Young People's Burden: Requirement of Negative CO_2 Emissions

James Hansen,[1] Makiko Sato,[1] Pushker Kharecha,[1] Karina von Schuckmann,[2] David J. Beerling,[3] Junji Cao,[4] Shaun Marcott,[5] Valerie Masson-Delmotte,[6] Michael J. Prather,[7] Eelco J. Rohling,[8,9] Jeremy Shakun,[10] Pete Smith[11]

[1]Climate Science, Awareness and Solutions, Columbia University Earth Institute, New York, NY 10115 [2]Mercator Ocean, 10 Rue Hermes, 31520 Ramonville St Agne, France [3]Leverhulme Centre for Climate Change Mitigation, University of Sheffield, Sheffield S10 2TN, UK [4]Key Lab of Aerosol Chemistry and Physics, SKLLQG, Institute of Earth Environment, Xi'an 710061, China [5]Department of Geoscience, 1215 W. Dayton St., Weeks Hall, University of Wisconsin-Madison, Madison, WI 53706 [6]Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ) Université Paris Saclay, Gif-sur-Yvette, France [7]Earth System Science Department, University of California at Irvine, CA [8]Research School of Earth Sciences, The Australian National University, Canberra, 2601, Australia [9]Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton, SO14 3ZH, UK [10]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA 02467 [11]Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, AB24 3UU, UK

E-mail: jeh1@columbia.edu

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Abstract

Global temperature is a useful metric for global climate that helps define the potential amplitude of slow climate feedbacks, such as ice sheet melt and sea level rise. Annual temperature, in 2016, enhanced by the 2015-2016 El Niño, was +1.3°C relative to 1880-1920. The underlying warming trend since 1970 is +0.18°C/decade, and current temperature excluding short-term variability has reached +1°C relative to 1880-1920, which is as warm as estimated for the prior (Eemian) interglacial, when sea level reached 6-9 meters higher than today. If temperature remains at this or a higher level, slow amplifying feedbacks will lead to greater climate change and consequences, on time scales that are difficult to predict but are dependent on the magnitude of warming. Targets for limiting global warming thus should aim to avoid leaving global temperature at Eemian or higher levels for centuries. Such targets now require "negative emissions", i.e., extraction of CO_2 from the air. If phasedown of fossil fuel emissions begins soon, improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content, may provide much of the necessary CO_2 extraction. In that case, the magnitude and duration of global temperature excursion above the natural range of the current interglacial (Holocene) could be limited and irreversible climate impacts minimized. In contrast, continued high fossil fuel emissions today place a burden on young people to undertake massive technological CO_2 extraction if they are to limit climate change. Proposed methods of extraction such as bioenergy with carbon capture and storage (BECCS) or air capture of CO_2 would have minimal estimated costs of 89-535 trillion dollars this century and also have large risks and uncertain feasibility. Continued high fossil fuel emissions unarguably sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both. These scenarios should provide incentive and obligation for governments to alter energy policies without further delay.

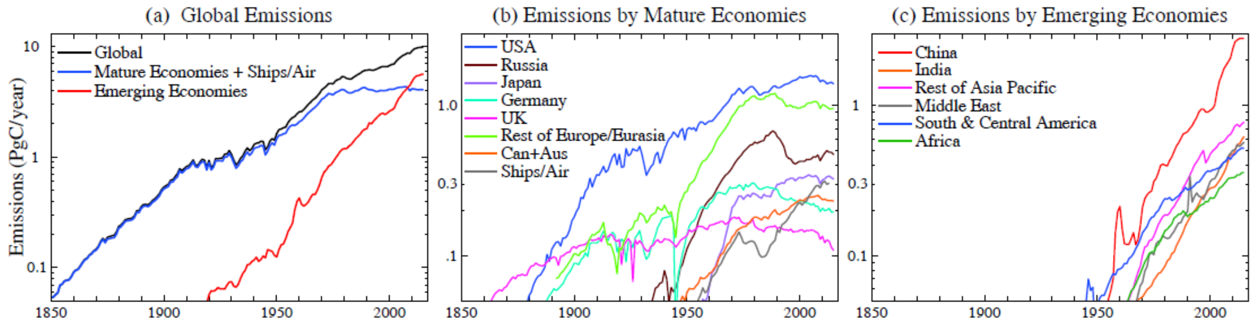

Figure 1. Fossil fuel (and cement manufacture) CO_2 emissions (note log scale) based on Boden et al. (2016) with BP data used to infer 2014-2015 estimates. Europe/Eurasia is Turkey plus the Boden et al. categories Western Europe and Centrally Planned Europe. Asia Pacific is sum of Centrally Planned Asia, Far East and Oceania. Middle East is Boden et al. Middle East less Turkey. Russia is Russian Federation since 1992 and 0.6 of USSR in 1850-1991. Ships/Air is sum of bunker fuels of all nations. Can+Aus is the sum of emissions from Canada and Australia.

1 Introduction

Almost all nations agree on the need to limit fossil fuel emissions to avoid dangerous human-made climate change, as formalized in the 1992 Framework Convention on Climate Change (UNFCCC, 1992). The Paris Agreement (2015), currently ratified by 120 parties representing 80% if today's greenhouse gas emissions, seeks to limit global warming to well below 2°C relative to preindustrial levels, with an aspirational goal of staying below 1.5°C.

Global mean surface temperature has many merits as the principal metric for climate change, but additional metrics, specifically atmospheric CO_2 amount and Earth's energy imbalance, help refine targets for avoiding dangerous human-made climate change. Extensive paleoclimate data and observations of Earth's present energy imbalance led Hansen et al. (2008, 2013a, 2016) to recommend, as an initial target, reducing CO_2 to less than 350 ppm, with the understanding that the target must be adjusted as CO_2 declines and empirical data accumulates. We advocate pursuit of this stricter goal within the time scale of a century to limit the period when global temperature is above the range of the current interglacial period, the Holocene[1]. Limiting the period and magnitude of temperature excursion above the Holocene range is crucial to avoid strong stimulation of slow feedback mechanisms. The slow feedbacks include ice sheet disintegration and thus sea level rise, which is probably the most threatening climate impact, but also release of greenhouse gases (GHGs) via such mechanisms as thawing tundra and loss of soil carbon. The relative climate stability of the Holocene has allowed sea level to be stable for the past several millennia (Kopp et al., 2016) in which civilizations developed, but there is now a danger that we may allow temperature to rise so far above the Holocene range that slow feedbacks are activated to a degree that continuing climate change will be out of humanity's control. The 350 ppm CO_2 target, which is moderately stricter than the 1.5°C warming target, is subject to some adjustment depending on the level of other trace gases and aerosols, as we will quantify. Both the 1.5°C and 350 ppm targets require rapid phasedown of fossil fuel emissions.

Despite widespread recognition of the risks posed by climate change, global fossil fuel emissions continue at a high rate that tends to make these targets increasingly improbable. Emissions are growing rapidly in emerging economies; while growth slowed in China in the past

[1] By Holocene we refer to the pre-industrial portion of the present interglacial period. As we will show, the rapid warming of the past century has brought temperature above the range in the prior 11.700 years of the Holocene.

two years, emissions remain high (Fig. 1). The Kyoto Protocol (1997), a policy instrument of the Framework Convention (UNFCCC, 1992), spurred emission reductions in some nations, and the collapse of the Soviet Union caused a large decrease of emissions by Russia (Fig. 1b). However, growth of international ship and air emissions (Fig. 1b) largely offset these reductions and the growth rate of global emissions actually accelerated from 1.5%/year in 1973-2000 to ~2.5%/year after 2000 (Fig. A1). China is now the largest source of fossil fuel emissions, followed by the U.S. and India, but on a per capita historical basis the U.S. is 10 times more accountable than China and 25 times more accountable than India for the increase of atmospheric CO_2 above its preindustrial level (Hansen and Sato, 2016). Tabular data for Figs. 1 and A1 are available on the web page www.columbia.edu/~mhs119/Burden.

In response to this situation, a lawsuit [Juliana et al. vs United States, 2016, hereafter J et al. vs US, 2016] was filed against the United States asking the U.S. District Court, District of Oregon, to require the U.S. government to produce a plan to rapidly reduce emissions. The suit requests that the plan reduce emissions at the 6%/year rate that Hansen et al. (2013a) estimated as the requirement for lowering atmospheric CO_2 to a level of 350 ppm. At a hearing in Eugene Oregon on 9 March 2016 the United States and three interveners (American Petroleum Institute, National Association of Manufacturers, and the American Fuels and Petrochemical Association) asked the Court to dismiss the case, in part based on the argument that the requested rate of fossil fuel emissions reduction was implausible. Magistrate Judge Coffin stated that he was “troubled” by the severity of the requested emissions reduction rate, but he also noted that some of the alleged climate change consequences, if accurate, could be considered “beyond the pale”, and he rejected the motion to dismiss the case. Judge Coffin’s ruling was certified, as required, by a second judge [Aiken, 2016] on 9 September 2016, and, barring a settlement that would be overseen by the court, the case is expected to proceed to trial in middle or late 2017. It can be anticipated that the plausibility of achieving the emission reductions needed to stabilize climate will be a central issue at the trial.

