much larger during the last 50 years than during the twentieth century as a whole, despite the increasing anthropogenic forcing. A relationship between global climate change and the rate of GMSLR is weak or absent in the twentieth century." |
| Judith A. Curry, "Statement to the Committee on Environment and Public Works of the United States Senate in the Hearing on Review of the President's Climate Action Plan," January 16, 2014. | Curry notes that even the IPCC data indicate little or no sea level rise attributable to AGW. The rate of rise during 1930-1950 was comparable to, if not larger than, the value in recent years. She concludes that "Hence the data does not seem to support the IPCC's conclusion of a substantial contribution from anthropogenic forcings to the global mean sea level rise since the 1970s." |
| Jack Eggleston and Jason Pope, *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region*, U.S. Geological Survey, prepared in cooperation with the Hampton Roads Planning District Commission, Circular 1392, Reston, Virginia, 2013 | These authors concluded that the water intrusion problems in Norfolk and the Chesapeake Bay region are due not to "sea level rise," but to land subsidence due to groundwater depletion and, to a lesser extent, subsidence from glacial isostatic adjustment. The difference is critical and the solutions |

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| | required to address the problem are entirely different. If the cause of the problem is land subsidence – as it is in Norfolk and the Chesapeake Bay region, then water intrusion will continue even if sea levels actually decline. Land subsidence is causing most of the relative "sea-level rise" that has been measured in the Chesapeake Bay. However, tidal-station measurements of sea levels do not distinguish between water that is rising and land that is sinking -- the combined elevation changes are termed "relative sea-level rise." |
| Federal Emergency Management Agency, "Flood Insurance Study of Franklin, Virginia, Community," September 2002. | FEMA finds that land subsidence can also increase flooding in areas away from the coast. Low-lying areas, such as the Blackwater River Basin in Virginia can be subject to increased flooding as the land sinks. Locations along the Blackwater River in the city of Franklin and the counties of Isle of Wight and Southampton have experienced large floods in recent years due to land subsidence -- not sea rise. |
| A.H. Sallenger, K.S. Doran, and P.A. Howd, "Hotspot of Accelerated Sea-Level Rise on the Atlantic Coast of North America," *Nature Climate Change*, v. 2, no. 12 (2012), pp. 884–888. [1]N.L Bindoff, et. al. 2007, "Observations -- Oceanic Climate Change And Sea Level," Chap. 5 of *Climate Change -- the Physical Science Basis*," Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, New York: Cambridge University Press, 2007, pp. 385–432 | These studies find thatalthough rates of absolute sea-level rise (rise due just to increases in ocean volume) can vary substantially from one location to another and change over time, the global average rate of 1.8 mm/yr. from 1961 to 2003 is a widely accepted global benchmark rate. The difference between the average sea-level rise computed from the four NOAA tidal stations in the study area (3.9 mm/yr.) and the benchmark global rate (1.8 mm/yr.) is 2.1 mm/yr., which is an estimate of the average rate of land subsidence at the four NOAA stations. These numbers indicate that land subsidence, not sea level rise, has been responsible for most of the relative sea-level rise measured in the Chesapeake Bay region. |
| Holgate, S.J., "On The Decadal Rates of Sea Level Change During the Twentieth Century." *Geophysical Research Letters* 34: 10.1029/2006GL028492, 2007. | Holgate derived a mean global sea level history over the period 1904-2003. According to his calculations, the mean rate of global sea level rise was "larger in the early part of the last century (2.03 ± 0.35 mm/year 1904-1953), in comparison with the latter part (1.45 ± 0.34 mm/year 1954-2003)." Thus, contrary to model projections, the mean rate of global sea level rise has not accelerated over the recent past. If anything, it has done just the opposite. Such observations are striking, especially considering they have occurred over a period of time when many have claimed that (1) the Earth warmed to a degree that is unprecedented over many millennia, (2) the warming resulted in a net accelerated melting of the vast majority of the world's mountain glaciers and polar ice caps, and (3) global sea |

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| | level rose at an ever increasing rate. |
| Boretti, A.A., “Short Term Comparison of Climate Model Predictions and Satellite Altimeter Measurements of Sea Levels.” *Coastal Engineering* 60: 319-322, 2012. | Boretti applied simple statistics to the two decades of information contained in the TOPEX and Jason series of satellite radar altimeter data to “better understand if the SLR is accelerating, stable or decelerating.” In doing so, he reported that the rate of SLR is reducing over the measurement period at a rate of -0.11637 mm/year and that this deceleration is also “reducing” at a rate of -0.078792 mm/year. In light of such observations, Boretti concludes that the huge deceleration of SLR over the last 10 years “is clearly the opposite of what is being predicted by the models,” and that “the SLR’s reduction is even more pronounced during the last 5 years.” To further illustrate the importance of his findings, he notes that “in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the SLR must be almost 11 mm/year every year for the next 89 years,” but he notes that “since the SLR is dropping, the predictions become increasingly unlikely,” especially in view of the facts that (1) “not once in the past 20 years has the SLR of 11 mm/year ever been achieved,” and that (2) “the average SLR of 3.1640 mm/year is only 20 percent of the SLR needed for the prediction of a one meter rise to be correct.” |
| N.A. Morner, “Estimating Future Sea Level Changes From Past Records.” *Global and Planetary Change* 40: 49-54, 2004; S. Jevrejeva et al., “Nonlinear Trends and Multiyear Cycles in Sea Level Records.” *Journal Of Geophysical Research* 111: 10.1029/ 2005JC003229, 2006; G. Wöppelmann et al., “Rates of Sea-Level Change Over the Past Century in a Geocentric Reference Frame.” *Geophysical Research Letters* 36: 10.1029/2009GL0 38720, 2009; J.R. Houston, and Dean, R.G., “Sea-Level Acceleration Based on U.S. Tide Gauges and Extensions of Previous Global-Gauge Analyses.” *Journal of Coastal Research* 27: 409-417, 2001. | These studies find that rising atmospheric $CO_2$ emissions are exerting no discernible influence on the rate of sea level rise. Damages that are based on model projections of a $CO_2$-induced acceleration of SLR must be considered inflated and unreliable. |
| ***G. Any Arctic and Antarctic Impacts (Including Ice and Non-Arctic Glaciers) Have Been Overstated, Are Not Linked To Warming, And Will Not Pose A Problem*** | |
| Judith Curry, “Statement to the Committee on Science, Space, and Technology of the U.S. House of Representatives,” Hearings on the President’s U.N. Climate Pledge, April 15, 2015, available at http://docs.house.gov/meetings/SY/SY00/20150415/103329/HHRG-114-SY00-Wstate-CurryJ- | “In 2013 and 2014, “Arctic sea ice recovered from its summertime minima during the period 2007-2012. Notably, Arctic sea ice volume (a metric that combines both horizontal extent and ice thickness) shows a continuing increase since 20127. During 2014, Antarctic sea ice set a wintertime maximum record. . . . Clearly, |

