

# Progress in Detection and Attribution Research

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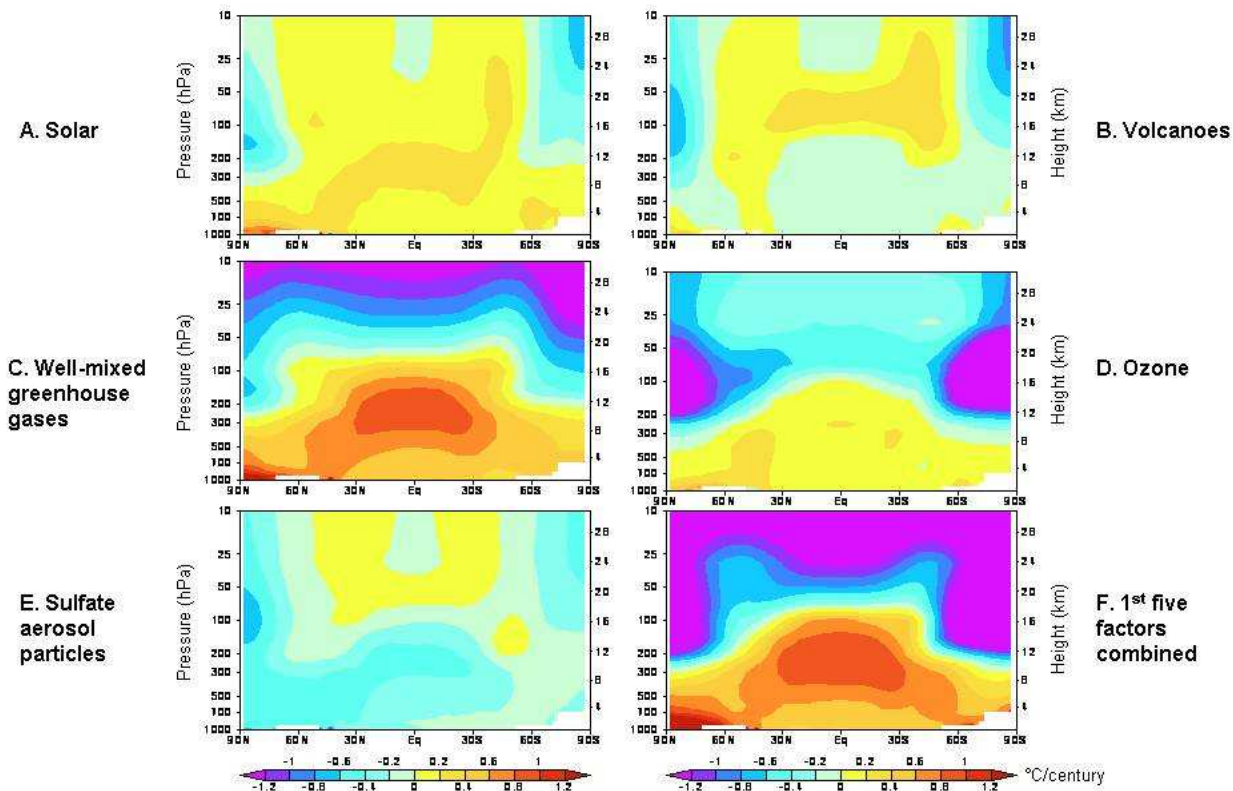
## 1. Introduction

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme. The goals of this panel were threefold: to assess available scientific information on climate change, to evaluate the environmental and societal impacts of climate change, and to formulate response strategies. The IPCC's first major scientific assessment, published in 1990, concluded that "unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more" (1).

Six years later, the IPCC's second scientific assessment reached a more definitive conclusion regarding human impacts on climate, and stated that "the balance of evidence suggests a discernible human influence on global climate" (2). This cautious sentence marked a paradigm shift in scientific understanding of the nature and causes of recent climate change. The shift arose for a variety of reasons. Chief amongst these was the realization that the cooling effects of anthropogenic sulfate aerosols had partially obscured the warming signal arising from increasing atmospheric concentrations of greenhouse gases (GHGs) (3). A further major area of progress was the increasing use of so-called "fingerprint" studies, which involve detailed statistical comparisons of modeled and observed climate change patterns (4, 5, 6). Fingerprinting relies on the fact that each climate forcing mechanism (*e.g.*, changes in solar irradiance, volcanic dust, sulfate aerosols, or GHG concentrations) has a unique pattern of climate response (see Figure 1). Fingerprint studies have greatly enhanced our ability to diagnose cause and effect relationships in the climate system.

The third IPCC assessment was published in 2001, and went one step further than its predecessor. It made an explicit statement about the magnitude of the human effect on climate, and concluded that "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (7). This conclusion was based on improved estimates of natural climate variability, better reconstructions of temperature fluctuations over the last millenium, continued warming of the climate system,

refinements in fingerprint methods, and the use of results from more (and improved) climate models, driven by more accurate and complete forcing estimates.



**Figure 1:** Zonally-averaged temperature changes as a function of latitude (from 90°N-90°S) and height (from 1000 hPa to 10 hPa). Results are from single forcing experiments (A through E) with historical changes in five individual forcings, and from an experiment with simultaneous changes in all five forcings (F). All experiments were performed with the coupled atmosphere-ocean Parallel Climate Model (PCM) (8). Temperature changes are expressed as linear trends in degrees Celsius per century, and were calculated over the period from 1890 to 1999. All results are ensemble means (averages over four individual realizations).

With the release of the IPCC Working Group I Fourth Assessment Report (AR4) in early 2007, this gradual strengthening of scientific confidence in the reality of human influences on global climate has continued. The IPCC AR4 reported that “warming of the climate system is unequivocal”, and that “most of the observed increase in global average

temperatures since the mid-20<sup>th</sup> century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations” (9), where the term “*very likely*” had a specific meaning (>90% probability that the statement is correct). Both of these statements were stronger than their counterparts in the Third Assessment Report. The AR4 justified this increase in scientific confidence on the basis of “...longer and improved records, an expanded range of observations and improvements in the simulation of many aspects of climate and its variability” (9). In its contribution to the AR4, IPCC Working Group II concluded that anthropogenic warming has had a “discernible influence” not only on the physical climate system, but also on a wide range of biological systems (10).

These “bottom line” conclusions of past and present IPCC scientific assessments have been endorsed by other independent bodies, such as the U.S. National Academy of Sciences (11), other Science Academies (12), and the first Synthesis and Assessment Product of the U.S. Climate Change Science Plan (13). The clear message from these assessments is that human activities have significantly altered not only the chemical composition of Earth’s atmosphere, but also the climate system. Changes in atmospheric composition are an immutable fact, not speculation. Human activities have led to increases in well-mixed and shorter-lived GHGs, decreases in stratospheric ozone, and changes in the atmospheric burdens of sulfate and soot aerosols. All of these atmospheric constituents interact with incoming solar and outgoing terrestrial radiation. Human-induced changes in the concentrations of these constituents modify the natural radiative balance of Earth’s atmosphere, and therefore perturb climate.

Despite the overwhelming scientific evidence of pronounced anthropogenic effects on climate, important uncertainties remain. The experiment that we are performing with the Earth’s atmosphere lacks a suitable control: we do not have a convenient parallel Earth on which there are no human-induced changes in atmospheric chemistry, and which would provide a reference for measuring the anthropogenic contribution to climate change. We must therefore rely on sources of information from times prior to any significant human influence on climate to estimate how Earth’s climate might have evolved in the absence of any human “forcing” (see Figure 2). Such sources include tree rings, ice

cores, corals, and boreholes (14) and numerical models of the “unforced” climate system. Climate changes inferred from paleoclimatic reconstructions and numerical models will always have uncertainties, so there will always be uncertainties in our estimates of the climate of an “undisturbed Earth”, and hence in the magnitude of human effects on climate.

