nature geoscience
SUPPLEMENTARY INFORMATION
DOI: 10.1038/NGEO2248

Persistent growth of CO_2 emissions and implications for reaching climate targets

Friedlingstein P.[1*], R. M. Andrew[2], J. Rogelj[3,4], G.P. Peters[2], J.G. Canadell[5], R. Knutti[3], G. Luderer[6], M. Raupach[7], M. Schaeffer[8,9], D.P. van Vuuren[10,11], C. Le Quéré[12]

[1]College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK

[2]Center for International Climate and Environmental Research – Oslo (CICERO), PO Box 1129 Blindern, 0318 Oslo, Norway

[3]Institute for Atmospheric and Climate Science, ETH Zurich, CH-8092 Zurich, Switzerland

[4]Energy Program, International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

[5]Global Carbon Project, CSIRO Ocean and Atmosphere Flagship, Canberra, ACT 2601, Australia

[6]Potsdam Institute for Climate Impact Research (PIK), P.O. Box 601203, 14412 Potsdam, Germany.

[7]Climate Change Institute, Australian National University, Canberra, ACT 0200, Australia

[8]Climate Analytics, 10969 Berlin, Germany

[9]Environmental Systems Analysis Group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands

[10]PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands

[11]Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

[12]Tyndall Centre for Climate Change Research, University of East Anglia, Norwich Research Park, NR47TJ, UK

* Corresponding author, email p.friedlingstein@exeter.ac.uk

Supplementary Information

Cumulative budgets and uncertainty

The transient climate response to cumulative carbon emissions (TCRE) is a CO_2 only metric which quantifies the near-linear relationship between cumulative emissions of CO_2 and the global surface temperature response. TCRE is defined as the transient global average surface temperature change per unit cumulated CO_2 emissions; usually 1000 GtC (3664 $GtCO_2$). IPCC AR5 estimates TCRE as 0.8 to 2.5°C/1000GtC (valid up to about 2000 GtC and until the time temperatures peak)[1]. TCRE combines both information on the airborne fraction of cumulated CO_2 emissions (the fraction of the total CO_2 emitted that remains in the atmosphere), and on the transient climate response (the transient global temperature change for prescribed atmospheric CO_2 concentrations). The near-linear property of TCRE allows this metric to be used to estimate the probability to exceed a given temperature threshold for a given cumulative emissions. For example, accounting for CO_2 emissions only, climate change would be limited to 2°C with a 66% probability if CO_2 emissions were kept below 3670 $GtCO_2$ (4440 $GtCO_2$ for a 50% probability). This probability incorporates the uncertainty in TCRE.

To be applied in practical applications, the cumulative CO_2 emissions quota needs to account for the radiative forcing from non-CO_2 emissions. We do this using the full set of the scenarios from the IPCC AR5 WGIII database, spanning a relative large range of non-CO_2 versus CO_2 radiative forcing (Figure S1). To estimate this quota, each WGIII scenario was run (emission-driven) with MAGICC6 with 600 runs per scenario[2-4], exploring the range of uncertainty in climate (from IPCC AR4 climate models) and carbon cycle (from C^4MIP climate carbon cycle models) sensitivities. From these runs, the cumulative emissions are derived in line with a certain modelled likelihood (% of model runs) that a specified warming level is exceeded (e.g. 2°C, 3°C above the average over 1850-1900). This was repeated for the full data set of WGIII scenarios. This leads to a full range of cumulative emissions associated with the time of global average temperature increase exceeding the warming levels for a specified fraction of model runs (e.g. 66%, 50% modelled likelihood). Here we use the 5-95% of this full range, excluding extreme scenarios, and obtain e.g. 2900-3600 $GtCO_2$ as the 5-95% range of cumulative CO_2 emissions, accounting for non-CO_2 emissions, where warming is still below 2°C in 66% of model runs by the time the quota is exhausted. Table S1 gives the cumulative budgets (since 1870) still consistent with a 2°C and 3°C warming (since pre-industrial) with a 50 and 66% probability. We note that the exact quantification of the cumulative CO_2 emissions quota will vary with the set of scenario used, due to variations in the relative contribution of non-CO_2 radiative forcing. Here we use all available WG3 scenarios, to provide a cumulative CO_2 emission quota without any prior assumption on how the future will be in terms of emissions mitigation. One could decide to use high mitigation scenarios only, in order to estimate the cumulative CO_2 emissions quota from scenarios specifically designed to remain below a given climate target (as could be derived from the AR5 WG3 SPM Table SPM.1 where 21st century cumulative CO_2 emissions are given per WG3 scenario categories), or using one scenario only (as done in AR5 WG1 SPM where only the RCP scenarios were available). Because of the non-CO_2 forcing not being a constant fraction of the CO_2 forcing in the WG3 scenarios, with high mitigation scenarios having generally a higher non-CO_2/CO_2 forcing (Figure S1), cumulative CO_2 emissions quota derived from high mitigation scenarios are about 15% lower than quota derived from the full set of WG3 scenarios. For example, when estimated from the subset of WGIII scenarios for which at least 66% of the 600 climate simulations per scenario keep global mean warming below 2°C (above the 1850-1900 average), one find a cumulative CO_2 emissions quota of 2550-3150 $GtCO_2$, significantly lower than the 2900-3600 $GtCO_2$ range obtained when using all WG3 scenarios.