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| 20150415-U1.pdf. | there is a lot going on with respect to variability in Arctic and Antarctic sea ice that cannot be explained directly or even indirectly by warming from human-caused greenhouse gases. Climate models do not simulate correctly the ocean heat transport and its variations. Scientists do not agree on the explanation for the increasing Antarctic sea ice extent, and the key issue as to whether human-caused warming is the dominant cause of the recent Arctic sea ice loss remains unresolved." |
| Judith Curry, "Statement to the Committee on Science, Space, and Technology of the U.S. House of Representatives," Hearings on the President's U.N. Climate Pledge, April 15, 2015, available at http://docs.house.gov/meetings/SY/SY00/20150415/103329/HHRG-114-SY00-Wstate-CurryJ-20150415-U1.pdf. | "The original rationale for the 2°C target is the idea that 'tipping points' - abrupt or nonlinear transition to a different state - become likely to occur once this threshold has been crossed, with consequences that are largely uncontrollable and beyond our management. The IPCC AR5 considered a number of potential tipping points, including ice sheet collapse, collapse of the Atlantic overturning circulation, and permafrost carbon release. Every single catastrophic scenario considered by the IPCC (Table 12.4) has a rating of *very unlikely* or *exceptionally unlikely* and/or has low confidence. The only tipping point that the IPCC considers *likely* in the 21st century is disappearance of Arctic summer sea ice (which reforms each winter, in any event). In the absence of tipping points on the timescale of the 21st century, the 2°C limit is more usefully considered by analogy to a highway speed limit: driving at 10 mph under the speed limit is not automatically safe, and exceeding the limit by 10 mph is not automatically dangerous, although the faster one travels the greater the danger from an accident. Analogously, the 2°C limit should not be taken literally as a real danger threshold." |
| Everatt, M.J., Convey, P., Worland, M.R., Bale, J.S. and Hayward, S.A.L. 2014. Are the Antarctic dipteran, *Eretmoptera murphyi*, and Arctic collembolan, *Megaphorura arctica*, vulnerable to rising temperatures? *Bulletin of Entomological Research* **104**: 494-503. | Polar invertebrates, thought to be unusually sensitive to climate change, show remarkable heat tolerance. Indeed, some warming may alleviate stresses associated with low temperatures and benefit species. |
| Rolstad Denby, C. and Hulth, J. 2011. Assessment of differentiated surface elevation data from 1949, 1975 and 2008 for estimates of ice-volume changes at Jan Mayen. *Journal of Glaciology* **57**: 976-980. | In coastal regions where warming causes winter sea-ice to no longer form, the extra moisture thus made available to the local atmosphere by nearby evaporation can sometimes enhance the delivery of precipitation (in the form of snowfall) to the land; and this phenomenon can lead to a buildup of glacial mass, even in a warming environment. |
| Hewitt, K. 2011. Glacier change, concentration, and elevation effects in the Karakoram | The Karakoram glaciers have declined at a lesser rate than previously assumed and has |

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| Himalaya, upper Indus Basin. *Mountain Research and Development* **31**: 188-200. | not undergone dramatic losses in between the mid-1980s and through the 1990s. Since then, the glaciers have stabilized and, in the high Karakoram, advanced. |
| Ma, Q., Wang, K. and Wild, M. 2014. Evaluations of atmospheric downward longwave radiation from 44 coupled general circulation models of CMIP5. *Journal of Geophysical Research: Atmospheres* **119**: 4486-4497. | Atmospheric downward longwave radiation at the surface--more or less a quantification of the atmospheric greenhouse effect--is not accurately simulated by the models in CMIP5, either in diurnal or monthly variation. |
| Schroeder, D.M., Blankenship, D.D., Young, D.A. and Quartini, E. 2014. Evidence for elevated and spatially variable geothermal flux beneath the West Antarctic Ice Sheet. *Proceedings of the National Academy of Sciences USA* **111**: 10.1073/pnas.1405184111. | New measures of ice in major Antarctic glacier show melting likely due to vulcanism, not warming. |
| Bahuguna, I.M., Rathore, B.P., Brahmbhatt, R., Sharma, M., Dhar, S., Randhawa, S.S., Kumar, K., Romshoo, S., Shah, R.D., Ganjoo, R.K. and Ajai. 2014. Are the Himalayan glaciers retreating? *Current Science* **106**: 1008-1013. | Study of Himalayan glaciers shows "steady state" corresponding to hiatus in global warming. |
| Tedstone, A.J., Nienow, P.W., Sole, A.J., Mair, D.W.F., Cowton, T.R., Bartholomew, I.D. and King, M.A. 2013. Greenland ice sheet motion insensitive to exceptional meltwater forcing. Proceedings of the National Academy of Sciences USA 110: 19,719-19,724. | Tedstone *et al.* conclude that their findings suggest that "surface melt-induced acceleration of land-terminating regions of the ice sheet will remain insignificant even under extreme melting scenarios." |
| Fan, T., Deser, C. and Schneider, D.P. 2014. Recent Antarctic sea ice trends in the context of Southern Ocean surface climate variations since 1950. *Geophysical Research Letters* **41**: 2419-2426. | A study of the Antarctic ice system (ice, sea, atmosphere) shows consistent expansion of ice between 1950 and 2011. |
| Lupascu, M., Welker, J.M., Seibt, U., Maseyk, K., Xu, X. and Czimczik, C.I. 2014. High Arctic wetting reduces permafrost carbon feedbacks to climate warming. *Nature Climate Change* **4**: 51-55. | Moisture from any Arctic melting would result in greening and increase the $CO_2$ sink effect. This may *decrease* warming overall through complex feedback mechanisms. |
| Alderkamp, A.-C., Mills, M.M., van Dijken, G.L., Laan, P., Thuroczy, C.-E., Gerringa, L.J.A., de Baar, H.J.W., Payne, C.D., Visser, R.J.W., Buma, A.G.J. and Arrigo, K.R. 2012. Iron from melting glaciers fuels phytoplankton blooms in the Amundsen Sea (Southern Ocean): Phytoplankton characteristics and productivity. *Deep-Sea Research II* **71-76**: 32-48. | "[M]elting glaciers have the potential to increase phytoplankton productivity and thereby $CO_2$ uptake, resulting in a small negative feedback to anthropogenic $CO_2$ emissions …." |
| Tortell, P.D., Long, M.C., Payne, C.D., Alderkamp, A.-C., Dutrieux, P. and Arrigo, K.R. 2012. Spatial distribution of $pCO_2$, ΔO2/Ar and dimethylsulfide (DMS) in polynya waters and the sea ice zone of the Amundsen Sea, Antarctica. *Deep-Sea Research II* **71-76**: 77-93. | Coastal polynyas that receive glacial meltwater have a higher iron content, which in turn encourages growth of organic matter, which in turn creates a substantial carbon sink. |
| Mulvaney, R., Abram, N.J., Hindmarsh, R.C.A., Arrowsmith, C., Fleet, L., Triest, J., Sime, L.C., | Warming in Antarctic Peninsula is still within "the bounds of natural variability in the pre- |

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| Alemany, O. and Foord, S. 2012. Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. *Nature* **489**: 10.1038/nature11391. | anthropogenic era." |
| Zheng, S., Wang, G. and Lin, S. 2012. Heat shock effects and population survival in the polar dinoflagellate *Polarella glacialis*. *Journal of Experimental Marine Biology and Ecology* **438**: 100-108. | Polar dinoflagellates, like those found elsewhere, exhibit remarkable stability when transplanted directly (i.e., with no intervening acclimation) to substantially hotter waters. |
| Opel, T., Fritzsche, D., Meyer, H., Schutt, R., Weiler, K., Ruth, U., Wilhelms, F. and Fischer, H. 2009. 115 year ice-core data from Akademii Nauk ice cap, Severnaya Zemlya: high-resolution record of Eurasian Arctic climate change. *Journal of Glaciology* **55**: 21-31. | There has been no net warming of the Atlantic and Eurasian sub-Arctic climate. |
| Schmidt, S. and Nusser, M. 2009. Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan. *Journal of Glaciology* **55**: 949-959. | An analysis of 70 years of the Himalayas' Raikot Glacier reveals relatively small rates of recession and surface change. |
| Tedesco, M. and Monaghan, A.J. 2010. Climate and melting variability in Antarctica. EOS, Transactions, American Geophysical Union 91: 1-2. | Over the course of the past three decades, continent-wide snow and ice melting trend was "negligible." During the 2008-2009 austral summer, snow and ice melt was, in a few more words, "a record low for the 30-year period between 1979 and 2009." In addition, they note that "December 2008 temperature anomalies were cooler than normal around most of the Antarctic margin, and the overall sea ice extent for the same month was more extensive than usual." |
| Wang, J., Bai, X. and Leshkevich, G. 2010. Severe ice cover on Great Lakes during winter 2008-2009. EOS, Transactions, American Geophysical Union 91: 41-42. | After an initial four years of relative warmth and lower annual average ice area, [surface air temperature ("SAT")] declined and ice area rose. Then, there began a long period of somewhat jagged SAT rise and ice area decline, which both leveled out, in the mean, from about 1998 to 2006, whereupon SAT once again began to slowly decline and ice area began to slowly rise, with each parameter terminating at about the same value that it exhibited initially. "Natural variability dominates Great Lakes ice cover." |
| Hall, B.L., Koffman, T. and Denton, G.H. 2010. Reduced ice extent on the western Antarctic Peninsula at 700-970 cal. yr B.P. Geology 38: 635-638. | "[P]eat from the overrun sediments dates between 707 ± 36 and 967 ± 47 cal. yr B.P.," leading them to conclude that "ice was at or behind its present position at ca. 700-970 cal. yr B.P. and during at least two earlier times, represented by the dates of shells, in the mid-to-late Holocene." Hall *et al.* say their findings mean that "the present state of reduced ice on the western Antarctic Peninsula is not unprecedented." |
| Blok, D., Heijmans, M.M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C. and | The data suggest that "the expected expansion of deciduous shrubs in the Arctic region, |