In the following, we provide a personal perspective on recent developments in the field of detection and attribution (D&A) research – that is, research directed towards detecting significant climate change, and attributing it to a specific cause or causes. Other reviews of this topic are given elsewhere (15, 16, 17, 18).

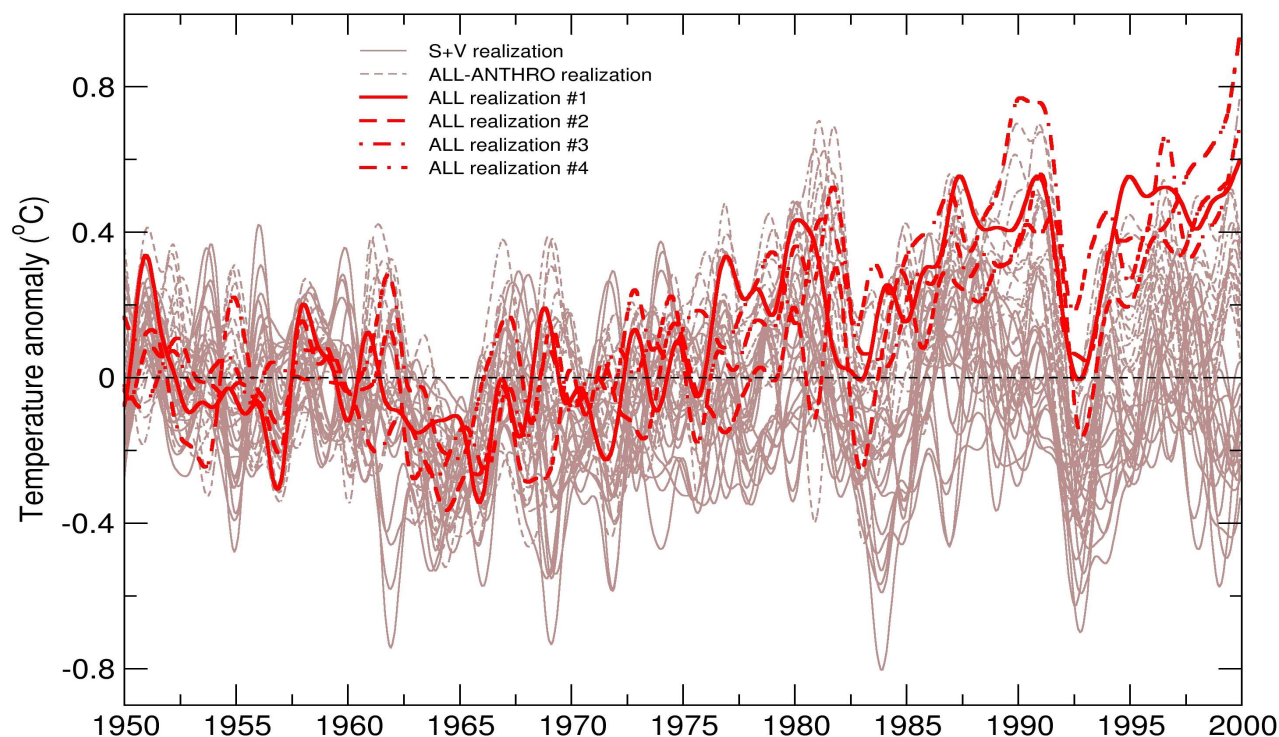
## **2. Recent Progress in D&A Research**

### *2.1 Physical Consistency and Robustness of D&A Results*

The IPCC and National Academy findings that human activities are affecting global-scale climate are based on multiple lines of evidence:

- Our continually-improving physical understanding of the climate system and the human and natural factors that cause climate to change.
- Evidence from paleoclimate reconstructions, which enables us to place the warming of the 20th century in a longer-term context (19).
- The qualitative consistency between observed changes in many different aspects of the climate system and model predictions of the changes that should be occurring in response to human influences (9, 20).
- Evidence from rigorous quantitative fingerprint studies, which compare model and observed patterns of climate change.

### Simulations of Total Natural Variability with PCM Surface air temperature. Anomalies w.r.t. 1950-59



**Figure 2:** Simulations of climate change and “total” natural variability using the Parallel Climate Model (8). Results are for global-mean, monthly-mean near-surface temperature changes. “Total” natural variability is the variability that would occur in the absence of any human influence on climate. It consists of both the “unforced” noise generated by processes internal to the climate system and the forced temperature variations caused by changes in solar energy output and volcanic aerosols. The brown lines represent 32 individual realizations of “total” natural variability. These were obtained from four different types of experiment: forcing the model with combined anthropogenic and natural forcing (“ALL”), anthropogenic forcing only (“ANTHRO”), solar forcing only (“S”), or volcanic forcing only (“V”). Estimates of “total” natural variability can be derived in two different ways: by adding the individual S and V temperature changes, or by subtracting ANTHRO results from ALL. For each experiment, four realizations were available, each starting from different initial conditions of the climate system. There are thus 16 different combinations of S+V and 16 combinations of ALL-ANTHRO. Adding or subtracting signals in this way amplifies the internal noise. Nevertheless, the forced temperature changes in the four different realizations of ALL clearly begin to emerge from the noise of “total” natural variability by the late 20th century. All anomalies were defined relative to climatological monthly means computed over 1950 to 1959.

This Section focuses on fingerprint evidence. The underlying strategy in fingerprint studies is to search for a model-predicted pattern of climate change (the “fingerprint”) in observational data. The fingerprint can be estimated in different ways, but is typically derived from a model experiment in which one or more human factors (such as atmospheric concentrations of GHGs or sulfate aerosol particles) are varied according to the best-available estimates of their historical changes. Different statistical techniques and metrics are then applied to quantify the level of agreement between the fingerprint and observations and between the fingerprint and model estimates of climate noise. This enables researchers to make rigorous tests of competing hypotheses regarding the possible causes of recent climate change (15, 16, 17, 18, 21, 22).

Many research groups around the world have been involved in fingerprinting studies (23). These groups have employed a wide variety of statistical methods, climate models, and observational data sets. While early fingerprint work dealt almost exclusively with changes in near-surface or atmospheric temperature, more recent studies have applied fingerprint methods to a range of different variables, such as ocean heat content (24, 25, 26), sea-level pressure (27), tropopause height (28), zonal-mean precipitation (29), and atmospheric moisture (30).

The common denominator in this research is the finding that natural climate variability alone cannot explain the observed climate changes over the second half of the 20th century. The best statistical explanation of these changes invariably involves a large human contribution. D&A results are robust to the processing choices made by different groups, and show a high level of physical consistency across different climate variables. Observed atmospheric water vapor increases, for example (31), are physically consistent with increases in ocean heat content (32, 33) and near-surface temperature (34).

There are a number of popular myths and misconceptions about fingerprint evidence. One misconception is that fingerprint studies consider global-mean temperatures only, and thus provide a very poor constraint on the relative contributions of

human and natural factors to observed changes (35). In fact, fingerprint studies rely on information about the detailed spatial structure (and often the combined space-time structure) of observed and simulated climate changes. Complex patterns provide much stronger constraints on the possible contributions of different factors to observed climate changes (36, 37, 38).

Another misconception is that model-based estimates of natural internal climate variability (“climate noise”) are simply accepted uncritically in fingerprint studies, and are never tested against observations (39). This is demonstrably untrue. Many fingerprint studies explicitly test whether model estimates of climate noise are realistic, at least on annual and decadal timescales, where observational data are of sufficient length to obtain reliable estimates of observed noise (40, 41, 42, 43).