Urgency of initiating emissions reductions is well recognized (IPCC, 2013, 2014; Huntingford et al., 2012; Friedlingstein et al., 2014; Rogelj et al., 2016a) and was stressed in the paper that the lawsuit J et al. vs US (2016) uses to prescribe an emissions reduction scenario (Hansen et al., 2013a). The climate research community also realizes that the goal to keep global warming less than 1.5°C probably requires negative net CO_2 emissions later this century if high global emissions continue in the near-term (Fuss et al., 2014; Anderson 2015; Rogelj et al., 2016b; Sanderson et al., 2016). The Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2013, 2014) do not address environmental and ecological feasibility and impacts of large-scale CO_2 removal, but recent studies (Smith et al., 2016; Williamson 2016) are taking up this crucial issue and raising the question of whether large-scale negative emissions are even feasible.

Our aim is to contribute to understanding of the required rate of CO_2 emissions reduction via an approach that is transparent to non-scientists. We consider potential drawdown of atmospheric CO_2 by reforestation and afforestation, the potential for improved agricultural practices to store more soil carbon, and potential reductions of non-CO_2 GHGs that could reduce human-made climate forcing[2]. Quantitative examination reveals the merits of these actions to partly offset demands on fossil fuel CO_2 emission phasedown, but also their limitations, thus

[2] A climate forcing is an imposed change of Earth’s energy balance, measured in W/m^2. For example, Earth absorbs about 240 W/m^2 of solar energy, so if the sun’s brightness increases 1% it is a forcing of +2.4 W/m^2.

clarifying the urgency of government actions to rapidly advance the transition to carbon-free energies to meet the climate stabilization targets they have set.

We first describe the status of global temperature change and then summarize the principal climate forcings that drive long term climate change. We show that observed global warming is consistent with knowledge of changing climate forcings, Earth's measured energy imbalance, and the canonical estimate of climate sensitivity[3], i.e., about 3°C global warming[4] for doubled atmospheric CO_2. This standard climate sensitivity estimate does not include the effect of "slow" climate feedbacks such as changes of ice sheet size, and there is increasing evidence that some slow feedbacks can be triggered within decades so they must be given major consideration in establishing the dangerous level of human-made climate interference. We thus incorporate consideration of slow feedbacks in our analysis and discussion, even though precise specification of their time scales is not possible. We present updates of GHG observations and find a notable acceleration during the past decade of the growth rate of GHG climate forcing. For future fossil fuel emissions we consider both the Representative Concentration Pathways (RCP) scenarios used in climate (CMIP5) and integrated assessment model (IMAC) simulations and the IPCC AR5, and simple emission growth rates that are helpful for determining the plausibility of required emission changes. We use a precisely defined Green's function calculation of global temperature with canonical climate sensitivity for each emissions scenario, thus allowing us to determine the amount of CO_2 that must be extracted from the air – effectively the climate debt – to achieve the targets of returning atmospheric CO_2 to less than 350 ppm or limiting global warming to less than 1.5°C above preindustrial levels. We discuss alternative extraction technologies and their estimated costs, and finally we consider the potential alleviation of CO_2 extraction requirements that might be obtained via special efforts to reduce non-CO_2 GHGs.

2 Global Temperature Change

The United Nations 1992 Framework Convention on Climate Change (UNFCCC, 1992) stated its objective as '…stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The 15th Conference of the Parties (Copenhagen Accord, 2009) concluded that this objective required a goal to '…reduce global emissions so as to hold the increase of global temperature below 2°C…'. The 21st Conference of the Parties (Paris Agreement, 2015) strengthened this objective 'to holding the increase of global average temperature to well below 2°C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5°C above preindustrial levels…'.

This framing of human-caused climate by the Paris Agreement has global mean surface temperature as the metric for assessing dangerous climate change. We have argued the merits of additional metrics, especially Earth's energy imbalance (Hansen et al., 2005; von Schuckmann et al., 2016) and atmospheric CO_2 amount (Hansen et al., 2008). Earth's energy imbalance, e.g., integrates over all climate forcings, known and unknown, and informs us where climate is heading, because it is this imbalance that drives continued warming. The CO_2 metric also has

[3] Climate sensitivity is the response of global average surface temperature to a standard forcing, with the standard forcing commonly taken to be doubled atmospheric CO_2, which is a forcing of about 4 W/m^2 (Hansen et al., 2005).
[4] IPCC (2013) finds that 2×CO_2 equilibrium sensitivity is likely in the range 3 ± 1.5°C, as was estimated by Charney et al. (1979). Median sensitivity in recent model inter-comparisons is 3.2°C (Andrews et al., 2012; Vial et al., 2013).

merit, as CO_2 is the dominant control knob on global temperature (Lacis et al., 2010, 2013), including paleo temperature change (cf. Fig. 28 of Hansen et al., 2016). However, in our present paper the main function of these alternative metrics is to help sharpen determination of the dangerous level of global warming and quantify the actions that are needed to stabilize climate.

We use global temperature as the principal metric in our present paper because several reasons of concern are scaled to global warming (O'Neill et al., 2017), including specifically the potential for slow feedbacks such as ice sheet melt and permafrost thaw. The slow feedbacks, which come into play on time scales that depend on how strongly the climate system is being forced, will substantially determine the magnitude of climate impacts and affect how difficult the task of stabilizing climate will be.

Quantitative assessment of both ongoing and paleo temperature change is needed to define acceptable limits on human-made interference with climate, with paleo climate especially helpful for characterizing long-term ice sheet and sea level response to temperature change. Thus we examine the modern period with near-global instrumental temperature data in the context of the current and prior (Holocene and Eemian) interglacial periods for which less precise proxy-based temperatures have recently emerged. The Holocene, over 11,700 years in duration, had relatively stable climate, prior to the remarkable warming in the past half century. The Eemian, which lasted from about 130,000 to 115,000 years ago, was moderately warmer than the Holocene and experienced sea level rise to heights 6-9 m (20-30 feet) greater than today.

2.1 Modern Temperature

The several analyses of temperature change since 1880 are in close agreement (Hartmann et al., 2013). Thus we can use the current GISTEMP analysis (see Supporting Information), which is updated monthly and available (http://www.columbia.edu/~mhs119/Temperature/).

The popular measure of global temperature is the annual-mean global-mean value (Fig. 2a), which is publicized at the end of each year. However, as discussed by Hansen et al. (2010), the 12-month running mean global temperature is more informative and removes monthly "noise" from the record just as well as the calendar year average. For example, the 12-month running mean for the past 65 years (Fig. 2b) defines clearly the super-El Niños of 1997-98 and 2015-16 and the 3-year cooling after the Mount Pinatubo volcanic eruption in the early 1990s.

Global temperature in each month in 2015-2016 was at or near a record for the month. Perhaps helped by a popular "spiral" temperature visualization (Hope, 2016), this has tended to create a popular impression that global temperature may be spiraling out of control. The series of monthly records has terminated; with data through November 2016 the 12-month running mean fell to 1.28°C relative to 1880-1920 from a peak 1.31°C, and is likely to decline further as it has after prior El Niños. The recent warming removes the illusion of a hiatus of global surface warming since the 1997-98 El Niño. Several studies, including Trenberth and Fasullo (2013), England et al. (2014), Dai et al. (2015) and Rajaratnam et al. (2015), showed that temporary plateaus are consistent with expected long-term warming due to increasing atmospheric GHGs. Other analyses of this specific plateau help illuminate the roles of unforced climate variability and natural and human-caused climate forcings in observed climate change, with the Interdecadal Pacific Oscillation (a recurring pattern of ocean-atmosphere climate variability) playing a major role in the warming slowdown (Kosaka and Xie, 2013; Meehl et al., 2014; Fyfe et al., 2016).