Remaining emission quota and equivalent emission-years

From the cumulative budget described above and the cumulative emissions up to date (2014 or 2019) we compute the remaining quota (from 2015 and from 2020 respectively) by difference. As cumulative budgets have a non-Gaussian, skewed distribution, one cannot calculate the uncertainty on the remaining quota by standard quadratic error propagation. We assume here that the uncertainty on remaining emission quota is the same as the uncertainty on the cumulative budget, i.e. neglecting the smaller (<10%) uncertainty on the historical budget. Remaining quotas are rounded to nearest 100 to account for the simplification adopted here in error propagation. Assuming Gaussian distributions gives the same rounded range of remaining quota for the 2°C target.

Equivalent emission-years are simply computed as the ratio of the remaining quota to the global annual CO_2 emission (37.0 $GtCO_2$ for 2014 and 46.5 $GtCO_2$ for 2019). The range in equivalent emission-years is obtained taking the range in remaining budget, neglecting the relatively small uncertainty on the global annual emission. The equivalent emission-years are only used to communicate the size of the remaining carbon budget compatible with a climate target given our current emission levels.

Growth rates

Growth rates between two years (e.g., 2012-2013) are based on the percentage increase over the first year

$$Growth = \frac{x_1 - x_0}{x_0} * 100\%$$

To prevent invalid interpretations of annual change we make leap year adjustments to these growth rates so that if *i* is a leap year:

$$x_i \rightarrow \frac{365}{366} x_i$$

and this causes growth rates to go up approximately 0.3% if the first year is a leap year and down 0.3% if the second year is a leap year.

Growth rates over more than two consecutive years are computed by taking the first derivative of the linear regression of the logarithm of all variables available in this time period. The quantity is called the Average Annual Growth Rate[5]

$$AAGR = \frac{d(\ln x)}{dt} * 100\% = \frac{1}{x}\frac{dx}{dt} * 100\%$$

Estimates of CO_2 emissions and Gross Domestic Product

Emissions from fossil-fuel combustion and cement production

Fossil-fuel combustion estimates up to 2010 are based on country-level UN energy statistics converted to carbon emissions by the Carbon Dioxide Information Analysis Center (CDIAC)[6]. We update both country-level and global emissions through to 2013 using the separate coal, oil, and gas consumption growth rates in BP's energy statistics[7]. Cement production estimates from the US Geological Survey[8] are similarly used to estimate changes in country-level cement emissions. Further details are found in the methodological description of the Global Carbon Budget[5].

Emission Uncertainty

We place an uncertainty of ±5% (1 standard deviation) on the fossil-fuel and cement emissions[5]. The uncertainty in the cumulative emissions will depend on the correlation between emission estimates over time. We tested a correlation coefficient of 0.9 that decays exponentially over time with a 20-year e-folding time as done for a recent carbon budget analysis[9]. We additionally assume uncertainty is higher in 1870 and declines to ±5% in 2000. Depending on assumptions of correlations and historical uncertainty, the uncertainty in cumulative emissions is ≈3-7%, and so we assume here for transparency a constant 5% uncertainty on cumulative CO_2 emissions, as for the annual emissions. We estimate the uncertainty on cumulative CO_2 emissions from fossil fuel from 1870 to 2014 to amounts to 70 $GtCO_2$.

We apply the same principles to the uncertainty in land-use change emissions, assuming an uncertainty in annual and cumulative emissions to be ±33% before the Mauna Loa record period (1959) and 0.5GtC yr^{-1} from 1958 onwards[5]. We estimate the uncertainty on cumulative CO_2 emissions from land-use changes from 1870 to 2014 to amounts to 190 $GtCO_2$.

Gross Domestic Product

We obtain country-level GDP estimates in purchasing-power parity terms from the IEA from 1971 to 2011[10], updated to 2013 (and beyond for our projections) using GDP growth rates from the IMF[11]. This data set provides a consistent constant price GDP at the country and global level in Market Exchange Rates and Purchasing Power Parity. We do not have direct estimates of the uncertainty in GDP, but estimate uncertainty in future growth rates (see below).