## *2.2 The MSU Debate: A Resolution?*

For over a decade, scientists critical of “fingerprint” studies have highlighted satellite-based estimates of tropospheric temperature change as evidence of a fundamental discrepancy between observations and climate model results. They have argued that tropospheric temperature measurements from satellites and weather balloons (radiosondes) show cooling of the troposphere over the past several decades, while climate models indicate that the troposphere should have warmed in response to increases in greenhouse gases (Figure 1C). This apparent discrepancy between models and observations has been used to cast doubt on both “discernible human influence” conclusions and on the reality of the surface warming inferred from thermometer measurements (44).

It is unquestionable that satellites have transformed our scientific understanding of the weather and climate of planet Earth. Since 1979, Microwave Sounding Units (MSU) on polar-orbiting satellites have measured the microwave emissions of oxygen molecules in the atmosphere. These emissions are proportional to atmospheric temperatures. Measurements of microwave emissions made at different frequencies can be used to



obtain information about the temperatures of broad atmospheric layers. Most attention has focused on estimates of the temperatures of the lower stratosphere and mid- to upper troposphere ( $T_4$  and  $T_2$ , respectively) as well as on a retrieval of lower tropospheric temperatures ( $T_{2LT}$ ) (45).

The first attempts to obtain climate records from MSU data were made by scientists at the University of Alabama in Huntsville (UAH) (46, 47, 48). Until recently, the UAH group's analysis of the MSU data suggested that the tropical lower troposphere had cooled since 1979. Concerns regarding the homogeneity and reliability of the MSU-based tropospheric temperature trends were dismissed with the argument that weather balloons also indicated cooling of the tropical troposphere (49), and constituted a completely independent temperature monitoring system (50, 51).

Throughout most of the 1990s, only one group (the UAH group) was actively working on the development of multi-decadal temperature records from MSU data. This situation persisted until 1998, at which time a second group, Remote Sensing Systems (RSS) in California, found a hitherto-unidentified problem with the UAH  $T_{2LT}$  data. The problem was related to the progressive orbital decay and altitude loss over the lifetimes of individual satellites. This affected the portion of the Earth's atmosphere that MSU instruments observe from space, and introduced a spurious cooling trend in the UAH  $T_{2LT}$  data (52). The RSS findings suggested that the lower troposphere had actually warmed over the satellite era (53).

The UAH group subsequently identified two new corrections that approximately compensated for the cooling influence of orbital degradation. These new factors were related to 1) the effects of orbital drift on the sampling of Earth's diurnal temperature cycle; 2) variations in measured microwave emissions arising from changes in the temperature of the MSU instrument itself, caused by changes in the instrument's exposure to sunlight (the so-called "instrument body effect", or IBE (54).

In the next phase of the MSU debate, three separate groups found that the mid- to upper troposphere had warmed markedly over the satellite era (55, 56, 57, 58, 59, 60), a conclusion strikingly different from the UAH results (49, 54). The UAH group continued to claim close correspondence between their own MSU-based estimates of tropospheric temperature trends and trends derived from radiosondes (49). This raised renewed questions regarding the quality of radiosonde temperature measurements. Were such measurements an unambiguous 'gold standard', suitable for making judgments about the relative quality of the MSU temperature datasets produced by different research groups?

Recent research indicates that the answer to this question is "no". The temperature sensors carried by radiosondes have changed over time, together with the shielding that protects sensors from direct solar heating. Solar heating of the sonde-borne sensors can affect the temperature measurements themselves. The introduction of progressively more effective shielding results in less solar heating of the sensors, thus imparting a non-climatic trend to the daytime measurements.

This effect was identified by Sherwood *et al.* (61), who contrasted the radiosonde-based temperature trends based on nighttime ascents (with no solar heating effects) and daytime launches. Tropospheric temperature trends over the satellite era were systematically warmer in the nighttime data, a finding subsequently confirmed by Randel and Wu (62). Accounting for this time-varying solar heating effect in the sonde data yielded tropospheric temperature trends that were in better agreement with RSS and UMD estimates than with UAH results (61).

Two papers published concurrently with Sherwood *et al.* shed further light on these issues. The first paper was by the RSS group, and described a new MSU retrieval of lower tropospheric temperatures (63). As in the case of the mid- to upper troposphere, RSS obtained substantially larger  $T_{2LT}$  trends than UAH, both globally and for the tropics (64). Mears and Wentz (63) attributed most of these differences to an error in UAH's method of adjusting for drift in the time of day at which satellites sample the Earth's daily temperature cycle. This error led to an adjustment term that had the wrong sign, a problem

acknowledged by Christy and Spencer (65). When the UAH group remedied this problem, however, their  $T_{2LT}$  trends increased by much smaller amounts than expected on the basis of the RSS analysis (66).

The second paper addressed the physics that governs changes in atmospheric temperature profiles. It compared the relationship between surface and tropospheric temperature changes over a wide range of observational and climate model datasets (67). These comparisons were performed on multiple timescales, using month-to-month, year-to-year, and decade-to-decade temperature changes. The focus was on the deep tropics (20°N-20°S), where the UAH, RSS, and UMD tropospheric temperature trends diverged markedly. The intent was to investigate whether the simple physics that governs the vertical structure of the tropical atmosphere could be used to constrain the uncertainties in satellite-based trends.

This “simple physics” involves the release of latent heat when moist air rises due to convection and condenses to form clouds. Because of this heat release, tropical temperature changes averaged over large areas (and averaged over sufficient time to damp day-to-day “weather noise”) are generally larger in the lower and mid-troposphere than at the surface (Figure 3). This “amplification” behavior is well-known from basic theory (68), observations (69, 70), and climate model results (71, 72, 73, 74).

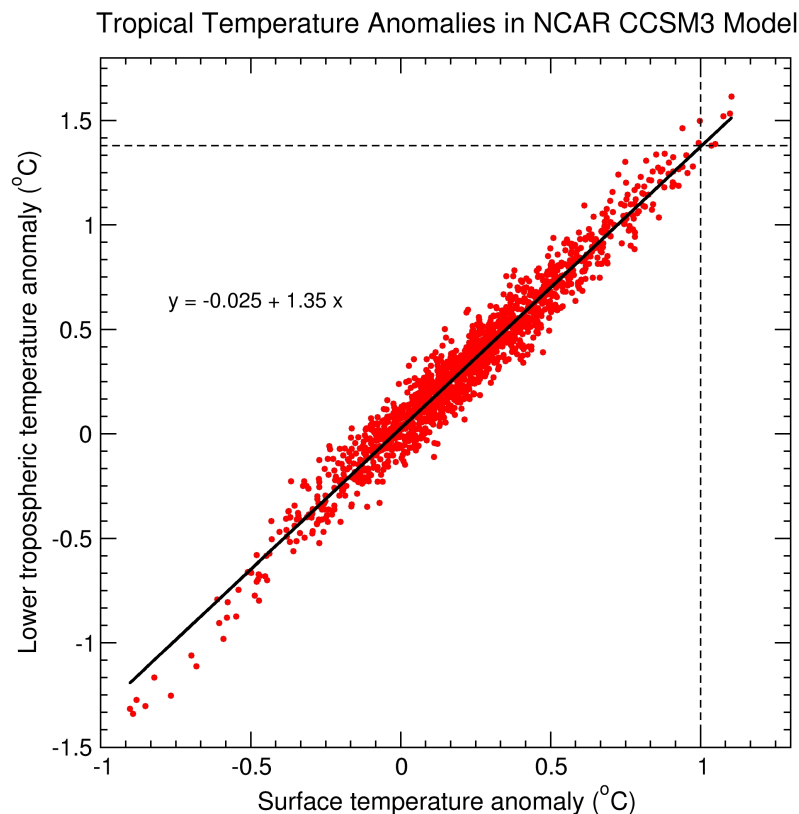
The UAH amplification results were puzzling. For “fast” (month-to-month and year-to-year) fluctuations in tropical temperatures, UAH  $T_{2LT}$  anomalies were 1.3 to 1.4 times larger than surface temperature anomalies, consistent with models, theory, and other observational datasets. But for “slow” (decade-to-decade) temperature changes, the UAH  $T_{2LT}$  trends were smaller than surface trends, implying that the troposphere damped surface warming. Damping occurs even in the newest version of the UAH  $T_{2LT}$  dataset (65), which has been corrected for the error identified by Mears and Wentz (63). In contrast, model amplification results were consistent across all timescales considered, despite large differences in model structure, parameterizations, and forcings. The RSS

$T_{2LT}$  data also showed amplification of surface warming for both “fast” and “slow” temperature changes.