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| Berendse, F. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. Global Change Biology 16: 1296-1305. | triggered by climate warming, may reduce summer permafrost thaw," and that the "increased shrub growth may thus partially offset further permafrost degradation by future temperature increases." |
| Wake, L.M., Huybrechts, P., Box, J.E., Hanna, E., Janssens, I. and Milne, G.A. 2009. Surface mass-balance changes of the Greenland ice sheet since 1866. Annals of Glaciology 50: 176-184. | Present-day SMB changes "are not exceptional within the last 140 years." In fact, they found that the SMB decline over the decade 1995-2005 was no different from that of the decade 1923-1933. Data show "that the recent changes that have been monitored extensively are representative of natural sub-decadal fluctuations in the mass balance of the ice sheet and are not necessarily the result of anthropogenic-related warming." |
| Scott, J.B.T. and Marshall, G.J. 2010. A step-change in the date of sea-ice breakup in western Hudson Bay. Arctic 63: 155-164. | Two researchers from the British Antarctic Survey found that "there has clearly not been a continuous trend in the [time of sea-ice breakup] data, and the change is best described by a step to 12 days earlier breakup occurring between 1988 and 1989, with no significant trend before or after this date." In addition, they remark that "an increase in regional southwesterly winds during the first three weeks of June and a corresponding increase in surface temperature are shown to be likely contributing factors to this earlier breakup." |
| Frauenfeld, O.W., Knappenberger, P.C. and Michaels, P.J. 2011. A reconstruction of annual Greenland ice melt extent, 1784-2009. Journal of Geophysical Research 116: 10.1029/2010JD014918. | The recent rate of ice melt in Greenland is not statistically significantly different than historical melt rates. |
| Mahlstein, I., Gent, P.R. and Solomon, S. 2013. Historical Antarctic mean sea ice area, sea ice trends, and winds in CMIP5 simulations. Journal of Geophysical Research: Atmospheres 118: 5105-5110. | Whereas most climate models "simulate a decrease in Antarctic sea ice over the recent past," real-world data demonstrate that the "average Antarctic sea ice area is not retreating but has slowly increased since satellite measurements began in 1979." |
| Gomez, N., Mitrovica, J.X., Huybers, P. and Clark, P.U. 2010. Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nature Geoscience* **3**: 850-853. | "Local sea-level change following rapid grounding-line migration will contribute a stabilizing influence on marine ice sheets, even when grounded on beds of non-negligible reversed slopes." |
| Murray, T., Scharrer, K., James, T.D., Dye, S.R., Hanna, E., Booth, A.D., Selmes, N., Luckman, A., Hughes, A.L.C., Cook, S. and Huybrechts, P. 2010. Ocean regulation hypothesis for glacier dynamics in southeast Greenland and implications for ice sheet mass changes. Journal of Geophysical Research 115: 10.1029/2009JF001522. | In 2006, after the initial acceleration of ice loss, "two of the largest outlet glaciers in the sector … were reported to have slowed down simultaneously, ceased thinning, and readvanced, and there was some indication that other glaciers in the region followed suit." "The slowdown from 2006 was widespread and synchronized throughout southeast Greenland," and "continued until at least 2008." These data suggest "a negative feedback that currently mitigates against continued very fast loss of ice from the ice sheet in a warming |

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| | climate," and "we should expect similar speedup and slowdown events of these glaciers in the future, which will make it difficult to elucidate any underlying trend in mass loss resulting from changes in this sector of the ice sheet." |
| Brown, Z.W., van Dijken, G.L. and Arrigo, K.R. 2011. A reassessment of primary production and environmental change in the Bering Sea. *Journal of Geophysical Research* **116**: 10.1029/2010JC006766. | Rather than declining, researchers found that mean annual sea ice extent in the Bering Sea "has exhibited no significant change over the satellite sea ice record." |
| Geibert, W., Assmy, P., Bakker, D.C.E., Hanfland, C., Hoppema, M., Pichevin, L.E., Schroder, M., Schwarz, J.N., Stimac, I., Usbeck, R. and Webb, A. 2010. High productivity in an ice melting hot spot at the eastern boundary of the Weddell Gyre. Global Biogeochemical Cycles 24: 10.1029/2009GB003657. | Data show that "this melting hot spot causes an enhanced input of iron and salinity-driven stratification of the surface waters," which are the ideal conditions for sustaining the "intense phytoplankton blooms" that characterize the waters they studied, implying "that future changes in sea-ice cover and dynamics could have a significant effect on carbon sequestration in the SO." |
| Peck, L.S., Barnes, D.K.A., Cook, A.J., Fleming, A.H. and Clarke, A. 2010. Negative feedback in the cold: ice retreat produces new carbon sinks in Antarctica. Global Change Biology 16: 2614-2623. | As the ice cover along the Antarctic Peninsula has retreated over the last 50 years, "more than 0.5 Mtonnes of carbon has been incorporated into biological standing stock that was not there previously. If only 15% of the remaining ice covered areas act in the same way, "over 50 Mtonnes of new carbon would be fixed annually and around 10 Mtonnes of this deposited to the seabed in coastal or adjacent areas." Over tens to hundreds of thousands of years "this process may act as a climate control mechanism." |
| Reid, P.A., Tully, M.B., Klekociuk, A.R., Krummel, P.B. and Rhodes, S.K. 2013. Seasonal climate summary Southern Hemisphere (spring 2012): Warmer and drier across much of Australia, along with a new Southern Hemisphere sea ice extent record. *Australian Meteorological and Oceanographic Journal* **63**: 427-442. | Sea ice extent in the Southern Hemisphere has experienced a mean *positive* trend of about 0.9% per decade contrary to predictions. |
| Neil C. Swart, *et al.*, "Influence of Internal Variability on Arctic Sea-Ice Trends," 5 Nature Climate Change 86 (2015). | Ordinary internal variability can mask anthropogenic effects on arctic sea ice. |
| Rong Zhang, "Mechanisms for Low-Frequency Variability of Summer Arctic Sea Ice Extent," 112 Proceedings Nat'l Acad. Scis. 4570 (Apr. 14, 2015). | The loss in sea ice can be attributed to natural phenomena other than warming. |

## VII. Economic Analysis of Climate Change Shows That Damages are Consistently Overestimated and Overvalued, and That Those Errors are Driven By Politics Rather Than Analysis