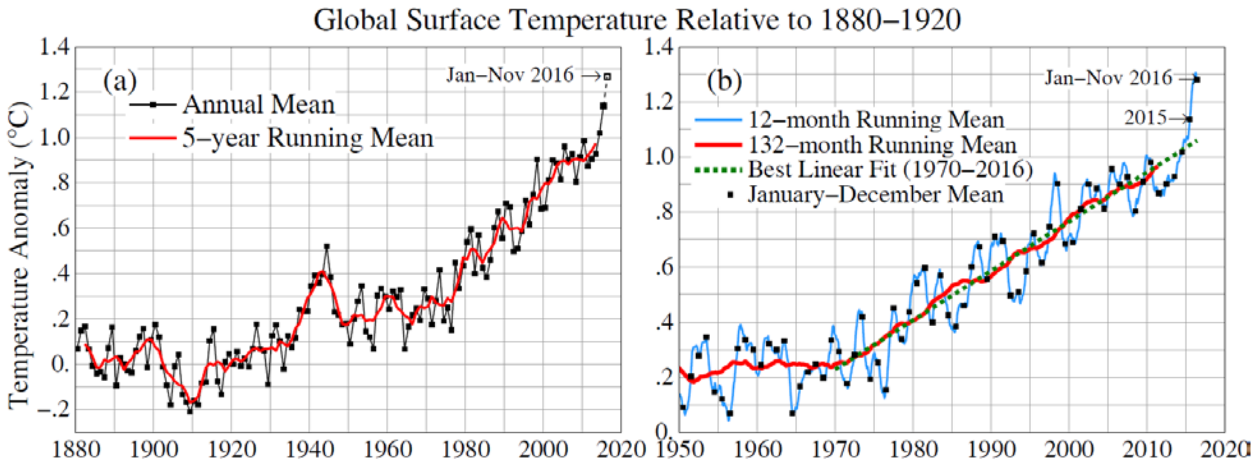

Figure 2. Global surface temperature relative to 1880-1920 based on GISTEMP data (Appendix A). (a) Annual and 5-year means since 1880, (b) 12- and 132-month running means since 1970. Black squares in (b) are calendar year (Jan-Dec) means used to construct (a). (b) uses data through November 2016.

The present global warming rate, based on a linear fit for 1970-present (dashed line in Fig. 2b) is +0.18°C per decade[5]. The period since 1970 is the time with high growth rate of GHG climate forcing, which has been maintained at approximately +0.4 W/m^2/decade (see section 6 below)[6] causing Earth to be substantially out of energy balance (Cheng et al., 2016). The energy imbalance drives global warming, so unless and until there is substantial change in the rate of added climate forcing we expect the underlying warming to continue at a comparable rate. Global temperature defined by the linear fit to temperature since 1970 now exceeds 1°C[7] relative to the 1880-1920 mean (Fig. 2b). At the rate of 0.18°C/decade the linear trend line of global temperature will reach +1.5°C in about 2040 and +2°C in the late 2060s. However, the warming rate can accelerate or decelerate, depending on policies that affect GHG emissions, developing climate feedbacks, and other factors discussed below.

2.2 Temperature during current and prior interglacial periods

Holocene temperature has been reconstructed at centennial-scale resolution from 73 globally distributed proxy temperature records by Marcott et al. (2013). This record shows a decline of 0.6°C from early Holocene maximum temperature to a "Little Ice Age" minimum in the early 1800s [that minimum being better defined by higher resolution data of Abram et al. (2016)].

Concatenation of the modern and Holocene temperature records (Fig. 3) assumes that 1880-1920 mean temperature is 0.1°C warmer than the Little Ice Age minimum (Abram et al., 2016). The early Holocene maximum in the Marcott et al. (2013) data is thus at +0.5°C relative to the 1880-1920 mean of modern data. However, model simulations suggest that the reconstructed early Holocene maximum may be exaggerated due to limitations of the proxy data, especially potential seasonality bias, as discussed by Marcott et al. (2013) and Liu et al. (2014).

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[5] Extreme endpoints affect linear trends, but if the 2016 temperature is excluded the calculated trend (0.176°C/decade) still rounds to 0.18°C/decade.

[6] As forcing additions from chlorofluorocarbons (CFCs) and CH_4 declined, CO_2 growth increased (section 6).

[7] It is 1.05°C for linear fit to 132-month running mean, but can vary by a few hundredths of a degree depending on the method chosen to remove short-term variability.

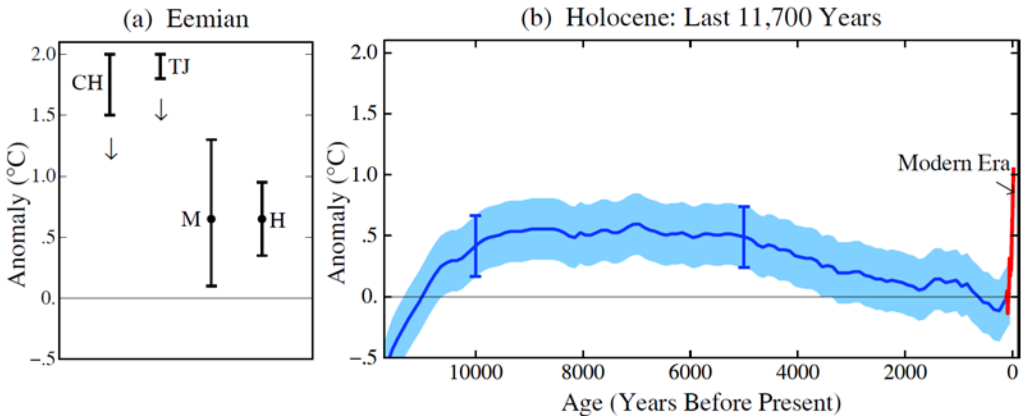

Figure 3. Estimated average global temperature for (a) last interglacial (Eemian) period (Clark and Huybers, 2009; Turney and Jones, 2010; McKay et al., 2011; Hoffman et al, 2017), (b) centennially-smoothed Holocene (Marcott et al., 2013) temperature and the 11-year mean of modern data (Fig. 2), as anomalies relative to 1880-1920. Vertical downward arrows indicate likely overestimates (see text).

Comparisons of current global temperature with the earlier Holocene must bear in mind the centennial smoothing inherent in the Holocene data (Marcott et al. 2013). Thus the temperature in an anomalous single year such as 2016 is not an appropriate comparison. However, the temperature in 2016 based on the 1970-present linear trend (at least 1°C relative to the 1880-1920 mean) does provide a meaningful comparison. The trend line reduces the effect of interannual variability, but the more important point is that Earth's energy imbalance assures that this temperature will continue to rise unless and until the global climate forcing begins to decline. In other words, we know that the mean temperature over the next several decades will not be lower than 1°C. The formal 2σ (95% confidence) uncertainty in the Marcott et al. (2013) Holocene temperature, shown by the blue area in Figure 3b, is ~0.25°C, but the total uncertainty is larger. Specifically, Liu et al. (2014) points out a bias effect caused by seasonality in the proxy temperature reconstruction. The sense of the bias is such that its correction will tend to push early Holocene temperatures lower, increasing the gap between today's temperature and early Holocene temperature (Marcott and Shakun 2015).

We conclude that the modern trend line of global temperature crossed the early Holocene (smoothed) temperature maximum (+0.5°C) already in about 1985. This conclusion receives support from the accelerating rate of sea level rise, which approached a rate of 3 mm/year at about that date (Fig. 29 of Hansen et al., 2016 shows a relevant concatenation of measurements). Such a high rate of sea level rise, which equates to 3 meters per millennium, far exceeds rates of Holocene sea level rise except in the earliest Holocene when melt was still coming from the final decay of mid-latitude ice sheets (Lambeck et al., 2014; Dutton et al., 2015).

The Framework Convention (UNFCCC, 1992) and Paris Agreement (2015) define goals relative to 'preindustrial' temperature, but do not define that period. We use 1880-1920, the earliest time with near global coverage of instrumental data, as the zero-point for temperature anomalies. Although human-caused increases of GHGs would be expected to have caused a small warming by then, that warming was at least partially balanced by cooling from larger than average volcanic activity in 1880-1920. Extreme Little Ice Age conditions may have been ~0.1C cooler than the 1880-1920 mean (Abram et al., 2016), but the Little Ice Age seems inappropriate to define preindustrial because the deep ocean did not have time to reach equilibrium with brief conditions. Choosing a preindustrial global temperature thus has uncertainty of at least 0.1°C, but 1880-1920 temperature seems about right and that period has the merit of near-global data.

The important point is that global temperature has risen above the centennially-smoothed Holocene range. Global warming is already having substantial adverse climate impacts (IPCC, 2014), including extreme events (NAS, 2016). There is widespread agreement that 2°C warming would commit the world to multi-meter sea level rise (Levermann et al., 2013; Dutton et al., 2015; Clark et al., 2016), and a case has been made that this could unfold within 50-150 years (Hansen et al., 2016). Sea level reached 6-9 m higher than today during the Eemian (Dutton et al., 2015), so it is particularly relevant to know how global mean Eemian temperature compares to the preindustrial level and thus to today.