These results have at least two possible explanations, which are not mutually exclusive (17, 75). The first is that the UAH data are reliable, and different physical mechanisms control the response of the tropical atmosphere to “fast” and “slow” surface temperature fluctuations. Such time-dependent changes in the physics seem unlikely given our present understanding, and mechanisms that might explain such changes have yet to be identified. If this explanation is valid, all current models must have common errors that prevent them from capturing the complex physics that governs ‘real world’ amplification behavior.

A second explanation is that significant inhomogeneities remain in the UAH tropospheric temperature records, leading to residual cooling biases in the UAH long-term trend estimates. In our view, this is both a simpler and more plausible explanation given the consistency of amplification results across models and timescales, our theoretical understanding of how the tropical atmosphere should respond to sustained surface heating (76), and the currently large uncertainties in observed tropospheric temperature trends (13).

In summary (using a phrase popularized by Carl Sagan), extraordinary claims demand extraordinary proof. The extraordinary claim that the tropical troposphere had cooled since 1979 has not survived rigorous scrutiny. We have learned that uncertainties inherent in satellite estimates of tropospheric temperature change are far larger than they were originally portrayed to be, and there is no longer a fundamental discrepancy between modeled and observed estimates of tropospheric temperature changes (77). Paradoxically, it is the expansion of observational uncertainties (arising from improvements in our ability to quantify uncertainty) that has removed a major stumbling block in our understanding of the causes of recent climate change.



**Figure 3:** Amplification of monthly surface temperature variability in the tropical lower troposphere. Results are from a simulation of historical climate change performed with version 3.0 of the Community Climate System Model (CCSM) developed at the National Center for Atmospheric Research (78). The simulation included estimated historical changes in well-mixed greenhouse gases, sulfate aerosol direct effects, carbonaceous aerosols, tropospheric and stratospheric ozone, solar irradiance, and volcanic aerosols. The lower tropospheric temperature changes were calculated with a so-called static weighting function, which facilitates comparison with observational MSU  $T_{2LT}$  data (67). Results were spatially-averaged over the deep tropics (20°N-20°S), and are in the form of monthly-mean anomalies relative to climatological monthly means (calculated over 1890 to 1909). There are 1,560 values (one for each month from January 1870 to December 1999). The black regression line is a least-squares fit to the data, and has a slope of roughly 1.35 – *i.e.*, tropical temperature changes in the lower troposphere are on average 1.35 times larger than at the surface.

### 2.3 *Detecting Anthropogenic Effects at Sub-Global Scales*

At the time of publication of the IPCC Third Assessment Report (“TAR”) (7), most formal D&A studies compared global patterns of modeled and observed climate change (79, 80, 81, 82, 83). Similarities in the largest features of these patterns were primarily responsible for the positive identification of human effects on climate (84, 85, 86, 87, 88). Comparatively little work had been done on the problem of identifying human effects on climate at regional and local scales.

Arguably, it these regional-scale changes that will determine societal impacts and drive climate-related policy decisions. Accordingly, many recent D&A studies have shifted their focus from global to regional scales. This is a key area of progress since the IPCC TAR. In the following, we briefly summarize this new research, and discuss some of the basic challenges inherent in regional-scale D&A work.

One fundamental problem in such work is that climate noise typically becomes larger when averaged over increasingly smaller domain sizes (89). An example of this is given in Figure 4, which shows surface temperature changes in an “unforced” control run and in simulations of 20th century climate. Temperature changes were spatially averaged over three different domains: the globe, the Northern Hemisphere, and the Western U.S. Even without rigorous statistical tests, it is obvious that global averaging produces the largest damping of climate noise. Of course, the signal also changes with spatial scale (*e.g.*, the modeled and observed surface warming over the 20th century is larger in the Arctic than for the global mean). In general, however, signal and noise are likely to be most easily separable in the global results.

Another problem relates to climate forcings. As attention shifts to smaller scales, it becomes more important to obtain reliable information about the climate forcings that have operated at these smaller scales. Some of these forcings are both uncertain and highly variable in space and time, and can have pronounced effects on local or even regional climate (90, 91). Examples include human-induced changes in land surface properties

(92) and in the concentrations of carbon-containing aerosols produced by the burning of fossil fuels and biomass (93, 94). Neglect or inaccurate specification of these heterogeneous forcings can hamper the identification of an anthropogenic fingerprint.

To date, most published D&A research relies on model simulations that do not include forcing by land-use changes and carbonaceous aerosols (95). Despite the exclusion of these forcings, and despite the signal-to-noise issues mentioned above, a number of authors have claimed that the combined and individual signals of greenhouse gases and sulfate aerosols are now identifiable at continental and sub-continental scales in many different regions around the globe (96, 97, 98, 99).

Related work (100, 101) suggests that an anthropogenic climate signal has already emerged from the background noise at even smaller spatial scales (at or below 500 km) (102), and may be contributing to regional changes in the distributions of plant and animal species (103). This new body of regional D&A research provides preliminary evidence that we are on the verge of detecting human effects on climate at scales of direct relevance to policymakers.