### *A. The Social Cost of Carbon Overestimates the Harms of $CO_2$ and is a Fundamentally Biased Derived Value*

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| Frank Ackerman & Elizabeth A. Stanton, *Climate Risks and Carbon Prices: Revising the Social Cost of Carbon*, 6 Economics 1 (Apr. 4, 2012), available at http://www.economics-ejournal.org/economics/journalarticles/2012-10. | The SCC assumes climate sensitivity values between 2.0 ºC and 4.5 ºC, far above the values best supported by science. |
| David Anthoff & Richard S.J. Tol, "Climate Policy under Fait-Tailed Risk: An Application of FUND," 220 Ann. Oper. Res. 223 (2014). | Fat-tailed risks do not warrant arbitrarily high carbon taxes/cost-of-carbon measures. |
| Jiehan Guo, *et al.*, "Discounting and the Social Cost of Carbon: A Closer Look at Uncertainty," 9 Envt'l Sci. & Policy 205 (Feb. 28, 2006). | A proper discount rate yields a much lower SCC than usually used, and would cause most policies--including the Kyoto Protocol--to fail a cost-benefit analysis. |
| Management Information Services, Inc., *The Social Costs of Carbon? No, the Social Benefits of Carbon*, prepared for the American Coalition for Clean Coal Electricity, Washington, D.C., January 2014. | The report noted that EPA stated that "The U.S. government has committed to updating the current estimates as the science and economic understanding of climate change and its impacts on society improves over time." Thus, it is likely that the current SCC estimates will be repeatedly and substantially revised over time – perhaps even in both directions. How useful or relevant can the SCC estimates be if they continually change over time? This also raises the question of whether regulatory decisions based on one set of SCC estimates will be revisited as the estimates change. Notwithstanding all of the problems and uncertainties, the IWG recommended that the SCC estimates developed be incorporated by federal agencies into cost-benefit analyses of regulatory actions. However, the SCC estimates developed and utilized by the IWG have little or no validity |
| Robert S. Pindyck, "Pricing Carbon When We Don't Know the Right Price," *Regulation* 43 (Summer 2013). | The value of the SCC is highly uncertain, and existing calculations have many shortcomings. |
| Richard S.J. Tol, "The Social Cost of Carbon: Trends, Outliers and Catastrophes," 2 Economics 1 (Aug. 12, 2008). | A full analysis of different studies of the SCC finds them to decrease over time, and notes that the Stern Report was an outlier. The article calls for quality research by newcomers in order to offset bias in the literature. |
| Roger H. Bezdek, "The Social Cost Of Carbon: The Actual, Real-World Impact Of Obama's Stealth Energy Tax," Management Information Services, Inc., March 2015, www.misi-net.com. | This report finds that SCCs are artificial constructs designed by Obama Administration to penalize fossil fuels<br>They allow the Administration to achieve via regulation what it cannot via Congress – carbon tax, Waxman-Markey, UN commitment, etc. |
| Roger H. Bezdek, "Do Carbon Dioxide's Pluses Trump Its Negatives? Yes: Despite EPA's Word Games, It's Profoundly Earth-friendly," *Duluth News Tribune*, January 11, 2015. | Bezdek finds that OMB's SCC is being used by federal agencies in regulatory actions, and is a thinly disguised assault on coal and hydrocarbons. The SCC is supposed to be an estimate of the monetized damages of an incremental increase in $CO_2$ in a given year -- an estimate of climate change damages. The SCC is based on flawed science: There is no |

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| | scientific evidence for significant climate effects of rising $CO_2$ levels and there is no evidence that global warming will produce catastrophic climate changes. There has been no global warming for two decades, during which $CO_2$ increased significantly. The only "evidence" comes from unvalidated climate models that disagree with each other and that are increasingly inaccurate. OMB is exaggerating climate sensitivity and relies on unsubstantiated claims in UN-IPCC reports. |
| ***B. The Economic Impacts of Climate Change are Highly Uncertain, and Almost Certainly Overestimated*** | |
| David Anthoff & Richard S.J. Tol, "The Impact of Climate Change on the Balanced Growth Equivalent: An Application of FUND," 43 Envt'l & Res. Econ. 351 (2009). | This article finds a wider variation of outcomes than the Stern Review, suggesting the Review's use of the PAGE model was not robust and led to an overestimation of the SCC. |
| Roy F. Darwin & Richard S.J. Tol, "Estimates of the Economic Effects of Sea Level Rise," 19 Envt'l & Res. Econ. 113 (2001). | The economic impacts of sea level rise is highly complex and difficult to state with precision, especialy when redistribution effects are included. |
| P. Michael Link & Richard S.J. Tol, "Estimation of the Economic Impact of Temperature Changes Induced by a Shutdown of the Thermohaline Circulation: An Application of FUND," 104 Climatic Change 287 (2011). | A breakdown of thermohaline circulation does not pose a huge threat globally, despite possible damage to individual nations, and may even offset harms from warming. |
| Robert Mendelsohn, "The Impact of Climate Change on Agriculture in Asia," 13 J. Integrative Agric. S2095 (2013). | There are positive impacts on Asian agriculture for low levels of warming. |
| Robert Mendelsohn, "A Critique of the Stern Report," *Regulation* 42 (Winter 2006-07). | The Stern Report proposed aggressive mitigation because of strong--and partially unwarranted--assumptions. |
| Robert Mendelsohn, *et al.*, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," 84 Am. Econ. Rev. 753 (1994). | The economic impacts of warming are overestimated, and U.S. agriculture may benefit from warming even absent $CO_2$ fertilization effects. |
| Daiju Narita, *et al.*, "Economic Costs of Extratropical Storms under Climate Change: An application of FUND," 53 J. Envt'l Planning and Mgmt. 371 (April 2010). | Extratropical storms have a relatively small impact compared to economic growth from climate change. |
| Roger Pielke Jr., "Mistreatment of the Economic Impacts of Extreme Events in the Stern Review Report on the Economics of Climate Change," 17 Global Envt'l Change 302 (2007). | The Stern Report overestimates future costs of extreme events by an order of magnitude, which affects all of its recommendations. |
| David Schimmelpfennig, *et al.*, U.S. Dep't of Agric. Econ. Rsch. Svc., *Agricultural Adaptation to Climate Change: Issues of Longrun Sustainability* (June 1996), available at http://www.ers.usda.gov/media/490977/aer740a_1_.pdf. | Uncertainties surround climate change predictions because of adaptation effects. |
| S. Niggol Seo, *et al.*, "A Ricardian Analysis of | Many portions of Africa will actually benefit |

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| the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa," 43 Envt'l. & Res. Econ. 313 (2009). | from climate change. |
| S. Niggol Seo & Robert Mendelsohn, "Climate Change Impacts on Latin American Farmland Values: The Role of Farm Type," 6 Revista de Economia e Agronegócio 159 (2008). | There will be a wide range of climate effects across South America, with most benefits for temperate and high elevation regions. |
| Richard S.J. Tol, "The Stern Review of the Economics of Climate Change: A Comment," 17 Energy & Envir. 977 (Oct. 30, 2006). | "The Stern Review can therefore be dismissed as alarmist and incompetent" because it uses unwarranted discount rates, cherrypicks the most pessimistic studies, and did not conduct a valid cost-benefit analysis. |
| Richard S.J. Tol, "On the Uncertainty About the Total Economic Impact of Climate Change," 53 Envt'l & Res. Econ. 97 (2012). | This article estimates the probability density of economic impacts, finding a likely positive effect below 2 ºC. |
| Roger H. Bezdek, "Carbon Dioxide: Social Cost or Social Benefit?" presented at the U.S. Energy Association, Washington, D.C., December 15, 2014. | Bezdek notes that $CO_2$ is demonized & blamed for everything and that the IGW's SSC imputes large costs to $CO_2$. However, $CO_2$ derives from fossil fuels, which are essential to modern life & will remain so in future. $CO_2$ benefits are extremely large compared even to the dubious IWG SCC estimates. Thus, the benefit-csot ratios are very high and will remain orders of magnitude larger than any reasonable SCC estimates. Policies designed to artificially reduce fossil fuel use will do much more harm than good and should be avoided. |
| Richard S.J. Tol & Hadi Dowlatabadi, "Vector-Borne Diseases, Development & Climate Change," 2 Integrated Assessment 173 (2001). | This article describes the role that vector-borne diseases (*e.g.*, malaria) play in IAMs and noting that some GHG-reducing policies may *increase* the risk of these diseases. |
| Richard S.J. Tol & Sebastian Wagner, "Climate Change and Violent Conflict in Europe over the Last Millennium," 99 Climatic Change 65 (2010). | There are more intense conflicts during colder periods. Warming would not cause greater conflict. |
| Jinxia Wang, *et al.*, "The Impact of Climate Change on China's Agriculture," 40 Agric. Econ. 323 (2009). | Irrigated farms in China will likely benefit from mild warming. |
| Roger H. Bezdek, "The Social Benefits of Carbon: *Not* The Social Costs of Carbon," presented at the SPN Energy Freedom Policy & Strategy Meeting, Arlington, Virginia, October 15, 2014. | This report noted that researchers analyzed IAMs and found they are deeply flawed and useless as tools for policy analysis, imply level of knowledge and precision that is illusory and misleading, contain serious weaknesses, and provide very weak foundation for policy. |
| O'Loughlin, J., Linke, A.M. and Witmer, F.D.W. 2014. Effects of temperature and precipitation variability on the risk of violence in sub-Saharan Africa, 1980-2012. Proceedings of the National Academy of Sciences USA **111**: 16,712-16,717. | Violence in sub-Saharan Africa correlates more with political, economic, and geographic factors than with warming, undermining the IPCC's conclusion that warming would lead to violence. |
| ***C. The Damage Functions Used in IAMs Consistently Overestimate the Damage from Warming*** | |
| Robert S. Pindyck, "Modeling the Impact of Warming in Climate Change Economics," MIT | IAM damage functions tend to place too much value ("willingness to pay") on abatement |