McKay et al. (2011) estimated peak Eemian annual global ocean SST as +0.7°C ± 0.6°C relative to late Holocene temperature, while models, as described by Masson-Delmotte et al. (2013), give more confidence to the lower part of that range. Hoffman et al. (2017) report the maximum Eemian annual global SST as +0.5°C ± 0.3°C relative to the 1870-1889, which is +0.65°C relative to 1880-1920. Global ocean SST response to climate forcings is half as large as global land response in models (Collins et al., 2013), in good agreement with observed warming in the industrial era (Appendix A this paper, Fig. A2a). Because land covers ~30% of the globe, SST warmings should be multiplied by 1.3 to estimate global temperature change. Thus the McKay et al. and Hoffman et al. data are equivalent to a global Eemian temperature almost +1°C relative to the Holocene. Clark and Huybers (2009) and Turney and Jones (2010) estimated global temperature in the Eemian as 1.5-2°C warmer than the Holocene (Fig. 3), but Bakker and Renssen (2014) point out two biases that may cause this range to be an overestimate. Bakker and Rennsen (2014) use a suite of models to estimate that the assumption that maximum Eemian temperature was synchronous over the planet overestimates Eemian temperature by 0.4 ± 0.3°C – a feature supported by improved records of synchronization that reveal lack of synchroneity in warmest conditions (Govin et al, QSR, 2015) – and they suggest that a possible seasonal bias of proxy temperature could make the total overestimate as large as 1.1 ± 0.4°C. Given uncertainties in the corrections, it becomes a matter of expert judgement. Dutton et al. (2015) conclude that the best estimate for Eemian temperature is +1°C relative to preindustrial. Consistent with these estimates and the discussion of Masson-Delmotte et al. (2013), we assume that Eemian temperature was +1°C relative to preindustrial with an uncertainty of at least 0.5°C.

These considerations raise the question of whether 2°C, or even 1.5°C, is an appropriate target to protect the well-being of young people and future generations. Indeed, Hansen et al. (2008) concluded "If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its (then) current 385 ppm to at most 350 ppm, but likely less than that." And further "If the present overshoot of the target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects."

A danger of 1.5°C or 2°C targets is that they are far above the Holocene temperature range. If such temperature levels are allowed to long exist they will spur "slow" amplifying feedbacks (Hansen et al., 2013b; Rohling et al., 2013; Masson-Delmotte et al., 2013), which may have potential to run out of humanity's control. The most threatening slow feedback likely is ice sheet melt and consequent sea level rise, but there are other risks in pushing the climate system far out of its Holocene range. Thawing permafrost and drying soils will expose long-stored soil carbon to oxidation and release of CO_2 to the atmosphere (Schädel et al., 2016). Methane release from thawing permafrost and methane hydrates is another potential feedback, for example, but the magnitude and time scale of this is unclear (O'Connor et al., 2010; Quiquet, 2015).

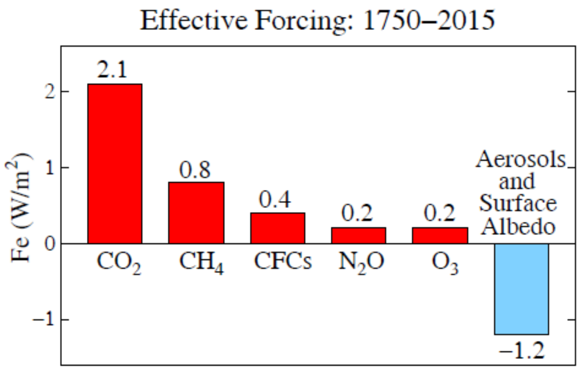

Figure 4. Estimated effective climate forcings (update through 2015 of Hansen et al., 2005). Forcings are based on observations of each gas, except simulated CH_4-induced changes of O_3 and stratospheric H_2O included in the CH_4 forcing. Aerosols and surface albedo change are estimated from historical scenarios of emissions and land use. Oscillatory and intermittent natural forcings (solar irradiance and volcanoes) are excluded. CFCs include not only chlorofluorocarbons, but all Montreal Protocol Trace Gases (MPTGs) and Other Trace Gases (OTGs). Uncertainties (for 5-95% confidence) is 0.6 W/m^2 for total GHG forcing and 0.9 W/m^2 for aerosol forcing (Myhre et al., 2013).

Here we examine the fossil fuel emission reductions required to restore atmospheric CO_2 to 350 ppm or less, so as to keep global temperature close to the Holocene range, in addition to the canonical 1.5°C and 2°C targets. Quantitative investigation requires consideration of Earth's energy imbalance, changing climate forcings, and climate sensitivity.

3 Global Climate Forcings and Earth's Energy Imbalance

The dominant human-caused drivers (forcings) of climate change are changes of atmospheric GHGs and aerosols. GHGs absorb Earth's infrared (heat) radiation, thus serving as a "blanket" that warms Earth's surface by reducing heat radiation to space. Aerosols, fine particles/droplets in the air that cause visible air pollution, both reflect and absorb solar radiation, but reflection of solar energy to space is their dominant effect, so they cause a cooling that partly offsets GHG warming. Estimated forcings (Fig. 4), an update of Fig. 28b of Hansen et al. (2005), are similar to those of Myhre et al. (2013) in the most recent IPCC report (IPCC, 2013).[8]

Climate forcings in Fig. 4 are the planetary energy imbalance caused by the preindustrial-to-present change of each atmospheric constituent. The CH_4 forcing includes its indirect effects, as increasing atmospheric CH_4 causes tropospheric ozone (O_3) and stratospheric water vapor to increase (Myhre et al., 2013). Uncertainties, discussed by Myhre et al. (2013), are typically 10-15% for GHG forcings. The aerosol forcing uncertainty, described by a probability distribution function (Boucher et al., 2013), is of order 50%. Our estimate of aerosol plus surface albedo forcing (−1.2 W/m^2) differs from the −1.5 W/m^2 of Hansen et al. (2005), as discussed below, but both are within the range of the distribution function of Boucher et al. (2013).

The positive net forcing (Fig. 4) causes Earth to be out of energy balance, with more energy coming in than going out, which drives slow global warming. Eventually Earth will become hot

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[8] Our GHG forcings, calculated with formulae of Hansen et al. (2000), yield a CO_2 forcing 6.7% larger than the central IPCC estimate [Table 8.2 of Myhre et al. (2013)] for the CO_2 change from 1750-2011. For all well-mixed (long-lived) GHGs we obtain 3.03 W/m^2, which is within the IPCC range 2.83 ±0.29 W/m^2.

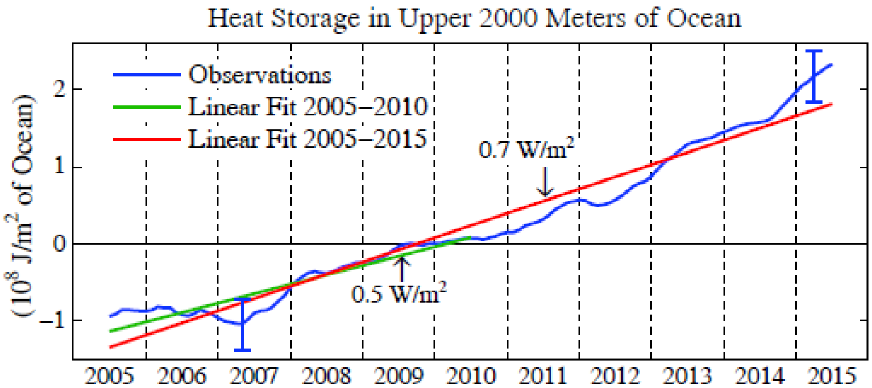

Figure 5. Ocean heat uptake in upper 2 km of ocean during 11 years 2005-2015 using analysis method of von Schuckmann and LeTraon (2011). Heat uptake in W/m^2 (0.5 and 0.7) refer to global (ocean + land) area, i.e., it is the contribution of the upper ocean to the heat uptake averaged over the entire planet.

enough to radiate to space an amount of energy matching absorbed sunlight. However, because of the ocean's great thermal inertia (heat capacity), full atmosphere-ocean response to the forcing requires a long time: atmosphere-ocean models suggest that even after 100 years only 60-75% of the surface warming for a given forcing has occurred, the remaining 25-40% still being "in the pipeline" (Hansen et al., 2011; Collins et al., 2013). Moreover, we outline in the next section that global warming can activate "slow" feedbacks, such as changes of ice sheets or melting of methane hydrates, so the time for the system to reach a fully equilibrated state is even longer.

GHGs have been increasing for more than a century and Earth has partially warmed in response. Earth's energy imbalance is the portion of the forcing that has not yet been responded to. This imbalance thus defines additional global warming that will occur without further change of forcings. Earth's energy imbalance can be measured by monitoring ocean subsurface temperatures, because almost all excess energy coming into the planet goes into the ocean (von Schuckmann et al., 2016). Most of the ocean's heat content change occurs in the upper 2000 m (Levitus et al., 2012), which has been well measured since 2005 when the distribution of Argo floats achieved good global coverage (von Schuckmann and Le Traon, 2011).