Trends and projections in E_{FF} at the regional and global level

Trends in I_{FF} at the regional and global level

The emission intensity of economic activity, I_{FF}, generally improves (i.e. declines) over time (Figures 1 and 2). At the global level, the rate of improvement has decreased over time, with the inflexion point coinciding with the rapid growth in Chinese emissions. The global emission intensity can be decomposed into components of country-level emissions E_i, emission intensity I_i, and GDP G_i as

$$I_{FF} = \frac{E_{FF}}{G} = \frac{\sum E_i}{G} = \frac{\sum I_i G_i}{G} = \sum I_i \frac{G_i}{G}$$

which shows that I_{FF} depends on the regional emission intensity and share of global GDP (G_i/G). This equation also gives a simple decomposition that can be normalised to I_{FF} (Figure S3c). Figure S3b shows that China's share of global GDP is increasing, and combined with a relatively large value of I_i for China (Figure 2) this leads to a growing Chinese contribution to I_{FF} at the global scale (Figure S3c). Since 2002, the deteriorating trend in I_{FF} is largely driven by China (and India to a lesser extent), combined with smaller contributions from the US and EU28. In particular, China's contribution to I_{FF} is larger than its contribution to global emissions (Figure S3a). These trends are expected to continue in the future in the absence of strong and globally coordinated climate policy.

Projections in CO_2 emissions at the regional and global level

Estimating future emissions is difficult, but the relatively linear trends in I_i and G_i over the previous 5-10 years (Figure 1 and 2) suggests that the simplified Kaya Identity is a relatively robust method of projecting emissions forward in the absence of large changes in climate policy and relatively stable development in GDP. The simplified Kaya Identity will lose explanatory power when breaks in historical trends occur, such as in China and India around 2000 and 2005 respectively (Figure 2) which would have led to underestimates in emissions, or when major economic events, such as the Global Financial Crisis, affect GDP growth rates.

We project emissions forward to 2019, using I_i and G_i in a simplified Kaya identity. In the absence of solid uncertainty data, we use sensitivity analysis to assess potential uncertainties in our emission estimates through to 2019. We use three types of sensitivities:

1. We use estimate trends in I_i based on the time periods 5, 10, and 20 years
2. Since 2008, the IMF World Economic Outlook publishes two forecasts (April and October) of GDP six years ahead. By combining these datasets from the period 2008-

2014 we can obtain an indication of the uncertainty in GDP growth estimates. We find that estimates of current year GDP (e.g., 2014 estimates of 2014 GDP) vary by ±1% at the global level, while estimates five years ahead are skew over the range [-2,0]%, i.e. more likely to be overestimated in the current time frame. The combined datasets indicate that forecasts for a year several years ahead have declined as that year approaches. The global economy is not recovering as quickly as expected from the Global Financial Crisis and it may be this continued failure of expectations that leads to the skewness we see in the forecasts, but the IMF six-year forecasts only started in 2008 and so we cannot estimate the level of skewness in the absence of the Global Financial Crisis. In general it seems reasonable to assume that unexpected events would be more likely to lead to lower global growth than higher global growth. Based on these analyses, we assume the current year GDP growth (2014 estimate of 2014) is ±1% and this changes linearly to the skew range of [-2,0]% in 2019.

3. Combining 1 and 2 requires further assumptions on the correlations between growth rates over time. For our projections, we assume there are no correlations over time. This is justified since financial crises are generally not anticipated. If crises were anticipated, counteracting measures would be put in place, potentially avoiding the crisis. Further, when a crisis occurs, countries put in measures to return to growth (as in the Global Financial Crisis of 2009). These measures in effect, break the potential correlation (e.g., consecutive years of negative growth, consecutive years of high growth). In effect, we simply assume that in each year, should growth be lower than expected then policies would be put in place to return economic growth towards its level based on long-term fundamentals.

When we combine the uncertainties, we take the range of CO_2 estimates (the extreme cases of GDP and I_{FF} growth together). The range in GDP growth has the biggest effect on the range in CO_2 emissions. We additionally add the ±5% uncertainty to the emission estimates. We only apply the uncertainty estimates at the global level, where inertia in the global economic system will smooth out potentially large regional variations. We do not characterise the uncertainty at the regional level due to the potential importance of unforeseen regional economic developments, but we acknowledge that the uncertainties may be large.

Regional projected trends in E_{FF}, GDP and I_{FF}

As presented at the global scale in Figure 4, we also analysed the 2010-2019 trends in CO_2 emissions, carbon intensity and GDP for the five regions defined by the integrated assessment models for the Representative Concentration Pathways database (OECD1990, EIT, ASIA, MAF, and LAM; see https://secure.iiasa.ac.at/web-apps/ene/AR5DB/ for their definition). Trends in the WGIII scenarios are compared to the trends projected in this study, taken from the IMF projections for GDP and the extrapolation of recent trends for I_{FF} (see above) (Figures S3 to S7).