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| Sloan School Working Paper No. 4769-10 (Jan. 11, 2010), available at http://ssrn.com/abstract=1539020. | because they track absolute levels of GDP rather than growth rate. |
| David L. Kelly and Charles D. Kolstad, "Integrated Assessment Models For Climate Change Control," US Department of Energy grant number DE-FG03-96ER62277, www.econ.ucsb.edu/papers/ wp31-98.pdf. | This study notes that policy evaluation models are used to assess the impact of a particular policy variable on the environment. Importantly, the models differ in the degree of complexity found in their respective sectors. Policy evaluation models tend to be much more complex, especially in their treatment of the physical sciences, whereas policy optimization models contain economic and climate sectors that are relatively simple. |
| Robert S. Pindyck, "Fat Tails, Thin Tails, and Climate Change Policy," NBER Working Paper No. 16353 (Sep. 2010). | Criticizing climate change analyses based on small risks of significantly harmful outcomes. |
| James Risbey, et al, "Assessing Integrated Assessments," *Climatic Change*, 1996, Volume 34, Issue 3-4, pp 369-395. | Risby reports that IAM modules frequently take the form of the practitioner's subjective judgments linking the disparate knowledge blocks. Unfortunately, while the bricks may be quite sound and well described, the subjective judgments (glue) are often never made explicit. As a result, it is difficult to judge the stability of the structure that has been constructed. Thus, in the case of integrated assessment, not only do we need criteria for assessing the quality of the individual components of the analysis, we also need criteria that are applicable to the glue or the subjective judgments of the analyst, as also for the analysis as a whole. While criteria for adequacy for the individual components may be obtained from the individual disciplines, a similar situation does not exist for the "glue" in the analysis. |
| Stephen H. Schneider, "Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool For Policy Making or Opaque Screen Hiding Value-Laden Assumptions?" *Environmental Modeling and Assessment*, Issue 2, October 1997, pp. 229-49. http://stephenschneider. stanford.edu/Publications/PDF_Papers/Integr_ Ass.pdf; and J. Weyant, et al, "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," pp. 367-439 in J. P. Bruce, et al. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, Cambridge (1996). http://www.ipcc.ch/publications_and_data/publi cations_and_data_ reports.shtml#1. | These studies found troubling and unresolved issues at each stage of an IAM, including: 1) What is the rate of carbon emissions, from natural and human sources? 2) How is the carbon cycle specified: The processes that impact the net change of the amount of carbon in the atmosphere? If more carbon enters the atmosphere than is absorbed by ocean and terrestrial carbon "sinks", then the concentration of carbon will increase. 3) How does the concentration of carbon in the atmosphere impact the climate, e.g. climate dynamics? What are the interactions between climate and oceans, between climate and land mass? 4) How do changes in temperature impact the oceans and the land? 5) What evidence is there that increasing temperatures will cause damages? 6) How much will those damages impact current and future rates of growth? Finally, if there are expected damages to future economic growth and output, how do we compare the current, or |

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| | present value of those future damages to the costs — present and future — of slowing or stopping, (i.e., "mitigating") the emission of carbon into the atmosphere. |
| Ramon Arigoni Ortiz and Anil Markandya, "Integrated Impact Assessment Models of Climate Change with an Emphasis on Damage Functions: a Literature Review," BC3 Working Paper Series 2009-06, Basque Center for Climate Change (BC3), October 2009. http://www.bc3research.org/d7H9dfT3Re2/2009102002 04231130584436.pdf | This study reports that the three IAM models used by the IWG in their computations of SCC, the FUND and PAGE models treat economic growth as an exogenous variable, while the DICE model uses an optimal growth model based on a Cobb-Douglas production function to forecast GDP. Technological change is treated exogenously in all three models. Critics of IAMs consistently cite the failure of IAMs to treat technological change (productivity) as well as population growth as endogenous variables as an important weakness in these models. |
| Also see Rachel Warren, et al, "Spotlighting Impacts Functions in Integrated Assessment," Research Report Prepared for the Stern Review on the Economics of Climate Change, Tyndall Centre for Climate Change Research Working Paper 91, September 2006. | This review of IAMs concluded that: "The assumption of a quadratic dependence of damage on temperature rise is even less grounded in any empirical evidence. Our review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function – although the practice is endemic in IAMs. |
| Robert S. Pindyck, "Climate Change Policy: What Do the Models Tell Us?," NBER Working Paper No. 19244 (July 2013). | In his review of IAMs Pindyck noted that the "loss functions" are not based on any economic theory, but, rather, "They are just arbitrary functions, made up to describe how GDP goes down when T goes up." |
| Michael D. Mastrandrea, *Calculating the Benefits of Climate Policy: Examining the Assumptions of Integrated Assessment Models,* The Pew Center on Global Climate Change, 2009. | Mastrandrea finds that the damage functions used by the three models used by the IWG – DICE, FUND and PAGE – have little or no disaggregation with regard to sectors and/or regions in their estimations. For example, the DICE model uses a single total damage function based on estimates of temperature related damages in several sectors including agriculture, forestry, coastal vulnerability, health, and outdoor recreation to name a few. The PAGE model includes three damage functions that cover economic sectors, noneconomic sectors, and potential climate discontinuities. The damage function in the FUND model is the most disaggregated of the three and it includes damage functions for several sectors: Agriculture, forestry, water resources, sea level increases, health, and several others. In addition, the FUND model includes regional impacts for the various sectors. |
| John P. Weyant, et.al, "Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results," in J. P. Bruce, et al. (eds), *Climate Change 1995: Economic and Social Dimensions of Climate* | The description and purposes of IAMs have changed little over the two decades since their use became common in the analysis of global climate change. |