Hansen et al. (2011) inferred an Earth energy imbalance with the solar cycle effect removed of +0.75 ± 0.25 W/m^2, based on an imbalance of 0.58 W/m^2 in 2005-2010; the latter was based on the analysis of von Schuckmann and Le Traon (2011) for the upper 2 km of the ocean and estimates of small heat gains by the deep ocean, continents, atmosphere, and net melting of sea ice and land ice. Here we update the von Schuckmann and Le Traon analysis with data for 2005-2015 (Fig. 5) finding a decade-average 0.7 W/m^2 heat uptake in the upper 2000 m of the ocean; addition of the smaller terms raises the imbalance to at least +0.8 W/m^2 for 2005-2015, consistent with the recent estimate of +0.9 ± 0.1 W/m^2 by Trenberth et al. (2016) for 2005-2015. Other recent analyses including the most up-to-date corrections for ocean instrumental biases yield +0.4 ± 0.1 W/m^2 by Cheng et al. (2016) for the period 1960-2015 and +0.7 ± 0.1 W/m^2 by Dieng et al. (2016) for the period 2005-2013. We conclude that the estimate of +0.75 ± 0.25 W/m^2 for the current Earth energy imbalance averaged over the solar cycle is still valid.

4 Climate Sensitivity and Feedbacks

Climate sensitivity has been a fundamental issue at least since the 19th century when Tyndall (1861) and Arrhenius (1896) stimulated interest in the effect of CO_2 change on climate. Evaluation of climate sensitivity involves the full complexity of the climate system, as all components and processes in the system are free to interact on all time scales. Tyndall and Arrhenius recognized some of the most important climate feedbacks on both fast and slow time scales. The amount of water vapor in the air increases as temperature increases, which is an amplifying feedback because water vapor is a very effective greenhouse gas; this is a "fast" feedback, because water vapor amount in the air adjusts within days to temperature change. The area covered by glaciers and ice sheets is a prime "slow" feedback; it, too, is an amplifying feedback, because the darker surface exposed by melting ice absorbs more sunlight.

Diminishing climate feedbacks also exist. Cloud-cover changes, e.g., can either amplify or reduce climate change (Boucher at al., 2013). Thus it is not inherent that amplifying feedbacks should be dominant, but climate models and empirical data concur that amplifying feedbacks dominate on both short and long time scales, as we will discuss. Amplifying feedbacks lead to large climate change in response to even weak climate forcings caused by small perturbations of Earth's orbit, and still larger climate change occurs on longer time scales in response to gradual changes in the balance between natural sources and sinks of atmospheric CO_2 on geological time scales (Zachos et al., 2001; Royer et al., 2012; Franks et al., 2014).

4.1 Fast-Feedback Climate Sensitivity

Doubled atmospheric CO_2, a forcing of about 4 W/m^2, is now a standard forcing in studies of climate sensitivity. Charney et al. (1979) concluded that equilibrium sensitivity, i.e., global warming after a time sufficient for the planet to restore energy balance with space, was 3°C ± 1.5°C for $2\times CO_2$ or 0.75°C per W/m^2 forcing. The Charney analysis was based on climate models in which ice sheets and all long-lived GHGs (except for the specified CO_2 doubling) were held fixed. The climate sensitivity thus inferred is the "fast-feedback" climate sensitivity. The central value found in a wide range of modern climate models (Flato et al., 2013) remains 3°C for $2\times CO_2$. The possibility of unknown unknowns in models would keep the uncertainty in the fast-feedback climate sensitivity high, if it were based on models alone, but paleoclimate data noted below and discussed by Rohling et al. (2012a) allows narrowing of the uncertainty.

Ice sheet size and the atmospheric amount of long-lived GHGs (CO_2, CH_4, N_2O) under natural conditions change on millennial time scales, with the changes largely coinciding with quasi-regular oscillations of Earth's orbit and the tilt of Earth's spin axis that occur with periodicities from about 20,000 to 400,000 years. These changes are so slow that the climate is in quasi-equilibrium with the changing surface condition and long-lived GHG amounts. Thus these changing boundary conditions, along with knowledge of the associated global temperature change, allow empirical assessment of the fast-feedback climate sensitivity. The central result is in good agreement with the model-based climate sensitivity estimate of 3°C for doubled CO_2 (Rohling et al., 2012b), with an uncertainty that is arguably 1°C or less (Hansen et al., 2013b).

Because the ocean has great heat capacity (thermal inertia), it requires decades to centuries for Earth's surface temperature to achieve most of its fast-feedback response to a change of climate forcing (Hansen et al., 1985). Therefore, Earth has only partially responded to the human-made increase of GHGs in the air today, the planet must be out of energy balance with the planet gaining energy (via reduction of heat radiation to space), and there is thus more global warming "in the pipeline."

We can make a useful check on understanding of ongoing climate change by examining the consistency of the net climate forcing (Fig. 4), Earth's energy imbalance, observed global warming, and climate sensitivity. Observed warming since 1880-1920 is 1.05°C based on the linear fit to the 132-month running mean (Fig. 2b), which limits bias from short-term oscillations. Global warming between 1700-1800 and 1880-1920 was ~0.1°C (Abram et al., 2016; Hawkins et al., 2017; Marcott et al., 2013), so 1750-2015 warming is ~1.16°C. Taking climate sensitivity as 0.75°C per W/m^2 forcing, global warming of 1.16°C implies that 1.55 W/m^2 of the total 2.5 W/m^2 forcing has been "used up" to cause observed warming. Thus 0.95 W/m^2 forcing should remain to be responded to, i.e., the expected planetary energy imbalance is 0.95 W/m^2, which is reasonably consistent with the observed 0.75 ± 0.25 W/m^2. If we instead take the aerosol + surface albedo forcing as -1.5 W/m^2, as estimated by Hansen et al. (2005), the net climate forcing is 2.2 W/m^2 and the forcing not responded to is 0.65 W/m^2, which is also within the observational error of Earth's energy imbalance.

4.2 Slow Climate Feedbacks

Large glacial-to-interglacial climate oscillations occur on time scales of tens and hundreds of thousands of years, with the amount of atmospheric CO_2, the size of ice sheets, and thus sea level all changing almost synchronously on these time scales (Masson-Delmotte et al., 2013). The large amplitude of climate oscillations is a result of two amplifying feedbacks: (1) atmospheric GHGs (mainly CO_2 but accompanied by CH_4 and N_2O), which increase as Earth warms and decrease as it cools (Ciais et al., 2013), thus amplifying the temperature change, and (2) the size of ice sheets, which decrease in size as Earth warms and increase as it cools, thus changing the amount of absorbed sunlight in the sense that also amplifies the climate change.

Amplifying feedbacks increase the magnitude of stochastic climate variability (Wunsch, 2004) as well as the response to climate forcings (Zachos et al., 2001; Hansen et al., 1984, 2007). A deterministic climate response to even weak forcings is readily apparent in the climate record for millennial time scales. Small changes in Earth's orbit and the tilt of Earth's spin axis alter the geographical and seasonal distribution of sunlight striking Earth, leading to large global climate change as a result of amplifying feedbacks. For example, 20,000 years ago most of Canada and parts of the United States were covered by an ice sheet, and sea level was about 130 m (~400 feet) lower than today. Global warming of ~5°C between the last glacial maximum and the Holocene (Masson-Delmotte et al., 2013) is accounted for almost entirely by radiative forcing caused by decrease in ice sheet area and the increase of GHGs (Lorius et al., 1990; Hansen et al., 2007).

The time scale of these large glacial-interglacial climate oscillations is set by the time scale of the weak orbital forcings. Before addressing the crucial issue of the time scale of slow feedbacks themselves, it is appropriate to say more about the two dominant slow feedbacks, which we have described as ice sheets and GHGs.

The ice sheet feedback works mainly via the albedo (reflectivity) effect. Not only does the area of ice sheets shrink and expose darker ground, but warming darkens the ice surface by increasing the area and seasonal period with wet ice, increasing the ice grain size, and increasing the surface concentration of light-absorbing impurities (Tedesco et al., 2016). The ice albedo effect is supplemented by a change of surface albedo in regions not covered by ice due to vegetation changes. This vegetation albedo effect provides a significant amplification of warming as Earth's temperature increases from its present climate state, because dark forests tend to replace tundra or sparse low-level vegetation in large areas of Eurasia and North America (Lunt et al., 2010).