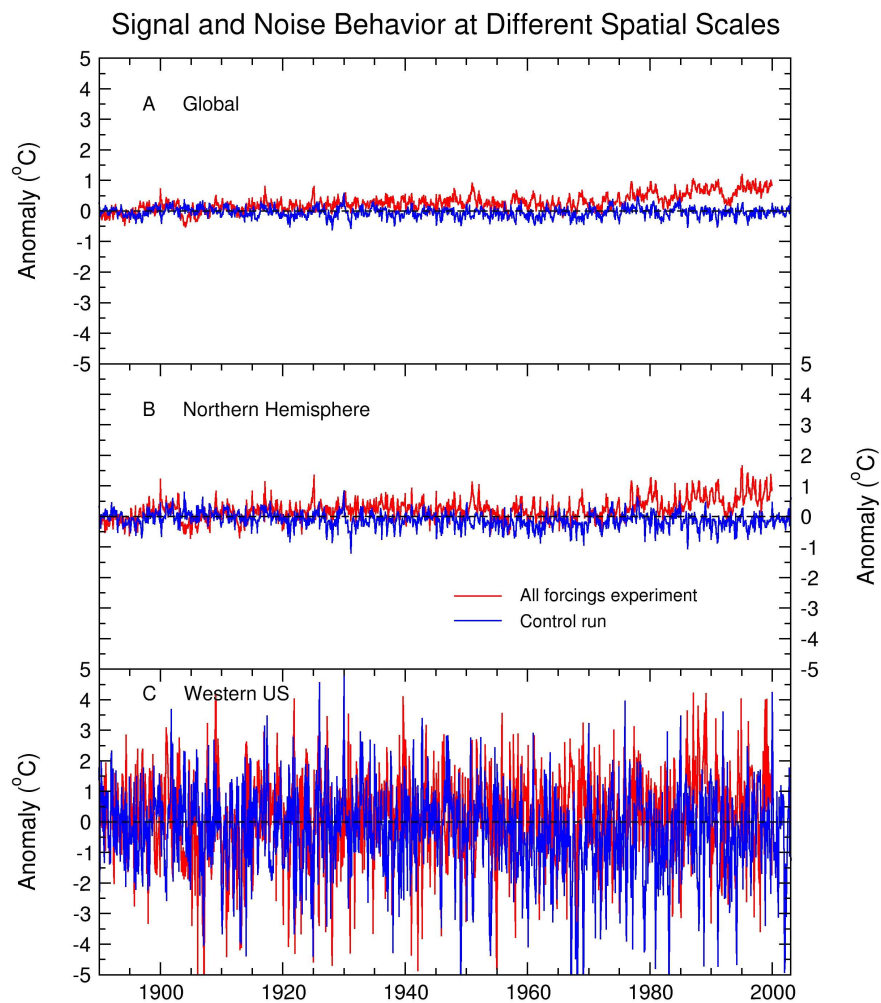


Figure 4: Simulated near-surface (2-meter) temperature changes averaged over the globe (A), the Northern Hemisphere (B), and the Western U.S. (30°N-50°N, 126°W-114°W; C). Results are from an “unforced” control run with no time-varying changes in natural or anthropogenic external forcings, and from an experiment (“All forcings”) with estimated historical changes in well-mixed greenhouse gases, sulfate aerosol direct effects, tropospheric and stratospheric ozone, solar irradiance, and volcanic aerosols. Both simulations were performed with the Parallel Climate Model (8). All monthly-mean temperature changes are defined relative to climatological monthly means calculated over 1890 to 1909. The “All forcings” run ends in December 1999.



## 2.4 *Assessing Risks of Changes in Extreme Events*

In the aftermath of the severe European summer heat wave of 2003 (104) and the anomalously active 2005 Atlantic hurricane season (105), questions are frequently posed regarding the relationship between human-caused climate change and changes in the frequency, intensity, and duration of extreme events. Are individual extreme events like hurricane Katrina simply “Acts of God”? (106) Or has human-induced climate change somehow influenced the severity of such events?

The standard (and correct) scientific answer to such questions is that we cannot confidently attribute any specific extreme event to human-induced climate change (107). However, we are capable of making informed scientific statements regarding the influence of human activities on the likelihood of extreme events (107, 108). This is an important distinction.

As noted previously, climate models can be used to perform the control experiment (no human effects on climate) that we cannot perform in the real world. Using the “unforced” climate variability from a multi-century control run, it is possible to determine how many times an extreme event of a given magnitude should have been observed in the absence of human interference. The probability of obtaining the same extreme event is then calculated in a perturbed climate – for example, in a model experiment with historical or future increases in anthropogenic forcings, or under some specified change in mean climate (104, 108). Comparison of the frequencies of extremes in the control and perturbed experiments allows one to make probabilistic statements about how human-induced climate change may have altered the likelihood of the extreme event (107, 109, 110). This is sometimes referred to as an assessment of “fractional attributable risk” (104).

Recently, a “fractional attributable risk” study involving the European summer heat wave of 2003 concluded that “there is a greater than 90% chance that over half the risk of European summer temperatures exceeding a threshold of 1.6 K is attributable to human influence on climate” (104). A similar investigation into the causes of sea-surface

temperature (SST) increases in Atlantic and Pacific hurricane formation regions found “an 84% chance that external forcing explains at least 67% of observed SST increases in the two tropical cyclogenesis regions” (42). The causes of SST changes in these hurricane breeding grounds are of considerable interest given scientific evidence of a link between rising SSTs and increases in hurricane intensity (111, 112).

These and related studies illustrate how the D&A community has moved beyond analysis of changes in the mean state of the climate, and now applies rigorous statistical methods to the problem of estimating how human activities may alter (or have altered) the probability of occurrence extreme events. Demonstration of human culpability in changing these risks is likely to have significant implications for the debate on policy responses to climate change.

### **3. Conclusions**

In evaluating how well a novel has been crafted, it is important to look at the internal consistency of the plot. Critical readers examine whether the individual storylines are neatly woven together, and whether the internal logic makes sense.

We can ask similar questions about the “story” contained in observational records of climate change. The evidence from numerous sources (paleoclimate data, rigorous fingerprint studies, and qualitative comparisons of modeled and observed climate changes) shows that the climate system is telling us an internally consistent story about the causes of recent climate change.

Over the last century, we have observed large and coherent changes in many different aspects of Earth’s climate. The oceans and land surface have warmed (24, 25, 26, 32, 33, 34, 113). Atmospheric moisture has increased (30, 31). Glaciers have retreated over most of the globe (114, 115). Sea level has risen (116). Snow and sea-ice extent have decreased in the Northern Hemisphere (117). The stratosphere has cooled (118), and there are now reliable indications that the troposphere has warmed (13, 17, 56,

57, 58, 59, 60, 61, 63, 67, 75). The height of the tropopause has increased (28). Individually, all of these changes are consistent with our scientific understanding of how the climate system should be responding to anthropogenic forcing. Collectively, this behavior is inconsistent with the changes that we would expect to occur due to natural variability alone.

There is now compelling scientific evidence that human activities have had a discernible influence on global climate. However, there are still significant uncertainties in our estimates of the size and geographical distribution of the climate changes projected to occur over the 21<sup>st</sup> century (9). These uncertainties make it difficult for us to assess the magnitude of the mitigation and adaptation problem that faces us and our descendants. The dilemma that confronts us, as citizens and stewards of this planet, is how to act in the face of both hard scientific evidence that our actions are altering global climate and continuing uncertainty in the magnitude of the planetary warming that faces us.

## References and Endnotes

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- 1 Houghton, J.T., *et al.*, 1990: *Climate Change. The IPCC Scientific Assessment*. Cambridge University Press, Cambridge, U.K., page xxix.
- 2 Houghton, J.T., *et al.*, 1996: *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge, U.K., page 4.
- 3 Wigley, T.M.L., 1989: Possible climatic change due to SO<sub>2</sub>-derived cloud condensation nuclei. *Nature*, **339**, 365-367.
- 4 Hasselmann, K., 1979: On the signal-to-noise problem in atmospheric response studies. In: *Meteorology of Tropical Oceans* (Ed. D.B. Shaw). Royal Meteorological Society of London, London, U.K., pp. 251-259.
- 5 Hasselmann, K., 1993: Optimal fingerprints for the detection of time dependent climate change. *Journal of Climate*, **6**, 1957-1971.
- 6 North, G.R., K.Y. Kim, S.S.P Shen, and J.W. Hardin, 1995: Detection of forced climate signals. Part I: Filter theory. *Journal of Climate*, **8**, 401-408.
- 7 Houghton, J.T., *et al.*, 2001: *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge, U.K., page 4.
- 8 Washington, W.M. *et al.*, 2000: Parallel Climate Model (PCM) control and transient simulations. *Climate Dynamics*, **16**, 755-774.
- 9 IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 10 IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, M. *et al.* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 11 NRC (National Research Council), 2001: *Climate Change Science. An Analysis of Some Key Questions*. Board on Atmospheric Sciences and Climate, National Academy Press, Washington D.C., 29 pp.
- 12 Prior to the Gleneagles G8 summit in July 2005, the Science Academies of 11 nations issued a joint statement on climate change (<http://www.nasonline.org/site>). The statement affirmed the IPCC finding that "most of the warming observed over the last 50 years is attributable to human activities" (Houghton *et al.*, 2001). The signatories were from the Academia Brasileira de Ciências, the Royal Society of Canada, the Chinese Academy of Sciences, the Academié des Sciences, France, the Deutsche Akademie der Naturforscher, the Indian National Science Academy, the Accademia dei Lincei, Italy, the Science Council of Japan, the Russian Academy of Sciences, the United Kingdom Royal Society, and the U.S. National Academy of Sciences.
- 13 Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.), 2006: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 164 pp.