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| *Change*, Cambridge University Press, Cambridge, 1996. | |
| Michael D. Mastrandrea, *Calculating the Benefits of Climate Policy: Examining the Assumptions of Integrated Assessment Models,* The Pew Center on Global Climate Change, 2009. | Mastrandrea finds it troubling that IAM damage functions are usually based on only one country or region because the literature on the topic of environmentally induced costs (or benefits) is very limited, except in agriculture. Market and non-market damages in DICE are based on studies of impacts on the U.S that are then scaled up or down for application to other regions. Many of the estimates to which market damages in PAGE are calibrated are also based on an extrapolation of studies of the U.S. Only FUND uses regional and sector-specific estimates. However, in some sectors these estimates also originate in one country, or may be dominated by estimates from one region. For example, in the energy sector, the sector which accounts for most of the economic damages in FUND, estimates for the UK are scaled across the world. While some progress is being made in estimating the potential damages from climate change, at present the research is still so limited that one would be hard pressed to describe the results as little more than educated guesses. Or, as Mastrandrea states: "Although the differences in formulation across models do not allow a perfectly parallel comparison, it is clear that the relationship between temperature increase and climate damages varies significantly among IAMs." |
| Elizabeth Stanton, et al, "Inside the Integrated Assessment Models: Four Issues in Climate Economics," *Climate and Development*, 1 (2009). | This paper notes that subtracting damages from output with no effect on capital, production or consumption in following periods is an "unrealistic assumption." Specifically: "In recognition of the fact that the parameters of the damage functions are questionable at best, IAM models increasingly include probability distributions of the parameters to explicitly address the issue of uncertainty. While the use of probability distributions – using a range of values around a norm – serves to acknowledge that we have no real scientific evidence to support one value over another – their use introduces another bias into IAM results. Since the structure of the damage functions are quadratic equations, the results of using probability distributions of equation parameters results in so-called 'fat tail' impacts that are larger for higher temperature increases than for lower increases." |
| Richard S.J. Tol, "Why Worry About Climate Change? A Research Agenda," *Environmental Values*, 17 (2008): 437–470 | Tol notes that while the IAM models include only a limited number of sectors in their assessments, the modelers argue that any unrepresented sectors would result in even |

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| | greater damage assessment if included. Also, admitting that that there may be some positive impacts from climate change, most modelers argue that any positive impacts would undoubtedly be outweighed by the negatives. However, little evidence is presented to support these claims. |
| Joseph E. Aldy, et al, "Designing Climate Mitigation Policy", Resources For the Future, RFF DP 08-16, May 2009. P. 50. http://www.rff.org/RFF/Documents/RFF-DP-08-16.pdf. | Aldy and his colleagues found that there was a significant amount of consistency among several disparate studies of the economic impact of a 2.5C° warming of average global temperatures, compared to pre-industrial levels, by 2100: Five different models predicted economic damages of between 1% and 2% of global GDP. However, although the gross damages estimates were similar, there were huge differences in the studies' estimates of the sources of the damages. The total damages, although similar, reveal large differences in the source of the damages – market impacts, non-market impacts, or catastrophic impact. Thus, it must be concluded that the similar results for the total damage estimates occurs because the selection of damage structures and parameters for the different sectors – economic and noneconomic – in the five model results just happened to aggregate to similar total damage values. |
| ***D. The Discount Rate Used in IAMs is Arbitrarily Chosen, Artificially Inflating the Harms Arising from Warming*** | |
| David Anthoff, *et al.*, "Discounting for Climate Change," 3 Economics 1 (June 9, 2009), available at http://www.economics-ejournal.org/economics/journalarticles/2009-24. | Most analyses of the discount rate ignore crucial components and thereby yield a completely arbitrary and artificially inflated SCC. |
| Kenneth J. Arrow, *et al.*, *How Should Benefits and Costs be Discounted in an Intergenerational Context? The Views of an Expert Panel* (Resources for the Future, Dec. 2012). | This article explains the wide divergence over the proper parameters for the discount rate and the form it should take. |
| Michael Greenstone, et al., "Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation", *Review of Environmental and Economic Policy* (Winter 2013) 7 (1): 23-46; Edward Parson, et al, "Global-Change Scenarios: Their Development and Use", U.S. Department of Energy, 2007, | Assessment of potential impacts of climate change in an IAM begins with an emission stream generated by a scenario of economic growth, and the IWG selected five different scenarios developed by the Energy Modeling Forum (EMF) at Stanford University. Several areas of climate research are often subject to the creation of "scenarios" – essentially "what if" exercises based on sets of assumptions about the structure of the models within the socio-economic module and variables that drive the creation of various climate model scenarios. In the case of emission scenarios, exogenously determined trends for economic growth, population growth, and technological |

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| | change are inputs into the socio-economic module to create scenarios of emissions that are compatible with the structure of the energy system. The remaining sectors are modeled as part of the IAMs. The scenarios are not to be considered forecasts of future emissions, but are developed to create a range of plausible trends for future emissions given the underlying assumptions about economic and population growth and technological change. |
| Geoffrey M. Heal & Antony Millner, "Agreeing to Disagree on Climate Policy," 111 Proceedings of the Nat'l Acad. of Scis. 3695 (Mar. 11, 2014). | No single discount rate is correct for climate policy; proposing a combined, monotonically-declining rate. |
| Christoph Böhringer, Andreas Löschel and Thomas F. Rutherford, *Decomposing the Integrated Assessment Climate Change,* Centre for European Economic Research, Discussion Paper No. 05-07. ftp://ftp.zew.de/pub/zew-docs/dp/dp0507.pdf. Edwards, N.; H. Grepin, A. Haurie and L. Viguier, "Linking Climate and Economic Dynamics", In *The Coupling of Climate and Economic Dynamics: Essays on Integrated Assessment*, Alain Haurie and Laurent Viguier (eds), Amsterdam: Springer. 2005. | Computational limits, weigh heavily in fully integrated optimization IAMs based on CGE (computable general equilibrium) economic modules, such as the DICE model, which compute optimal growth paths by computing thousands of iterations over hundreds of periods. |
| William Nordhaus, "Critical Assumptions in the Stern Review of Climate Change," 317 Science 201 (Jul. 13, 2007). | The Stern Review used "extreme" views on discounting in order to reach its aggressive conclusions. |
| William D. Nordhaus, "A Review of the *Stern Review on the Economics of Climate Change*," 45 J. Econ. Lit. 686 (Sep. 2007). | The assumptions used in the Stern Review are inconsistent with observed marketplace realities of interest and savings rates. |
| "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis," Interagency Working Group on the Social Cost of Carbon, The White House, the United States Government, Under Executive Order 12866, Washington, D.C., May 2013 | In the 2013 IWG report, the ranges of estimated SCC values are huge even though the range of discount rates tested is not. For the three discount rates considered (2.5%, 3% and 5%) using the PAGE IAM and the IMAGE scenario (for projections of economic growth and $CO_2$ emissions), the model results extended over a range of average values for the SCC of from $28 per metric ton of $CO_2$ at a 5% discount rate to $129 at a 2.5% rate. Using the FUND model and the same IMAGE scenario of growth, the results ranged from $3 (at 5%) to $44 (at 2.5%). The results in these two examples show that cutting the discount rate in half, from 5% to 2.5%, produces SCC values that range from five times to 12 times as large when computed at 2.5% rather than 5%. |
| William D. Nordhaus, "A Review of the Stern review on the Economics of Climate Change," *Journal of Economic Literature*, V. XLV, September 2007, pp. 689-97. | Of the many parameters found in IAMs, none attracts as much criticism as the choice of the discount rate used to estimate the present value of future impacts. The discount rate is criticized, first, because of the heavy ethical baggage that it carries. Unlike the majority of benefit-cost studies that use discount rates to |

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| | assess values only a few years or even decades into the future, IAMs that are developed to evaluate the impacts of climate change must look generations ahead. This characteristic of IAMs raises important ethical issues, and one of the most basic ethical arguments is that to use any rate of discount other than zero would be a violation of inter-generational neutrality. That is, a positive value of the discount rate is an indication that future generations are held to be less valuable than the current or "present" one. Second, and more important, in simulations of the sensitivity of IAM results using different variable values, the choice of the values of the discount rate causes greater variation in model results than do other model parameters. |
| Management Information Services, Inc., *The Social Costs of Carbon? No, the Social Benefits of Carbon*, prepared for the American Coalition for Clean Coal Electricity, Washington, D.C., January 2014. | This study notes that almost nothing in the literature of IAMs could be less certain than having a discount rate that is "consistent with estimates provided in the economics literature." Rather, the choice of the discount rate is the most contentious issue in the IAM literature. In 2007 when Nicholas Stern published "The Economics of Climate Change: The Stern Review," the report was notable because it was the first major report from a well-respected economist that forcefully argued for immediate and major actions to slow the growth of $CO_2$ emissions. The report was met with a barrage of criticism, most of which pointed out that the major reason for the report's conclusions was it has used a discount rate near zero to generate its gloomy outlook. |
| ***E. The IAMs Used to Derive the SCC are Too Uncertain to be a Basis for Policymaking*** | |
| Robert S. Pindyck, "Climate Change Policy: What Do the Models Tell Us?," NBER Working Paper No. 19244 (July 2013). | What do models tell us? "Very little." "[T]he models are so deeply flawed as to be close to useless as tools for policy analysis." |
| See David L. Kelly and Charles D. Kolstad, "Integrated Assessment Models For Climate Change Control", US Department of Energy grant number DE-FG03-96ER62277, Current Version: November 1998. Pp. 8-9. http://www.econ.ucsb.edu/papers/wp31-98.pdf. | Kelly and Kolstad note in their review of IAMs that there are two kinds of uncertainty, which they label stochastic uncertainty and parametric uncertainty. The latter can be expected to decline over time as scientists learn more about the operation of the global climate system and the value for parameters such as "climate sensitivity" become more accurate. Stochastic uncertainty refers to those phenomena that impact economic or geophysical processes but are not included in the model, processes such as earthquakes, volcanic eruptions, or abrupt economic downturns such as the Global Financial Crisis. A major element of stochastic uncertainty is the fact that we cannot know the future trend of |