Ice sheet change, spurred by mutual interactions of amplifying feedbacks, potentially has great practical importance. Foster and Rohling (2013) find that a CO_2 level of 400-450 ppm, or global warming of 2°C, leads to eventual sea level rise of at least 9 m (about 30 feet) with probability greater than 68 percent. Paleoclimate data from many global sites corrected for isostatic crustal movement suggest that the eventual sea level rise caused by global warming of 1-2°C is at least 6-9 m (Dutton et al., 2015). Such sea level rise would render most coastal cities dysfunctional, and more than half of the world's large cities are located on coastlines.

The GHG feedback on glacial-interglacial time scales is 75-80 percent from CO_2 change, with N_2O and CH_4 accounting for the other 20-25 percent (Lorius et al., 1990, Hansen et al., 2007), Masson-Delmotte et al., 2013). In simple terms, the ocean and land release more of all three gases to the atmosphere as the planet becomes warmer. The mechanisms that control release of GHGs as Earth warms, and drawdown of GHGs as Earth cools, are complex, including multiple processes that affect the distribution of carbon, among the ocean, atmosphere, and biosphere (Yu et al., 2016; Ciais et al., 2013 and references therein). Changes of large carbon deposits in methane hydrates and permafrost have contributed to climate change in past warm periods in Earth's history (Zachos et al., 2008; DeConto et al., 2012). Although there is little evidence to suggest and potentially could have a significant effect in the future (O'Connor et al., 2010; Schädel et al., 2016).

The GHG amplifying feedback could have large practical importance, because of its impact on the ice sheet feedback. Climate modeling studies of the past century usually employ observed GHG amounts, without concern whether a portion of CO_2, CH_4 and N_2O growth is a climate feedback rather than direct human-caused emissions. Indeed, until the past few decades, global temperature was within the Holocene range, so there was little reason to expect a significant GHG feedback. However, the recent steep temperature rise out of the Holocene range (Fig. 3), and the accelerating growth of CH_4, N_2O and CO_2, raise questions about the GHG feedback. Efforts to scale back emissions so as to avoid dangerous climate change may become much more difficult if there is a substantial GHG amplifying feedback this century. For example, the warming of the world ocean and ocean acidification reduce the ability of the ocean to take up CO_2 (Heinze et al., 2015; Riebesell, et al., 2009).

The time scale of the ice sheet and GHG feedbacks depends on the magnitude and rate of the climate forcing. The rate of increase of the human-made GHG climate forcing in the past century and near future exceeds by at least a factor of 10 the fastest known natural increase, the Paleocene-Eocene Thermal Maximum (Kennett and Stott, 1991; Zeebe et al., 2016), which included a carbon release comparable to burning all fossil fuels, at least a doubling of atmospheric CO_2, causing global warming of about 6°C over a period of a few thousand years (Dunkley Jones et al., 2010).

Paleoclimate data has relevance, albeit limited, to assessment of the time scale for ice sheet change. Ice sheet size, judged from sea level, appears to vary almost synchronously with temperature for the temporal resolution available in paleoclimate records, but Grant et al. (2012) find that sea level change, as expected, does lag temperature change, with the lag being 1-4 centuries. Paleoclimate forcing, however, is both weak and very slow, changing on millennial time scales. Hansen (2005, 2007) argues on heuristic grounds that the much faster and stronger human-made climate forcing projected this century with continued high fossil fuel emissions, equivalent to doubling atmospheric CO_2, would likely lead to substantial ice sheet collapse and multi-meter sea level rise on the time scale of a century. Pollard et al. (2015) found that addition of hydro-fracturing and cliff failure to their ice sheet model not only increased simulated sea level rise from 2 m to 17 m in response to only 2°C ocean warming; it also accelerated the time for multi-meter change from several centuries to several decades. Ice sheet modeling of Applegate et al. (2015) explicitly shows that the time scale for large ice sheet melt decreases dramatically as the magnitude of global warming increases. Hansen et al. (2016), based on a combination of climate modeling, paleo data, and modern observations, conclude that continued high GHG emissions would likely cause multi-meter sea level rise within 50-150 years.

The magnitude and time scale of GHG feedbacks in response to human-made climate change are uncertain, but we have reasons to expect that the feedbacks will be important. Rising temperatures increase the risk of CO_2 and CH_4 release from drying soils, thawing permafrost (Schädel et al., 2016; Schuur et al., 2015) and warming continental shelves (Kvenvolden, 1993; Judd et al., 2002), as well as the ocean carbon cycle feedbacks mentioned above. Glacial-interglacial GHG feedbacks are amplifying and substantial. There are notable instances in which the CO_2 change lags the temperature change (Figure 27 of Hansen et al., 2016), possibly a result of the time scale of deep ocean overturning, but within the coarse-resolution of paleoclimate data the GHG feedbacks seem to almost coincide with temperature change. Synthesis of 49 field experiments across North America, Europe and Asia (Crowther et al., 2016) implies that 1°C global warming could lead to a 30 PgC soil carbon loss and climate scenarios with continued high fossil fuel emissions could drive a 55 PgC carbon loss from the soil by 2050. Although this analysis admits large uncertainty, such large soil carbon loss could wreak havoc with efforts to achieve the net soil and biospheric carbon storage that is likely necessary for climate stabilization, as we discuss in subsequent sections.

Recent changes of GHGs are a result of human-driven emissions from industrial and agricultural activities, but they also include any existing climate feedback effects. CO_2 and CH_4 are the largest forcings of global climate change (Fig. 4), so it is especially important to examine their ongoing changes.

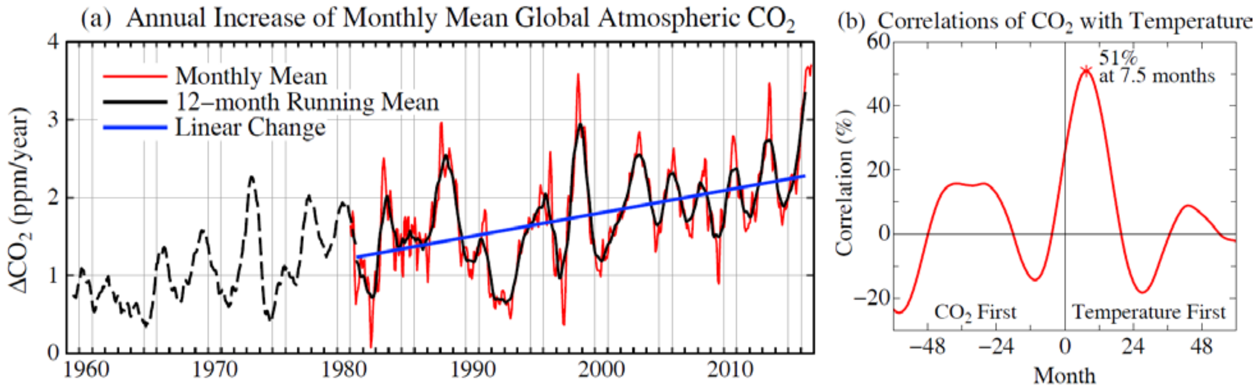

Figure 6. (a) Global CO_2 annual growth based on NOAA data (http://www.esrl.noaa.gov/gmd/ccgg/trends/). Dashed curve is for a single station (Mauna Loa). Red curve is monthly global mean relative to the same month of prior year; black curve is 12-month running mean of red curve. (b) CO_2 growth rate is highly correlated with global temperature, the CO_2 change lagging global temperature change by 7-8 months.

5 Observed CO_2 and CH_4 Growth Rates

Annual increase of atmospheric CO_2, averaged over a few years, grew from less than 1 ppm/year 50 years ago to more than 2 ppm/year today (Fig. 6), with the global mean and Mauna Loa CO_2 amounts now exceeding 400 ppm (Betts et al., 2016). The large oscillations of the annual growth are correlated with global temperature and with the El Niño/La Niña cycle[9]. Correlations are calculated for the 12-month running means, which effectively remove the seasonal cycle and monthly noise. Maxima of the CO_2 growth rate lag global temperature maxima by 7-8 months (Fig. 6b) and lag Niño3.4 [latitudes 5N-5S, longitudes 120-170W] temperature by ~10 months. These lags imply that the current CO_2 growth spike (Fig. 6 uses data through July 2016), associated with the 2015-16 El Niño, should be near its maximum, as Niño3.4 peaked in December 2015 and global temperature peaked in February 2016.