- 14 Mann, M.E., and P.D. Jones, 2003: Global surface temperatures over the past two millenia. *Geophysical Research Letters*, **30**, 1820, doi:10.1029/2003GL017814.
- 15 Mitchell, J.F.B. *et al.*, 2001: Detection of climate change and attribution of causes. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al.*, (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.
- 16 IDAG (International Detection and Attribution Group), 2005: Detecting and attributing external influences on the climate system: A review of recent advances. *Journal of Climate*, **18**, 1291-1314.
- 17 Santer, B.D., J.E. Penner, and P.W. Thorne, 2006a: How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes? In: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, pp. 89-108.
- 18 Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, J.E. Penner and P.A. Stott, 2007: Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 19 A recent assessment of the U.S. National Academy of Sciences concluded that "It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries" (NAS, 2006, page 3). The same study also found "it plausible that the Northern Hemisphere was warmer during the last few decades of the 20th century than during any comparable period over the preceding millennium" (NAS, 2006, pages 3-4).
- 20 Examples include increases in surface and tropospheric temperature, increases in atmospheric water vapor and ocean heat content, sea-level rise, widespread retreat of glaciers, *etc.*
- 21 Allen, M.R. *et al.*, 2007: Quantifying anthropogenic influence on recent near-surface temperature. *Surveys in Geophysics* (in press).
- 22 An example includes testing the null hypothesis that there has been no external forcing of the climate system against the alternative hypothesis that there has been significant external forcing. Currently, all such hypothesis tests rely on model-based estimates of "unforced" climate variability (also known as natural internal variability). This is the variability that arises solely from processes internal to the climate system, such as interactions between the atmosphere and ocean. The El Niño phenomenon is a well-known example of internal climate noise. In contrast, "total" natural variability incorporates both internal noise and the effects of natural external forcings (changes in solar irradiance and the volcanic dust loading of the atmosphere). Our own unpublished work shows that anthropogenic forcing can be detected against "total" natural variability about as well as we can detect the signal arising from combined anthropogenic and natural external forcing against the background of unforced variability. Figure 2 shows estimates of "total" natural variability.
- 23 Leading fingerprint practitioners include groups at the Canadian Climate Centre, the Climatic Research Unit, the Geophysical Fluid Dynamics Laboratory, the Hadley Centre for Climate Prediction and Research, the Jet Propulsion Laboratory, Lawrence Livermore National Laboratory, the Massachusetts Institute of Technology, the Max-Planck Institute for Meteorology, the National

Center for Atmospheric Research, Oklahoma State University, Oxford University, Scripps Institution of Oceanography, and Texas A&M University.

- 24 Barnett, T.P., D.W. Pierce, and R. Schnur, 2001: Detection of anthropogenic climate change in the world's oceans. *Science*, **292**, 270-274.
- 25 Barnett, T.P. *et al.*, 2005: Penetration of human-induced warming into the world's oceans. *Science*, **309**, 284-287.
- 26 Pierce, D.W. *et al.*, 2006: Anthropogenic warming of the oceans: Observations and model results. *Journal of Climate* (in press).
- 27 Gillett, N.P., F.W. Zwiers, A.J. Weaver, and P.A. Stott, 2003: Detection of human influence on sea level pressure. *Nature*, **422**, 292-294.
- 28 Santer, B.D. *et al.*, 2003: Contributions of anthropogenic and natural forcing to recent tropopause height changes. *Science*, **301**, 479-483.
- 29 Zhang, X. *et al.*, 2007: Detection of human influence on 20th century precipitation trends. *Nature* (in press).
- 30 Santer, B.D., *et al.*, 2007: Identification of human-induced changes in atmospheric moisture content. *Proceedings of the U.S. National Academy of Sciences* (submitted).
- 31 Trenberth, K.E., J. Fasullo, and L. Smith, 2005: Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics*, **24**, doi:10.1007/s00382-005-0017-4.
- 32 Levitus, S. *et al.*, 2001: Anthropogenic warming of Earth's climate system. *Science*, **292**, 267-270.
- 33 Levitus, S., J.I. Antonov, and T.P. Boyer, 2005: Warming of the world ocean, 1955-2003. *Geophysical Research Letters*, **32**, L02604, doi:10.1029/2004GL021592.
- 34 Jones, P.D., M. New, D.E. Parker, S. Martin, and I.G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, **37**, 173-199.
- 35 Prof. Richard Lindzen, Kuehnast Lecture Series, "Global climate change: Uncertainties, risks, and values in determining public policy", University of Minnesota, October 11th, 2002. The argument here is that some anthropogenic "forcings" of climate (particularly the so-called indirect forcing caused by the effects of anthropogenic aerosols on cloud properties) are highly uncertain, so that many different combinations of these factors could yield the same global-mean changes. While this is a valid concern for global-mean temperature changes, it is highly unlikely that different combinations of forcing factors could produce the same complex spatio-temporal patterns of climate change (see Figure 1).
- 36 For example, some 'solar enthusiasts' have argued that all of the observed near-surface warming over the 20th century is attributable to an overall increase in solar irradiance. The effect of such an increase would be to warm most of the atmosphere (from Earth's surface through to the stratosphere; see Figure 1A). Such behavior is not seen in observations. While temperature measurements from satellites and radiosondes do show warming of the troposphere, they also indicate that the stratosphere has cooled over the past 2-4 decades (13). Stratospheric cooling is fundamentally inconsistent with a 'solar forcing only' hypothesis of observed climate change, but is consistent with simulations of the response to anthropogenic GHG increases and ozone decreases (Figures 1C and D, respectively). The possibility of a large solar forcing effect has been further weakened by recent research indicating that changes in solar luminosity on multi-decadal timescales are likely to be significantly smaller than previously thought (37, 38).

- 37 Foukal, P., G. North, and T.M.L. Wigley, 2004: A stellar view on solar variations and climate. *Science*, **306**, 68-69.
- 38 Foukal, P., C. Fröhlich, H. Spruit, and T.M.L. Wigley, 2007: Physical mechanisms of solar luminosity and its effect on climate. *Nature* (in press).
- 39 In order to assess whether observed climate changes over the past century are truly unusual, we require information on the amplitude and structure of climate noise on timescales of a century or longer. Unfortunately, direct instrumental measurements are of insufficient length to provide such information. This means that D&A studies must rely on decadal- to century-timescale noise estimates from climate model control runs.
- 40 Allen, M.R., and S.F.B. Tett, 1999: Checking for model consistency in optimal fingerprinting. *Climate Dynamics*, **15**, 419-434.
- 41 Thorne, P.W. *et al.*, 2003: Probable causes of late twentieth century tropospheric temperature trends. *Climate Dynamics*, **21**, 573-591.
- 42 Santer, B.D. *et al.*, 2006: Causes of ocean surface temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proceedings of the National Academy of Sciences*, **103**, 13905-13910.
- 43 AchutaRao, K.M., M. Ishii, B.D. Santer, P.J. Gleckler, K.E. Taylor, T.P. Barnett, D.W. Pierce, R.J. Stouffer, and T.M.L. Wigley, 2007: Simulated and observed variability in ocean temperature and heat content. *Proceedings of the National Academy of Sciences*, **104**, [www.pnas.org/cgi/doi/10.1073/pnas.0611375104](http://www.pnas.org/cgi/doi/10.1073/pnas.0611375104).
- 44 See, for example, an op-ed by James Schlesinger (former Secretary of Energy, Secretary of Defense, and Director of the CIA) in the January 22, 2004 edition of the *Los Angeles Times*. Mr. Schlesinger noted that "...the theory that increasing concentrations of greenhouse gases like carbon dioxide will lead to further warming is at least an oversimplification. It is inconsistent with the fact that satellite measurements over 35 years (*sic*) show no significant warming in the lower atmosphere, which is an essential part of the global-warming theory".
- 45 The designations  $T_4$  and  $T_2$  reflect the fact that the original MSU measurements employed MSU channels 4 and 2 (subsequently replaced by equivalent data from other channels in the latest Advanced Microwave Sounding Units). The bulk of the microwave emissions monitored by channel 2 is from roughly 14 to 29 km above Earth's surface (150 to 15 hPa). Channel 2 primarily samples emissions from the surface to 18 km (75 hPa). The  $T_{2LT}$  retrieval is constructed using the outer and inner "scan angles" of channel 2 (Spencer and Christy, 1992b), and is a measure of temperatures from the surface to 8 km (350 hPa). For further details of the atmospheric layers sampled by MSU, see (13) (their Table 2 and Figure 2.2).
- 46 Spencer, R.W., and J.R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science*, **247**, 1558-1562.
- 47 Spencer, R.W., and J.R. Christy, 1992: Precision and radiosonde validation of satellite grid-point temperature anomalies, Part I, MSU channel 2. *Journal of Climate*, **5**, 847-857.
- 48 Spencer, R.W., and J.R. Christy, 1992: Precision and radiosonde validation of satellite grid-point temperature anomalies, Part II, A tropospheric retrieval and trends during 1979-90. *Journal of Climate*, **5**, 858-866.