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| | technology or the economy and are, therefore, always susceptible to "surprises". |
| Nicola Cantore, "The Relevance of Climate Change Integrated Assessment Models," in *Policy Design*," Overseas Development Institute, Background Note, December 2009, p. 3, www.odi.org.uk/ sites/odi.org.uk/ files/\odi-assets/publications-opinion-files/5060. pdf | Cantore summarized some of the positive results that arise from using IAMs to help design climate policies. He noted that compared to other less sophisticated complex scientific tools, IAMs offer a number of benefits when designing policy. Nevertheless, despite the progress that has been made in the building and use of IAMs, perhaps most importantly in bringing together scholars and scientist in a joint effort to assess global climate change, the IAM process remains a very questionable tool for establishing explicit policy goals. |
| Jose A. Tapia Granados and Oscar Carpintero, "Dynamics and Economic Aspects of Climate Change", Chapter 3 in *Combating Climate Change: An Agricultural Perspective*, edited by Manjit S. Kang & Surinder S. Banga, CRC Press, 2013. Pp. 37-38. | In an assessment of the limitations of IAMs for use in policy, Granados and Carpintero conclude: The lack of robustness of results of different IAMs indicates the limitations of the neoclassical approach, which constitutes the theoretical base of most IAMs -- limitations of of so-called ad hoc assumptions, and the controversial nature of the methods to estimate the monetary value of non-market costs and benefits (mortality, morbidity, damage to ecosystems, etc.). These features explain why many contributions of this type of macroeconomics-oriented IAMs have been criticized for their dubious political usefulness and limited scientific soundness. They list several important shortcomings of IAMs, including lack of transparency to explain and justify the assumptions behind the estimates, questionable treatment of uncertainty and discounting of the future, assumption of perfect substitutability between manufactured capital and "natural" capital in the production of goods and services, and the way IAMs estimate monetary costs of non-market effects, which can lead to skepticism about policies based on the results of the models. |
| Nicholas Stern, "The Economics of Climate Change," *American Economic Review: Papers and Proceedings*, Vol. 98, No. 2, 2008. | Stern summarizes the many of the weaknesses of integrated assessment modeling, "As I have argued, it is very hard to believe that models where radically different paths have to be compared, where time periods of hundreds of years must be considered, where risk and uncertainty are of the essence, and where many crucial economic, social, and scientific features are poorly understood, can be used as the main quantitative plank in a policy argument. Thus, IAMs, while imposing some discipline on some aspects of the argument, risk either confusing the issues or throwing out crucial features of the problem.<br>However, as the Stern Review stressed, IAM |

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| | analysis has very serious weaknesses and must not be taken too literally." |
| U.S. Chamber of Commerce, "Petition for Correction: Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866 (February 2010) and Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866 (May 2013)," Washington, D.C., September 4, 2013 | The COC argued that SCC estimates should be withdrawn and not used in rule-making and policy-making for the following reasons: 1. The SCC estimates fail in terms of process and transparency. The SCC estimates fail to comply with OMB guidance for developing influential policy-relevant information under the Information Quality Act. The SCC estimates are the product of an opaque process and any pretensions to their supposed accuracy (and therefore usefulness in policy-making) are unsupportable. 2. The models with inputs used for the SCC estimates and the subsequent analyses were not subject to peer review as appropriate. 3. Even if the SCC estimate development process was transparent, rigorous, and peer-reviewed, the modeling conducted in this effort does not offer a reasonably acceptable range of accuracy for use in policy-making. 4. The IWG has failed to disclose and quantify key uncertainties to inform decision makers and the public about the effects and uncertainties of alternative regulatory actions as required by OMB. 5. By presenting only global SCC estimates and downplaying domestic SCC estimates in 2013, the IWG has severely limited the utility of the SCC for use in benefit cost analysis and policy-making. |
| Frank Ackerman, et al, "Limitations of Integrated Assessment Models of Climate Change," *Climatic Change*, 2009, 95: 297–315. | In an overview of questions of ethics and uncertainty that are endemic in the construction and application of IAMs to questions of global climate change this paper noted that, regarding the appropriateness of IAMs for policy choices: Policy makers and scientists should be skeptical of efforts by economists to specify optimal policy paths using the current generation of IAMs; these models do not embody the state of the art in the economic theory of uncertainty; the foundations of the IAMs are much shakier than the general circulation models that represent our best current understanding of physical climate processes; not only do the IAMs entail an implicit philosophical stance that is highly contestable, they suffer from technical deficiencies that are widely recognized within economics; IAMs cannot be viewed as the ultimate arbiter of climate policy choices. |
| Joseph Bast and James M. Taylor, "Global Warming: Not a Crisis," Heartland Institute, June 30, 2014. | The authors finds that the burning of fossil fuels to generate energy produces $CO_2$, a GHG which, everything else being equal, could lead to some warming of the global climate. Most scientists believe the Earth experienced a |

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| | small rise in temperatures during the second half of the twentieth century, but they are unsure how large a role human activities may have played. The important questions from a public policy perspective are: How much of the warming is natural? How sure are we that it will continue? Would continued warming be beneficial or harmful? The answers, in brief, are: Probably 2/3 of the warming in the 1990s was due to natural causes; the warming trend already has stopped and forecasts of future warming are unreliable; and the benefits of a moderate warming are likely to outweigh the costs. Global warming, thus, is not a crisis. |
| Kevin D. Dayaratna and David W. Kreutzer, "Loaded DICE: An EPA Model Not Ready for the Big Game," Backgrounder #2860 on Energy and Environment, Heritage Foundation, November 21, 2013. | The authors note that EPA uses three IAMs to determine the value of the SCC, defined by the EPA as the economic damage that a ton of CO2 emitted today will cause over the next 300 years. This study analyzes the IAM that generates the intermediate EPA results (the DICE model) and inds it flawed beyond use for policymaking. In addition to more fundamental problems outlined by others, the authors find that reasonable changes in a few assumptions lead to order-of-magnitude changes in estimates of the SCC. |
| ***F. Predictions of Economic Catastrophe are Not Supported by the Evidence*** | |
| Partha Dasgupta, "Commentary: The Stern Review's Economics of Climate Change," 199 Nat'l Inst. Econ. Rev. 4 (Jan. 2007). | The strong response advocated by the Stern Review was based more on ethical imperatives rather than economics or climatic facts. |
| Richard S.J. Tol, "Is the Uncertainty About Climate Change Too Large for Expected Cost-Benefit Analysis?," 56 Climatic Change 265 (2003). | Infinite variance in costs and benefits related to climate change need not make cost-benefit analysis impossible. |
| Richard Tol, "Bogus Prophecies of Doom Will Not Fix the Climate," *Financial Times*, March 31, 2014. | According to Professor Tol, the first rule of climate policy should be to do no harm to economic growth. But the IPCC was asked to focus on the risks of climate change alone, and those who volunteered to be its authors "eagerly obliged." Every clause that could possibly be used against a government position, either in a domestic debate or in international negotiations, was neutered or removed. The WHO estimates that about seven million people are now dying each year as a result of air pollution. Even on the most pessimistic estimates, climate change is not expected to cause loss of life on that scale for another 100 years. In fact, Dr. Tol now believes that rising temperatures may even be beneficial, since many more people die in unusually cold winters than in unusually hot summers. $CO_2$ helps plants grow, and higher ambient concentrations make them less thirsty. |