In OECD90, during the period 2010-2019, the IPCC WGIII baseline scenarios have overestimated CO_2 emission growth due to overestimated GDP (Figure S4). In ASIA, the IPCC WGIII baseline scenarios have underestimated CO_2 emission growth due to overestimated improvements in I_{FF} (Figure S5). In EIT (Economies in Transition), the IPCC WGIII baseline scenarios have been consistent with recent trends (Figure S6). In MAF (Middle East and Africa), the IPCC WGIII baseline scenarios have been consistent with recent CO_2 trends, but this is due to an offset of overestimated GDP growth and underestimated I_{FF} (Figure S7). In LAM (Latin America and Caribbean), the IPCC WGIII baseline scenarios have been consistent with recent CO_2 trends, but this is due to an offset of overestimated GDP growth and underestimated I_{FF} (Figure S8).

References

1 Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner. in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley) Ch. 12, 1029-1136 (Cambridge University Press, 2013).

2 Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* **458**, 1158-1162, (2009).

3 Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6-Part 1: Model description and calibration. *Atmospheric Chemistry and Physics* **11**, 1417-1456, (2011).

4 Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old an new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change* **2**, 248-253, (2012).

5 Le Quéré, C. *et al.* Global carbon budget 2013. *Earth Syst. Sci. Data* **6**, 235-263, (2014).

6 Boden, T. A., Marland, G. & Andres, R. J. Global, Regional, and National Fossil-Fuel CO_2 Emissions in Trends. (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, http://cdiac.ornl.gov/, Oak Ridge, Tenn., U.S.A., 2013).

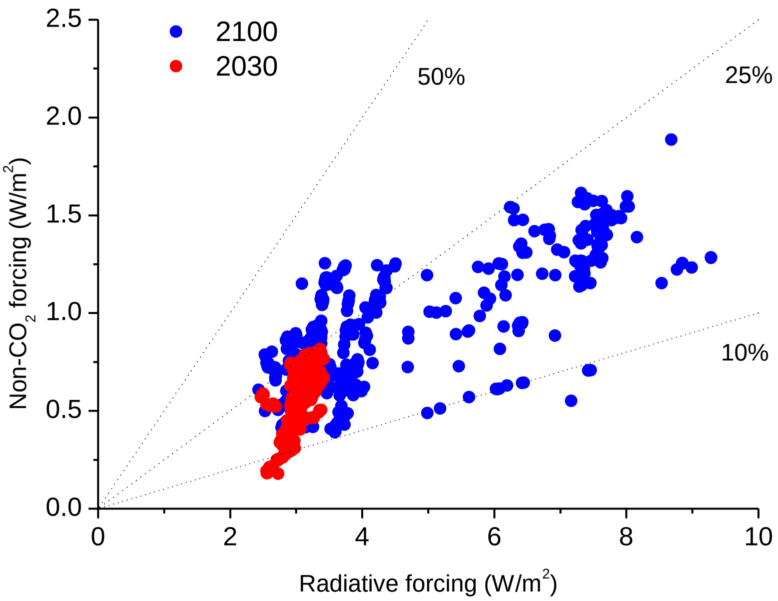
7 BP. *Statistical Review of World Energy 2013*, <http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html> (2013).