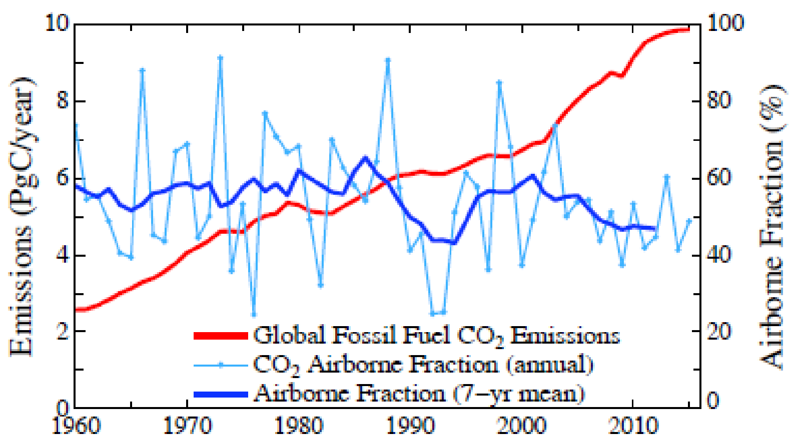

Figure 7. Fossil fuel CO_2 emissions (left scale) and airborne fraction, i.e., the ratio of observed atmospheric CO_2 increase to fossil fuel CO_2 emissions.

[9] One mechanism for greater than normal atmospheric CO_2 growth during El Niños is the impoverishment of nutrients in equatorial Pacific surface water and thus reduced biological productivity that result from reduced upwelling of deep water (Chavez et al., 1999). However, the El Niño/La Niña cycle seems to have an even greater impact on atmospheric CO_2 via the terrestrial carbon cycle through effects on the water cycle, temperature, and fire, as discussed in a large body of literature (referenced, e.g., by Schwalm et al., 2011).

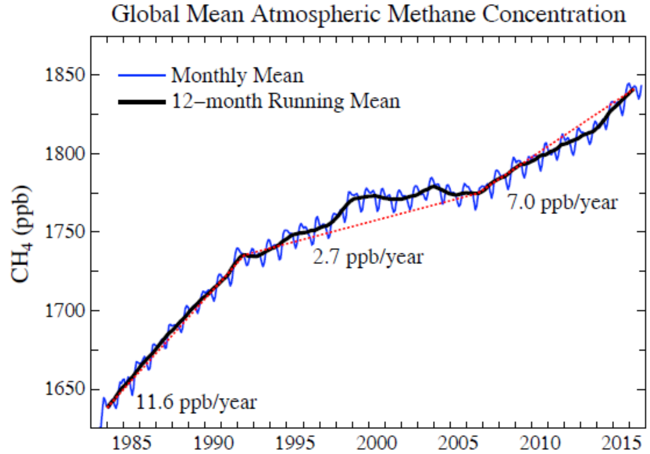

Figure 8. Global CH_4 from Dlugokencky (2016), NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends_ch4/). End months for three indicated slopes are January 1984, May 1992, August 2006, and September 2016.

Growth of airborne CO_2 appears to be about half of fossil fuel CO_2 emissions (Fig. 7), the remaining portion of emissions being the net uptake by the ocean and biosphere (Ciais et al., 2013). Here we use the Keeling et al. (1973) definition of airborne fraction, which is the ratio of quantities that are known with good accuracy: the annual increase of CO_2 in the atmosphere and the annual amount of CO_2 injected into the atmosphere by fossil fuel burning. The data reveal that, even as fossil fuel emissions have increased by a factor of four over the past half century, the ocean and biosphere have continued to take up about half of the emissions (Fig. 7, right-hand scale). This seemingly simple relation between emissions and atmospheric CO_2 growth is not predictive as it depends on the growth rate of emissions being maintained, and, indeed, it is not expected to continue in cases with major changes in the emission scenario, so we use a carbon cycle model in Section 7 to compute atmospheric CO_2 as a function of emission scenario.

Atmospheric CH_4 stopped growing between 1998 and 2006, indicating that its sources and sinks were nearly in balance, but growth resumed in the past decade (Fig. 8). Growth of CH_4 exceeded 10 ppb/year in 2014 and 2015, almost as fast as in the 1980s. CH_4 changes in the past two decades were driven primarily by changes in emissions, as observations of CH_3CCl_3 show very little change in the atmospheric sink for CH_4 (Montzka et al., 2011; Holmes et al., 2013). Future changes in the sink could lead to increased atmospheric CH_4 separate from emission changes, but this effect is difficult to project in the RCP scenarios (Voulgarakis et al., 2013).

Carbon isotopes provide a valuable constraint (Saunois et al., 2016) that aids analysis of which CH_4 sources[10] contribute to the CH_4 growth resurgence in the past decade (Fig. 8). Schaefer et al. (2016) conclude that the growth was primarily biogenic, thus not fossil fuel, and located outside the tropics, most likely ruminants and rice agriculture. Such an increasing biogenic source is consistent with effects of increasing population and dietary changes (Tilman and Clark 2014). Nisbet et al. (2016) concur with Schaefer et al. (2016) that the CH_4 growth is from biogenic sources, but from the latitudinal distribution of growth they conclude that tropical wetlands[11] have been an important contributor to the CH_4 increase. Their conclusion that

[10] Estimated human-caused CH_4 sources (Ciais et al., 2013) are: fossil fuels (29%), biomass/biofuels (11%), Waste and landfill (23%), ruminants (27%) and rice (11%)

[11] Wetlands compose a majority of natural CH_4 emissions and are estimated to be equivalent to about 36% of the anthropogenic source (Ciais et al., 2013)

increasing tropical precipitation and temperature may be major factors driving CH_4 growth suggests the possibility that the slow climate-methane amplifying feedback might already be significant. There is also concern that global warming will increase CH_4 emissions from methane hydrates and permafrost (O'Connor et al., 2010), but as yet there is little evidence for a substantial increase of emissions from hydrates or permafrost (Berchet et al., 2016; Warwick et al., 2016; Quiquet et al., 2015).

Schwietzke et al. (2016) use isotopic constraints to show that the fossil fuel contribution to atmospheric CH_4 is larger than previously believed, but total fossil fuel CH_4 emissions are not increasing. This conclusion is consistent with the above studies, and it does not contradict evidence of increased fossil fuel CH_4 emissions at specific locations (Turner et al., 2016).

The continued growth of atmospheric CO_2 and the reaccelerating growth of CH_4 raise important questions related to prospects of stabilizing climate. How consistent with reality are scenarios for phasing down climate forcing when tested by observational data? What changes to industrial and agricultural emissions are required to stabilize climate? We address these issues below.

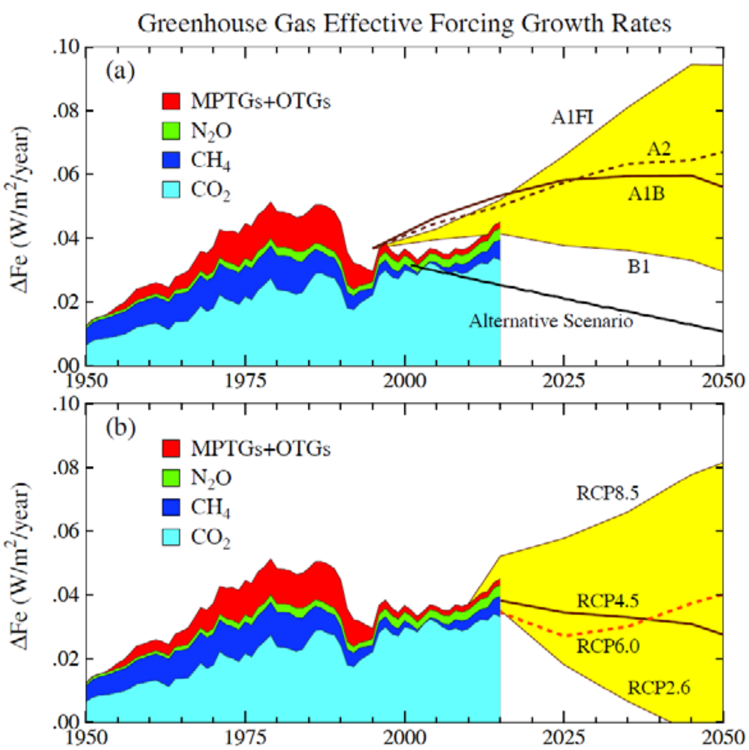

Figure 9. GHG climate forcing growth rate with historical data being 5-year running means, except data for 2014 and 2015 are 3- and 1-year means. (a) includes scenarios used in IPCC AR3 and AR4 reports, and (b) has AR5 scenarios. All GHG amounts are from NOAA/ESRL Global Monitoring Division.

6 GHG Climate Forcing Growth Rates and Emission Scenarios

Insight is obtained by comparing the growth rate of GHG climate forcing based on observed GHG amounts with past and present GHG scenarios. We examine forcings of IPCC Special Report on Emissions Scenarios (IPCC SRES, 2000) scenarios used in the 2001 AR3 and 2007 AR4 reports (Fig. 9a) and Representative Concentration Pathways scenarios (RCP: Moss et al., 2010; Meinshausen et al., 2011a) used in the 2013 IPCC AR5 report (Fig. 9b). We include the "alternative scenario" of Hansen et al. (2000) in which CO_2 and CH_4 emissions decline such that global temperature stabilizes near the end of the century.[12] We use the same radiation equations for observed GHG amounts and scenarios, so errors in the radiation calculations do not alter the comparison. Equations for GHG forcings are from Table 1 of Hansen and Sato (2004) with the CH_4 forcing using an efficacy factor 1.4 to include effects of CH_4 on tropospheric O_3 and stratospheric H_2O (Hansen et al., 2005).