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| Roger H. Bezdek, "Benefits of Carbon Use Far Outweigh its Costs," *The Hill*, September 25, 2014. | Bezdek notes that while, fear mongering may capture headlines, there are several major fallacies in this approach. First, there has been no global warming for at least the past two decades, which means such warming could not have caused any weather events. Second, the dire climate-related occurrences being cited as evidence are not happening. For example: Any sea level rise is modest, and there is no evidence of a cause and effect from $CO_2$; there is no indication of increased tornadoes, hurricanes, snowfall, or other extreme weather events and, in fact, such events have decreased over the past century; sea ice is not melting; rather, it has increased to a new record high in the Antarctic; floods are not getting worse, and there has been no particular change in the frequency or severity of floods worldwide; droughts are not becoming more severe, and the fraction of the world's land under drought has been declining for 30 years. |
| Richard S. J. Tol, The Economic Effects of Climate Change, *Journal of Economic Perspectives,* Volume 23, Number 2 (Spring 2009) pp 29-51. | Tol believes that the uncertainties about climate change are vast -- indeed, so vast that the standard tools of decision making under uncertainty and learning may not be applicable. He originally thought that all aspects of the problem were roughly known, and that research would be complete within a few years. This view turned out to be so overoptimistic as to be entirely mistaken. The quantity and intensity of the research effort on the economic effects of climate change seems income-mensurate with the perceived size of the climate problem, the expected costs of the solution, and the size of the existing research gaps. He concludes that "Politicians are proposing to spend hundreds of billions of dollars on greenhouse gas emission reduction, and at present, economists cannot say with confidence whether this investment is too much or too little." |
| White House Council of Economic Advisers, "The Cost of Delaying Action to Stem Climate Change," Executive Office of the President of the United States, July 2014. | The CEA notes that "In addition to projecting future climate variables and other economic variables, the IAMs estimate the total economic damages (and, in some cases, benefits) of climate change which includes impacts on agriculture, health, ecosystems services, productivity, heating and cooling demand, sea level rise, and adaptation." CEA also states "Some studies estimate that small temperature increases have a net economic *benefit*, for instance due to increased agricultural production in regions with colder climates. However, projected temperature increases even under immediate action fall in a range with a strong consensus that the costs of |

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| | climate change exceed such benefits." |
| National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, Washington, D.C.: National Academies Press, 2009. | NRC found that assessments based on IAMs suffer from uncertainty, speculation, and lack of information about future emissions of greenhouse gases, the effects of past and future emissions on the climate system, the impact of changes in climate on the physical and biological environment, and the translation of these environmental impacts into economic damages. NRC thus concludes that "As a result, any effort to quantify and monetize the harms associated with climate change will raise serious questions of science, economics, and ethics and should be viewed as provisional." |
| ***G. Adaptation to Warming is an Economically Superior Response Compared to Radical Abatement*** | |
| Robert Mendelsohn, *The Challenge of Global Warming*, Perspective Paper, Copenhagen Consensus 2004 (Apr. 30, 2004). | The marginal utility of aggressive abatement policies does not warrant those policies. |
| Robert P. Murphy, "Are Climate Change Mitigation Policies a Form of Insurance?" Institute for Energy Research, April 17, 2014. Robert P. Murphy, "New IPCC Report Unwittingly Shows Weakness of Alarmist Camp," Institute for Energy Research, April 3, 2014. | Murphy finds that climate mitigation policies cannot be legitimately considered to be insurance. For example, the likely damages from climate change through the end of the century are entirely manageable, and are lower than credible estimates of the costs of mitigation strategies. Thus, one of the implications of the IPCC report is that using mean estimate projections, the likely damages from climate change are actually less than what reputable studies estimate as the costs of government action to curb carbon dioxide emissions, such as a carbon tax or cap-and-trade scheme. In other words, even stipulating the entire IPCC framework and numbers, one can make a strong case that "on average" the various proposals to tax and regulate emissions would be a cure worse than the disease: They would cost more in terms of forfeited economic growth than they would save in terms of reduced climate change damages. Thus, aggressive government action to slow emissions does not pass a standard cost-benefit test. |
| Robert Mendelsohn, "The Economics of Adaptation to Climate Change in Developing Countries," 3 Climate Change Econ. 1250006-1 (2012). | Adaptation can offset harms to developing countries. |
| Roger H. Bezdek, "Carbon Policy Around the Globe: Degrees of Disaster," presented at the Energy Council 2013 Global Energy and Environmental Issues Conference, Lake Louise, Alberta, Canada, December 2013. | This paper warns that the effects of carbon restriction policies are predictable and inevitable: Huge increases in electricity and energy costs; economic stagnation; decline of industry and commerce; massive job destruction; large increase in energy poverty; social chaos; political upheaval. It concludes |

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| | that these policies should beavoided and, where implemented, reversed. |
| Alex Epstein, *Fossil Fuels Improve the Planet*, Center for Industrial Progress, 2013 | Epstein finds that The mass production of sturdy, weather-proof buildings, the universal availability of heating and air conditioning, the ability to flee the most vicious storms through modern transportation, the protection from drought through modern irrigation, the protection from disease through modern sanitation -- all have been powered by fossil fuels. Combined, they have led to a 98 percent reduction in the number of climate-related deaths over the last century, indicating that humanity is coping better with extreme weather events than it is with other far more important health and safety problems. The decreases in the numbers of deaths and death rates reflect a remarkable improvement in society's adaptive capacity. Imposing additional restrictions on the use of hydrocarbon fuels will slow or even reverse the rate of improvement of this adaptive capacity and thereby worsen any negative impact of climate change. |
| Bjorn Lomborg, *Cool It: The Skeptical Environmentalist's Guide to Global Warming*, Cyan Communications, 2008. | Lomborg argues that many of the elaborate and staggeringly expensive actions currently being considered to meet the challenges of global warming ultimately will have little impact on the world's temperature. He suggests that rather than focusing on ineffective solutions that will cost us trillions of dollars over the coming decades, we should be looking for smarter, more cost-effective approaches that will allow us to deal not only with climate change but also with other pressing global concerns, such as malaria and HIV/AIDS. |
| Roger H. Bezdek, "White House Study Is Dangerously Delusional," *World Oil*, October 2014. | Bezdek finds that It is very costly to incur huge global warking abatement expenses now on the basis of flawed science and that there is no reliable evidence that the costs of climate change are substantial. The argument that climate policy can be thought of as "climate insurance" is not valid, and likely damages from climate change are actually less than the costs of government actions to reduce $CO_2$ emissions. They would cost more in terms of forfeited economic growth than they would save in terms of reduced damages and would not pass a standard cost/benefit test. |
| Nassim Taleb, *Antifragile: Things That Gain From Disorder* (Random House 2012). | This book describes techniques and strategies for create "antifragile" individual, organizations, and societies. |
| Roger H. Bezdek, "The Failure of Global Carbon Policies," *American Coal*, issue 1, 2014, pp. 50-54. | This paper notes that, as of early 2014, more than two dozen nations and sub-national jurisdictions have imposed some type of carbon restrictions. It finds that carbon restriction policies are working perfectly in |

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| | every country that has tried them: They are ruining economies, devastating industry, destroying jobs and impoverishing citizens. It summarizes the disastrous impacts of radical abatement polocies in the EU. |
| Peter J. Webster, "Myanmar's Deadly Daffodil," 1 Nature Geosci. 488 (2008). | Simple mitigation and adaptation could have prevented deaths from cyclone in Myanmar. |