8 US Geological Survey. *Mineral Commodities Summaries*. (US Geological Survey, 2013).

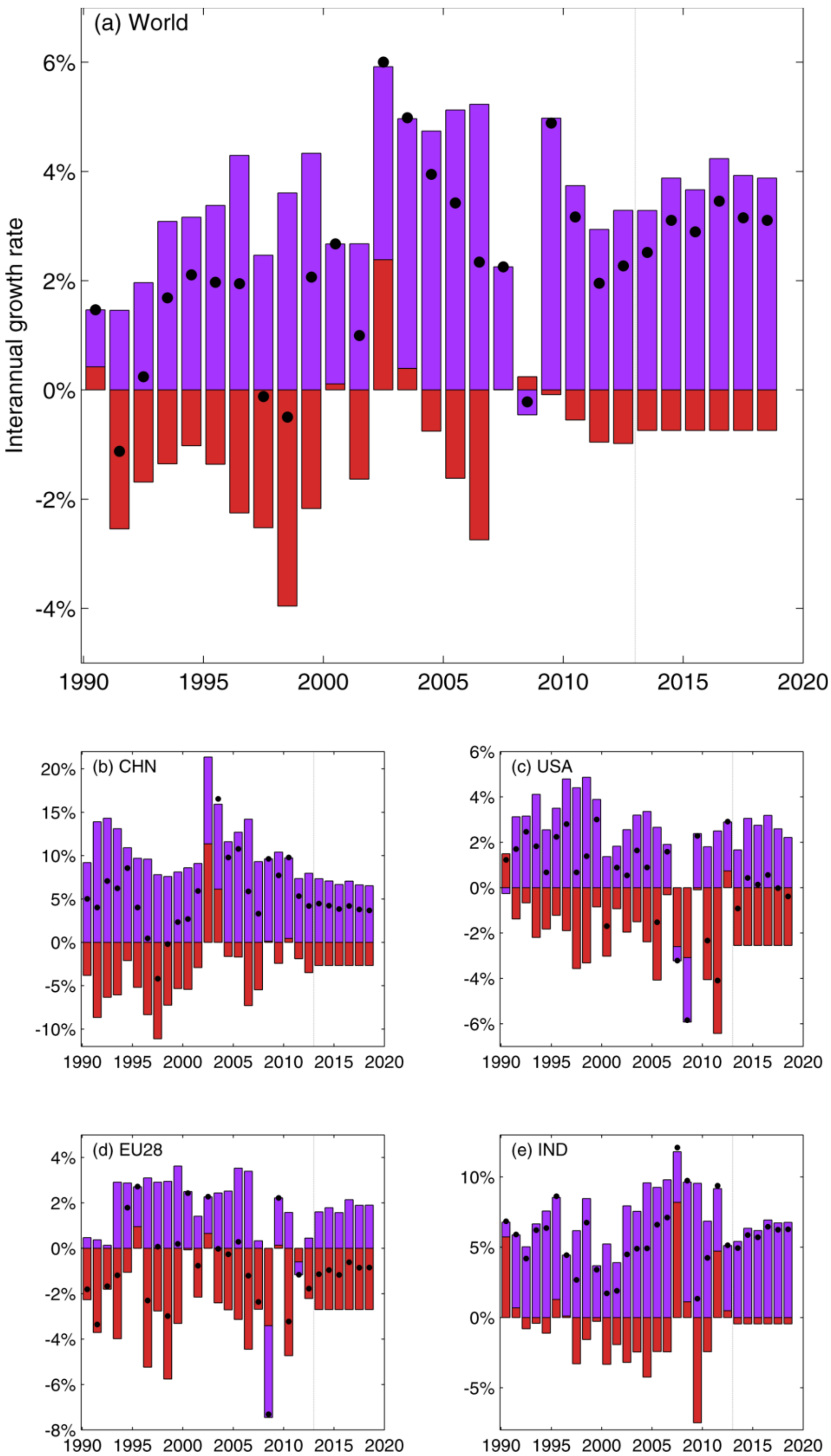
9 Ballantyne, A. P., Alden, C. B., Miller, J. B., Tans, P. P. & White, J. W. C. Increase in observed net carbon dioxide uptake by land and oceans during the last 50 years. *Nature* **488**, 70-72, (2012).

10 IEA/OECD. CO2 emissions from fuel combustion. (Paris, 2013).

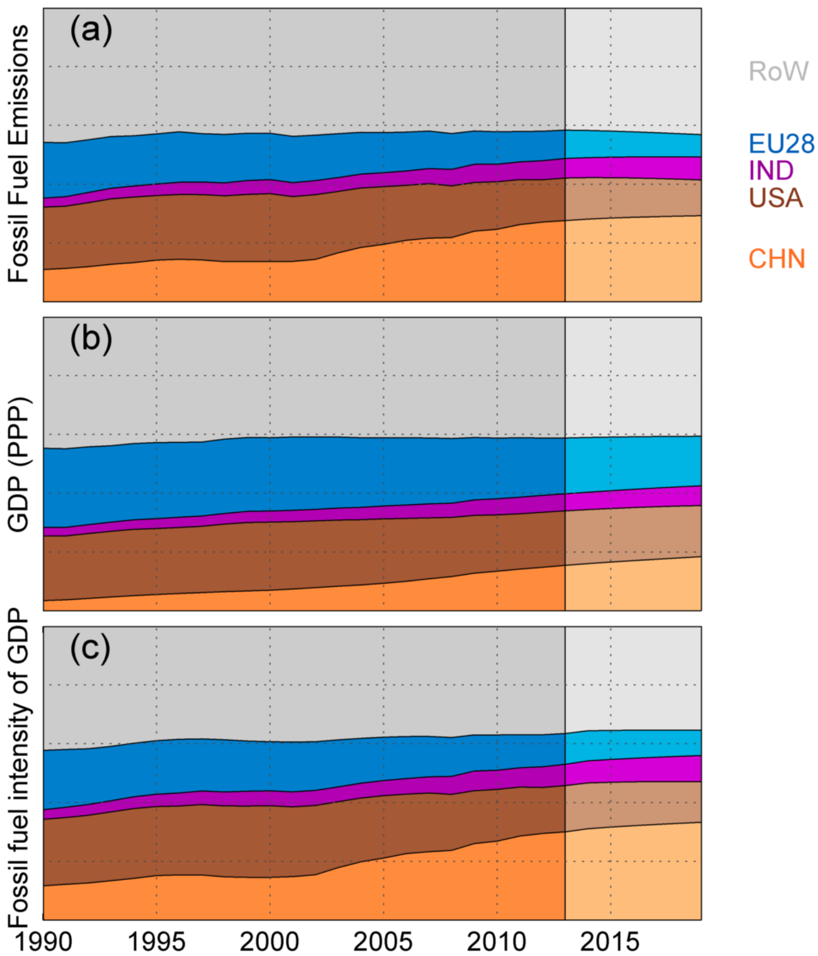
11 IMF. *World Economic Outlook of the International Monetary Fund*, <http://www.imf.org/external/ns/cs.aspx?id=29> (2014).