- 49 Christy, J.R., R.W. Spencer, W.B. Norris, W.D. Braswell, and D.E. Parker, 2003: Error estimates of version 5.0 of MSU-AMSU bulk atmospheric temperatures. *Journal of Atmospheric and Oceanic Technology*, **20**, 613-629.
- 50 The true degree of independence is uncertain. In their early work, the UAH group apparently relied on radiosonde-derived temperatures to choose between different possible “adjustment pathways” in the complex process of correcting MSU data for known inhomogeneities (51).
- 51 Christy, J.R., R.W. Spencer, and E.S. Lobl, 1998: Analysis of the merging procedure for the MSU daily temperature time series. *Journal of Climate*, **11**, 2016-2041.
- 52 Wentz, F.J., and M. Schabel, 1998: Effects of orbital decay on satellite-derived lower-tropospheric temperature trends. *Nature*, **394**, 661-664.
- 53 In the RSS analysis, accounting for orbital decay effects changed the global-mean  $T_{2LT}$  trend from -0.05 to +0.07°C/decade over 1979-1995.
- 54 Christy, J.R., R.W. Spencer, and W.D. Braswell, 2000: MSU Tropospheric temperatures: Data set construction and radiosonde comparisons. *Journal of Atmospheric and Oceanic Technology*, **17**, 1153-1170.
- 55 The three groups involved were at RSS (56), the University of Maryland (UMD) (57, 58), and the University of Washington/NOAA (UW) (59, 60). The RSS and UMD groups independently reprocessed the raw  $T_2$  data used by UAH, using different adjustment procedures to account for orbital drift and IBE effects. In the RSS and UMD analyses, the mid- to upper troposphere warmed by 0.1 to 0.2°C/decade over the satellite era (56, 57, 58). These values were substantially larger than the satellite era  $T_2$  trends estimated by UAH, which ranged from 0.02 to 0.04°C/decade (49, 54). The UW group applied a statistical approach to quantify and remove the influence of stratospheric cooling on MSU  $T_2$  data (59, 60). This enhanced the estimated warming of the mid- to upper troposphere in both the UAH and RSS datasets. The approach also highlighted the physically-implausible behavior of the UAH group’s tropical  $T_2$  and  $T_{2LT}$  trends, which showed sustained warming and cooling (respectively) of adjacent layers of the troposphere (60).
- 56 Mears, C.A., M.C. Schabel, and F.W. Wentz, 2003: A reanalysis of the MSU channel 2 tropospheric temperature record. *Journal of Climate*, **16**, 3650-3664.
- 57 Vinnikov, K.Y., and N.C. Grody, 2003: Global warming trend of mean tropospheric temperature observed by satellites. *Science*, **302**, 269-272.
- 58 Vinnikov, K.Y. *et al.*, 2006: Temperature trends at the surface and the troposphere. *Journal of Geophysical Research*, doi:10.1029/2005jd006392.
- 59 Fu, Q., C.M. Johanson, S.G. Warren, and D.J. Seidel, 2004: Contribution of stratospheric cooling to satellite-inferred tropospheric temperature trends. *Nature*, **429**, 55-58.
- 60 Fu, Q., and C.M. Johanson, 2005: Satellite-derived vertical dependence of tropical tropospheric temperature trends. *Geophysical Research Letters*, **32**, L10703, doi:10.1029/2004GL022266.
- 61 Sherwood, S.C., J. Lanzante, and C. Meyer, 2005: Radiosonde daytime biases and late 20th century warming. *Science*, **309**, 1556-1559.
- 62 Randel, W.J., and F. Wu, 2007: Biases in stratospheric temperature trends derived from historical radiosonde data. *Journal of Climate* (in press).



- 63 Mears, C.A., and F.W. Wentz, 2005: The effect of diurnal correction on satellite-derived lower tropospheric temperature. *Science*, **309**, 1548-1551.
- 64 The RSS estimate of the global-mean  $T_{2LT}$  trend over 1979 to 2003 was 0.1 °C/decade warmer than the UAH estimate (0.193 versus 0.087 °C/decade, respectively). Differences were even larger in the tropics, where the lower troposphere cooled in the UAH data (by 0.015 °C/decade), but warmed markedly in the RSS analysis (by 0.189 °C/decade) (63).
- 65 Christy, J.R., and R.W. Spencer, 2005: Correcting temperature data sets. *Science*, **310**, 972.
- 66 The UAH global-mean  $T_{2LT}$  trend over December 1978 to July 2005 increased by only 0.035 °C/decade (to 0.123 °C/decade). This change was stated to be “within our previously published error margin of  $\pm 0.05K/decade$ ” (65).
- 67 Santer, B.D. *et al.*, 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science*, **309**, 1551-1556.
- 68 Hess, S.L., 1959. *Introduction to Theoretical Meteorology*. Holt, Rinehart and Winston, New York, 362 pp.
- 69 Horel, J.D., and J.M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Monthly Weather Review*, **109**, 813-829.
- 70 Wentz, F.J., and M. Schabel, 2000: Precise climate monitoring using complementary satellite data sets. *Nature*, **403**, 414-416.
- 71 Manabe, S., and R.J. Stouffer, 1980: Sensitivity of a global climate model to an increase of CO<sub>2</sub> concentration in the atmosphere. *Journal of Geophysical Research*, **85**, 5529-5554.
- 72 Hurrell, J.W. and Trenberth, K.E. 1998: Difficulties in obtaining reliable temperature trends: Reconciling the surface and satellite microwave sounding unit records. *Journal of Climate*, **11**, 945-967.
- 73 Hegerl, G.C., and J.M. Wallace, 2002: Influence of patterns of climate variability on the difference between satellite and surface temperature trends. *Journal of Climate*, **15**, 2412-2428.
- 74 The term “lapse rate” describes the overall decrease in temperature with increasing height above the Earth’s surface. Where atmospheric moisture levels are very low, temperatures decrease by roughly 9.8 °C/km, with the rate of decrease (the dry adiabatic lapse rate, or DALR) virtually independent of height. This constancy of the DALR requires temperature changes to be very similar at the surface and in the troposphere. In broad areas of the tropics, however, temperatures behave according to a moist adiabatic lapse rate (MALR), with much smaller decreases with height (as low as 4 °C/km in the lower troposphere). In regions where the vertical profile of temperature is determined by the MALR, temperature changes in the lower and mid-troposphere are larger than at the surface (see Figure 3). For example, an increase in surface temperature of 1K (*e.g.*, from 293 to 294K) yields a temperature change of approximately 1.4K at 3.5 km (*e.g.*, from 276.4 to 277.8K (70)).
- 75 Wigley, T.M.L. *et al.*, 2006: Executive Summary. In: *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, pp. 1-14.
- 76 Prolonged surface warming should destabilize tropical temperature profiles, thus producing the conditions necessary for moist convection and readjustment of atmospheric temperatures to a moist adiabatic lapse rate (67).