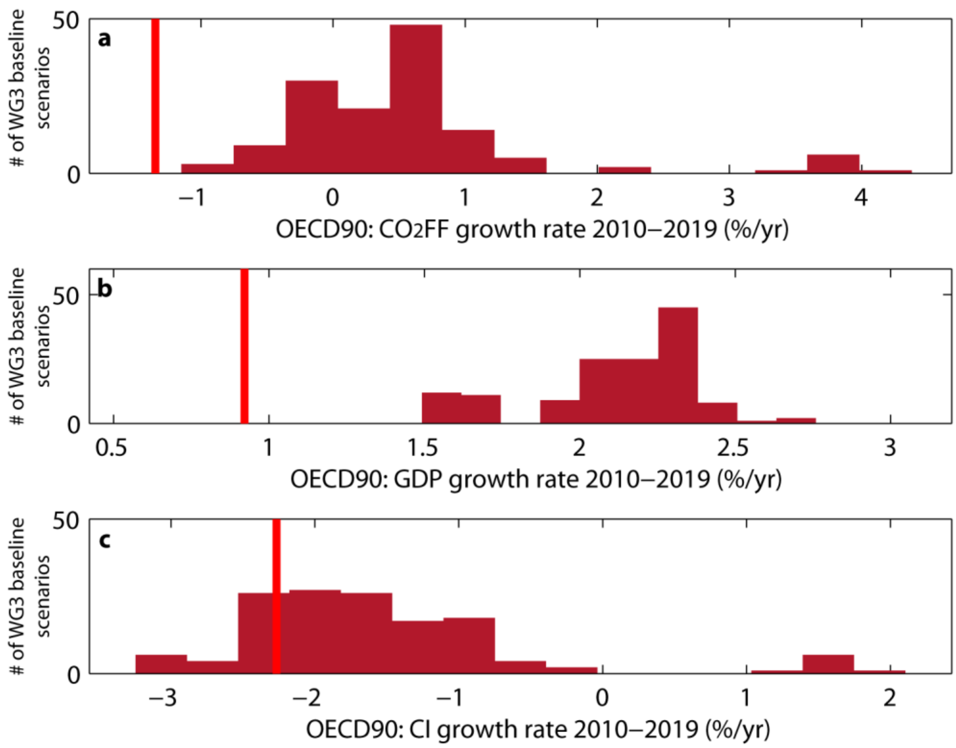
Supplementary Figure S1 | The radiative forcing from non-CO_2 (y-axis) and total radiative forcing (x-axis) for a range of scenarios in the IPCC WGIII scenario database.



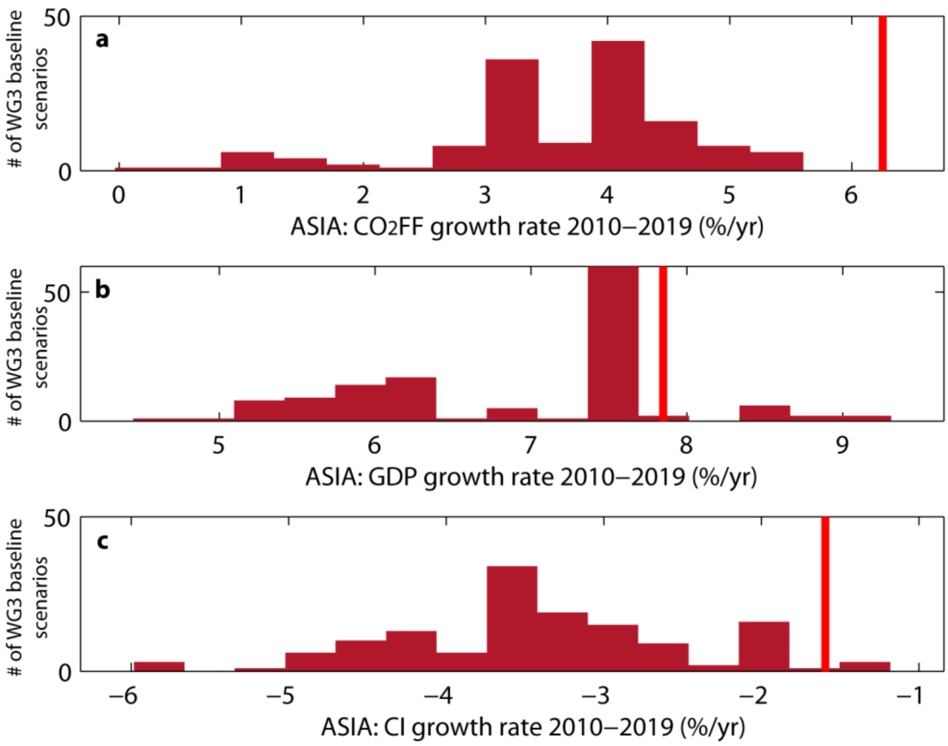
Supplementary Figure S2 | A decomposition using the simplified Kaya Identity of CO_2 emissions into GDP and I_{FF} (see Figure 2). The GDP growth is from the IMF statistics and I_{FF} is estimated based on historical data before 2013 and projected following our method from 2014 onwards. The growth rates have been adjusted for leap years.



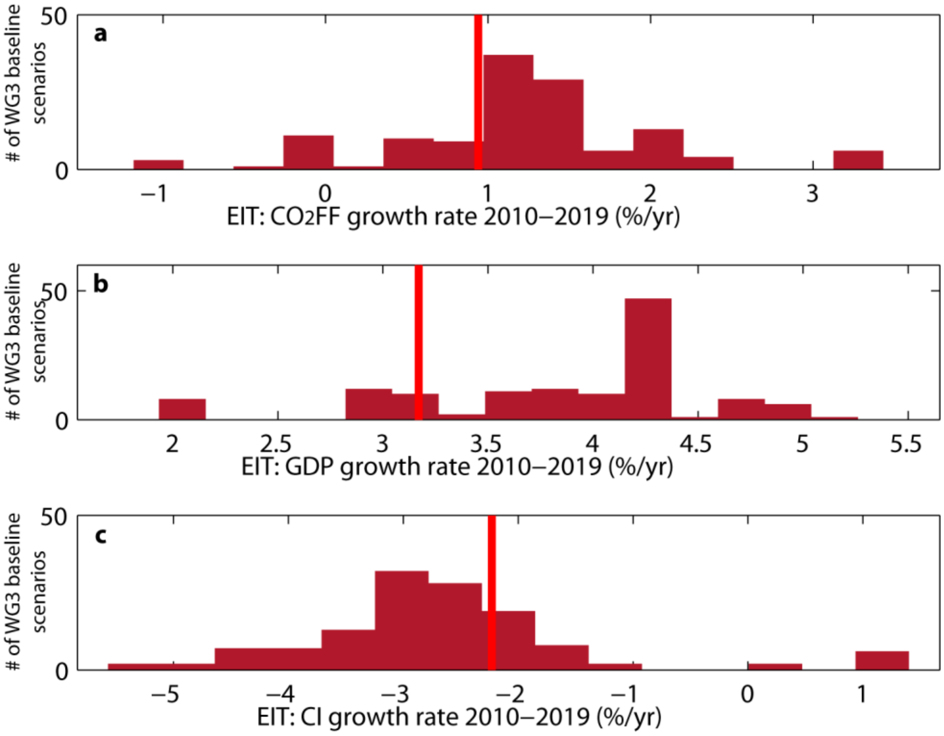
Supplementary Figure S3 | The share of global CO_2 emissions, GDP measured in purchasing power parity (PPP), and fossil fuel intensity of GDP amongst the four top emitters and the Rest of the World (RoW).



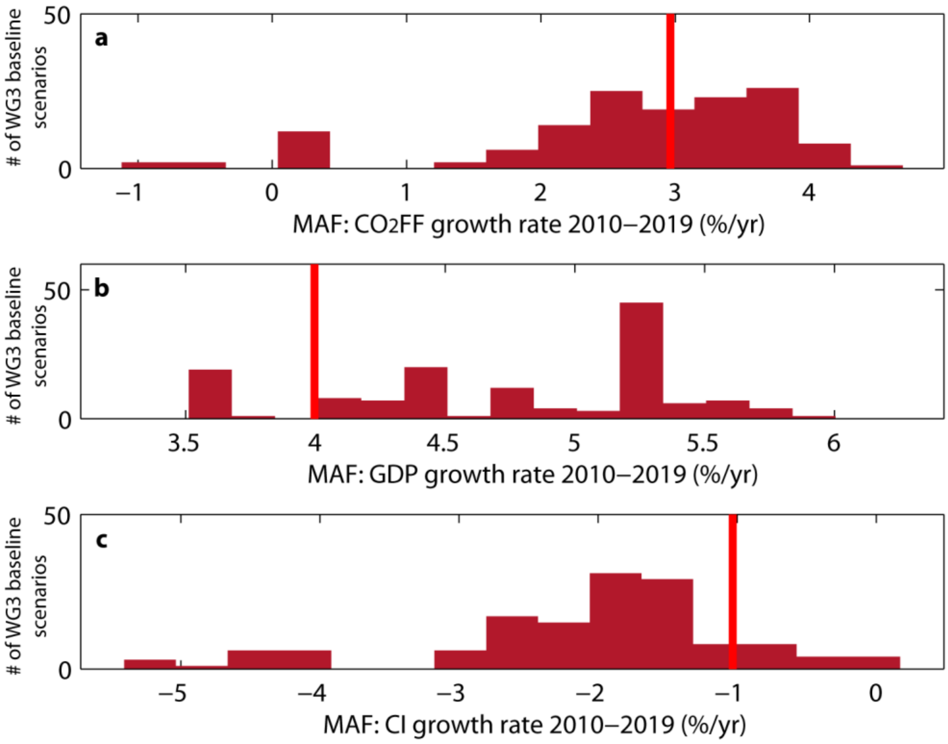
Supplementary Figure S4 | Comparison of near-term evolutions in WGIII baseline scenarios and recent trends for the OECD 1990 region. Data is provided for (a) carbon dioxide emissions from fossil fuel and industry growth rates from 2010 to 2019 (CO_2FF) (b) Gross Domestic Product (GDP) growth rates from 2010 to 2019, and (c) carbon intensity growth rates (CI) from 2010 to 2019. Negative growth rates imply a decline. Red histogram indicates the baseline scenarios available in the WGIII scenarios database. Red vertical lines indicate the regional values projections from this study.