- 77 After spending over two years in an exhaustive review of this issue, the first scientific deliverable under the U.S. Climate Change Science Plan concluded that “Previously reported discrepancies between the amount of warming near the surface and higher in the atmosphere have been used to challenge the reliability of climate models and the reality of human-induced global warming. Specifically, surface data showed substantial global-average warming, while early versions of satellite and radiosonde data showed little or no warming above the surface. This significant discrepancy no longer exists...” (13).
- 78 Collins, W.D. *et al.*, 2006: The Community Climate System Model: CCSM3. *Journal of Climate*, **19**, 2122-2143.
- 79 Hegerl, G.C. *et al.*, 1996: Detecting greenhouse-gas-induced climate change with an optimal fingerprint method. *Journal of Climate*, **9**, 2281-2306.
- 80 Hegerl, G.C. *et al.*, 1997: Multi-fingerprint detection and attribution of greenhouse-gas- and aerosol-forced climate change. *Climate Dynamics*, **16**, 737-754.
- 81 North, G.R., and M.J. Stevens, 1998: Detecting climate signals in the surface temperature record. *Journal of Climate*, **11**, 563-577.
- 82 Tett, S.F.B., P.A. Stott, M.R. Allen, W.J. Ingram, and J.F.B. Mitchell, 1999: Causes of twentieth-century temperature change near the Earth's surface. *Nature*, **399**, 569-572.
- 83 Stott, P.A. *et al.*, 2000: External control of 20th century temperature by natural and anthropogenic forcings. *Science*, **290**, 2133-2137.
- 84 Stott, P.A., and S.F.B. Tett, 1998: Scale-dependent detection of climate change. *Journal of Climate*, **11**, 3282-3294.
- 85 One example is the correspondence between modeled and observed changes in the temperature difference between the Northern and Southern Hemispheres (NH and SH) (86). Changes in this difference over the 20th century are thought to be due to partly compensating factors: 1) radiative forcing differences (there is larger negative forcing from sulfate aerosols in the NH, reducing greenhouse-gas-induced warming in the NH relative to the SH (3); 2) hemispheric differences in the climate system's thermal inertia (the larger ocean area in the SH leads to more rapid warming in the NH); and 3) land/ocean differences in the climate sensitivity (which further enhances warming in the NH relative to the SH (87, 88).
- 86 Stott, P.A. *et al.*, 2006: Robustness of estimates of greenhouse attribution and observationally constrained predictions of global warming. *Journal of Climate*, **19**, 3055-3069.
- 87 Raper, S.C.B., T.M.L. Wigley, and R.A. Warrick, 1996: Global sea level rise: past and future. In: *Sea-Level Rise and Coastal Subsidence: Causes, Consequences and Strategies* [Milliman, J. and B.U. Haq 9eds.]. Kluwer Academic Publishers, Dordrecht, The Netherlands, 11-45.
- 88 Raper, S.C.B., J.M. Gregory, and T.J. Osborn, 2001: Use of an upwelling-diffusion energy balance climate model to simulate and diagnose A/OGCM results. *Climate Dynamics*, **17**, 601-613.
- 89 Wigley, T.M.L., and P.D. Jones, 1981: Detecting CO<sub>2</sub>-induced climatic change. *Nature*, **292**, 205-208.
- 90 Ramaswamy, V. *et al.*, 2001: Radiative forcing of climate change. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al.*, (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

- 91 NRC (National Research Council), 2005: *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties*. Board on Atmospheric Sciences and Climate, National Academy Press, Washington D.C., 168 pp.
- 92 Feddema, J. *et al.*, 2005: A comparison of a GCM response to historical anthropogenic land cover change and model sensitivity to uncertainty in present-day land cover representations. *Climate Dynamics*, **25**, 581-609.
- 93 Penner, J.E. *et al.*, 2001: Aerosols, their direct and indirect effects. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T. *et al.* (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.
- 94 Menon, S., J. Hansen, L. Nazarenko, and Y.F. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*, **297**, 2250-2253.
- 95 Many of the recent model simulations performed in support of the IPCC Fourth Assessment Report now include changes in land use and carbonaceous aerosols (17).
- 96 Stott, P.A., 2003: Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophysical Research Letters*, **30**, doi: 10.1029/2003GL017324.
- 97 Zwiers, F.W., and X. Zhang, 2003: Towards regional-scale climate change detection. *Journal of Climate*, **16**, 793-797.
- 98 Karoly, D.J. *et al.*, 2003: Detection of a human influence on North American climate. *Science*, **302**, 1200-1203.
- 99 Min, S.-K., A. Hense, and W.-T. Kwon, 2005: Regional-scale climate change detection using a Bayesian detection method. *Geophysical Research Letters*, **32**, L03706, doi:10.1029/2004GL021028.
- 100 Karoly, D.J., and Q. Wu, 2005: Detection of regional surface temperature trends. *Journal of Climate*, **18**, 4337-4343.
- 101 Knutson, T.R. *et al.*, 2007: Assessment of twentieth-century regional surface temperature trends using the GFDL CM2 coupled models. *Journal of Climate* (in press).
- 102 Knutson *et al.* (101) state that their "regional results provide evidence for an emergent anthropogenic warming signal over many, if not most, regions of the globe".
- 103 Root, T.L., D.P. MacMynowski, M.D. Mastrandrea, and S.H. Schneider, 2005: Human-modified temperatures induce species changes: Joint attribution. *Proceedings of the National Academy of Sciences*, **102**, 7465-7469.
- 104 Stott, P.A., D.A. Stone, and M.R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **423**, 61-614.
- 105 Trenberth, K.E., and D.J. Shea, 2006: Atlantic hurricanes and natural variability in 2005. *Geophysical Research Letters*, **33**, L12704, doi:10.1029/2006GL026894.
- 106 Kennedy, D., 2006: Acts of God? *Science*, **311**, 303.
- 107 Allen, M.R., 2003: Liability for climate change. *Nature*, **421**, 891-892.

- 108 Wigley, T.M.L., 1988: The effect of changing climate on the frequency of absolute extreme events. *Climate Monitor*, **17**, 44-55.
- 109 Meehl, G.A., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994-997.
- 110 Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl, 2007: Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change* (in press).
- 111 Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686-688.
- 112 Hoyos, C.D., P.A. Agudelo, P.J. Webster, and J.A. Curry, 2006: Deconvolution of the factors contributing to the increase in global hurricane intensity. *Science*, **312**, 94-97.
- 113 Jones, P.D, and A. Moberg, 2003: Hemispheric and large scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate*, **16**, 206-223.
- 114 Arendt, A.A. *et al.*, 2002: Rapid wastage of Alaska glaciers and their contribution to rising sea level. *Science*, **297**, 382-386.
- 115 Paul, F., A. Kaab, M. Maisch, T. Kellenberger, and W. Haeberli, 2004: Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters*, **31**, L21402, doi:10.1029/2004GL020816.
- 116 Cazenave, A., and R.S. Nerem, 2004: Present-day sea level change: Observations and causes. *Reviews of Geophysics*, **42**, RG3001, doi:10.1029/2003RG000139.
- 117 Vinnikov, K.Y. *et al.*, 1999: Global warming and Northern Hemisphere sea ice extent. *Science*, **286**, 1934-1937.
- 118 Ramaswamy, V. *et al.*, 2006: Anthropogenic and natural influences in the evolution of lower stratospheric cooling. *Science*, **311**, 1138-1141.