Supplementary Figure S5 | Comparison of near-term evolutions in WGIII baseline scenarios and recent trends for the ASIA region. As in figure S4 but for the ASIA region.

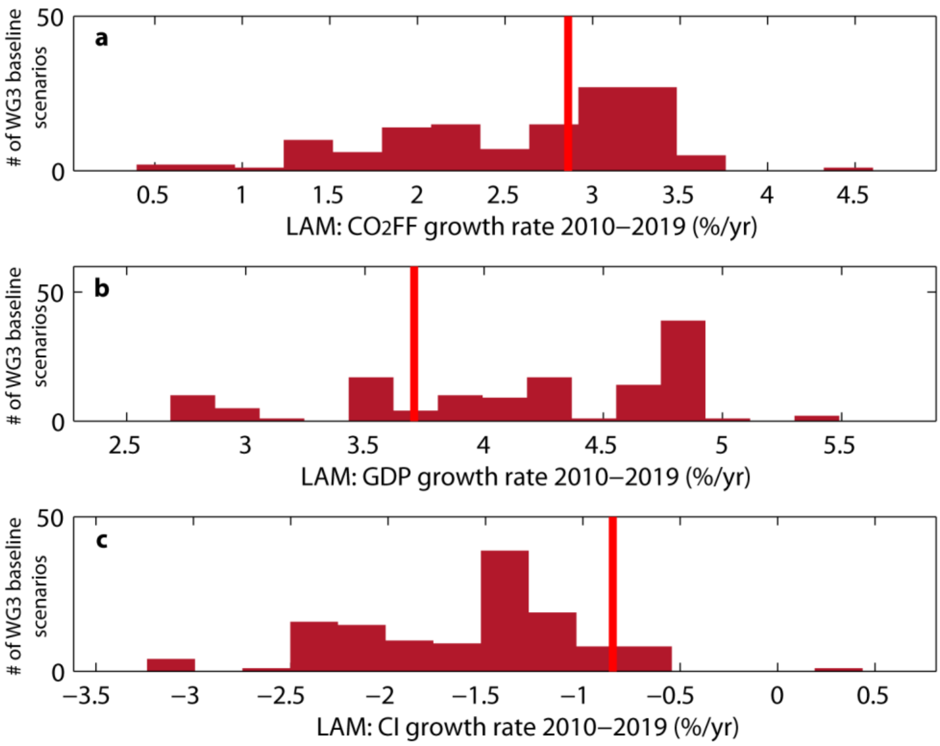


Supplementary Figure S6 | Comparison of near-term evolutions in WGIII baseline scenarios and recent trends for the EIT (Economies In Transition) region. As in figure S4 but for the EIT region.



Supplementary Figure S7 | Comparison of near-term evolutions in WGIII baseline scenarios and recent trends for the MAF (Middle East and Africa) region. As in figure S4 but for the MAF region.

.



Supplementary Figure S8 | Comparison of near-term evolutions in WGIII baseline scenarios and recent trends for the LAM (Latin America and Caribbean) region. As in figure S4 but for the LAM region.

Supplementary Table S1 | Cumulative emission since 1870 compatible with a 66% or 50% chance to remain below the 2°C and 3°C climate targets by the time the quota is exhausted. 1GtCO_2=3.664GtC.

	2°C		3°C	
	66%	50%	66%	50%
Cumulative emissions (GtCO_2)	2900-3600	3100-3900	4500-5700	5000-6200
Cumulative emissions (GtC)	790-985	845-1065	1230-1555	1365-1690