The growth of GHG climate forcing peaked at ~0.05 W/m^2/year (5 W/m^2/century) in 1978-1988, then falling to a level 10-25% below IPCC SRES (2000) scenarios during the first decade of the 21st century (Fig. 9a). The decline was due to (1) decline of the airborne fraction of CO_2 emissions (Fig. 7), (2) slowdown of CH_4 growth (Fig. 8), and (3) the Montreal Protocol, which initiated phase-out of gases that destroy stratospheric ozone, primarily chlorofluorocarbons (CFCs).

The situation in 2000 seemed ripe for a pathway to climate stabilization more rapid than any of the IPCC scenarios. The slowing growth of forcings was partly good fortune, but also due to the prescience of the Montreal Protocol, whose design and implementation to reduce the ozone-depleting gases also allowed it to be used to slow or reverse growth of some other GHGs. The alternative scenario aimed to extend the downward trend in the growth rate of climate forcing by: (1) slowing the growth of CO_2 emissions, as may occur with a substantial rising price on carbon emissions to accelerate development of carbon-free energies, (2) a global effort to reduce CH_4 emissions, (3) continued use and tightening of the Montreal Protocol to constrain trace GHGs. The slowly decreasing forcing of this alternative scenario yields maximum global warming ~1.5°C, for climate sensitivity 0.75°C/W/m^2 (Fig. A4).

However, in reality, in the absence of a universally rising carbon price and substantial support for energy research and development, global fossil fuel CO_2 emissions accelerated, from 1.5%/year in 1973-2000 to ~2.5%/year after 2000 (Figs. 1 and A1). The growth rate of GHG forcing now exceeds the alternative scenario by ~70% (Fig. 9a). New scenarios must begin from current reality, and, as a consequence of recent growth, ambitious targets for limiting global warming now require much steeper emissions reductions.

The 2013 IPCC RCP scenarios (Fig. 9b) use observed GHG amounts up to 2005 and diverge thereafter, fanning out into an array of potential futures driven by assumptions about energy demand, fossil fuel prices, and climate policy, chosen to be representative of an extensive literature on possible emissions trajectories (Moss et al., 2010; van Vuuren et al., 2011; Meinshausen et al., 2011a,b). Numbers on the RCP scenarios (8.5, 6.0, 4.5 and 2.6) refer to the GHG climate forcing (W/m^2) in 2100.

[12] This scenario is discussed by Hansen and Sato (2004). CH_4 emissions decline moderately, producing a small negative forcing. CO_2 emissions (not captured and sequestered) are assumed to decline until in 2100 fossil fuel emissions just balance uptake of CO_2 by the ocean and biosphere. CO_2 emissions continue to decline after 2100.

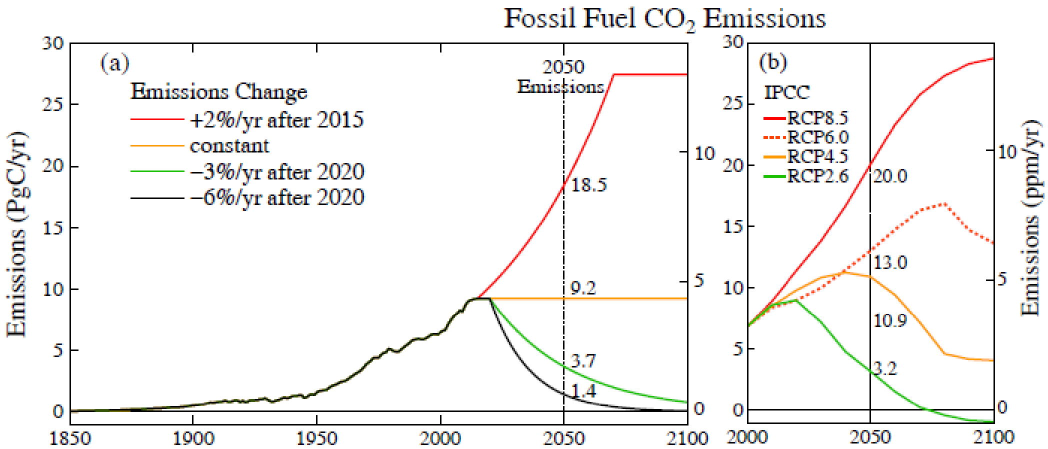

Figure 10. Fossil fuel emission scenarios. (a) Scenarios with simple specified rates of emission increase or decrease. (b) IPCC (2013) RCP scenarios.

As a complement to RCP scenarios, we define scenarios simply by percent annual emission decrease or increase. We consider rates −6%/year, −3%/year, constant emissions, and +2%/year; emissions stop increasing in the +2%/year case when they reach 25 Gt/year (Fig. 10a). Scenarios with decreasing emissions are preceded by constant emissions for 2015-2020, in recognition that some time is required to achieve policy change and implementation. Note similarity of RCP 2.6 with −3%/year, RCP 4.5 with constant emissions, and RCP 8.5 with +2%/year (Fig. 10).

Scenario RCP2.6 has the world moving into negative growth of GHG forcing 25 years from now (Fig. 9b), through rapid reduction of GHG emissions, along with CO_2 capture and storage. Already in 2015 there is a huge gap between reality and RCP2.6. Closing the gap (0.01 W/m^2) between actual growth of GHG climate forcing in 2015 and RCP2.6 (Fig. 9b), with CO_2 alone, would require extraction from the atmosphere of more than 0.7 ppm of CO_2 or 1.5 PgC due to the emissions gap of a single year (2015). We discuss the plausibility and estimated costs of scenarios with CO_2 extraction in Section 9.

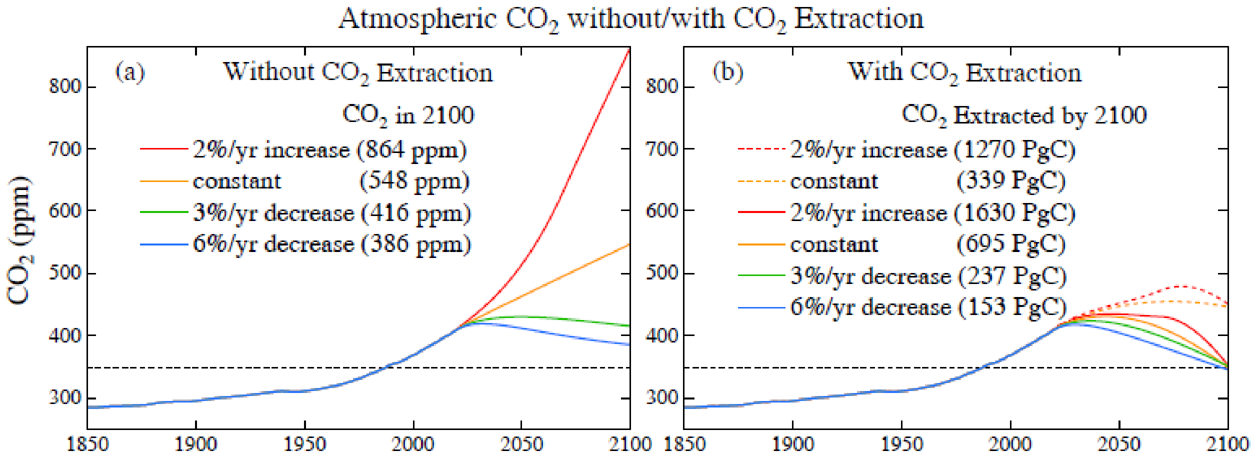

Figure 11. (a) Atmospheric CO_2 for Fig. 10a emission scenarios. (b) Atmospheric CO_2 including effect of CO_2 extraction that increases linearly after 2020 (after 2015 in +2%/year case).

7 Future CO_2 for Assumed Emission Scenarios

We must model Earth's carbon cycle, including ocean uptake of carbon, deforestation, forest regrowth and carbon storage in the soil, for the purpose of simulating future atmospheric CO_2 as a function of the fossil fuel emission scenario. Fortunately, the convenient dynamic-sink pulse-response function version of the well-tested Bern carbon cycle model (Joos et al., 1996) does a good job of approximating more detailed models, and it produces a good match to observed industrial-era atmospheric CO_2. Thus we use this relatively simple model, described elsewhere (Joos et al., 1996; Kharecha and Hansen, 2008, and references therein), to examine the effect of alternative fossil fuel use scenarios on the growth or decline of atmospheric CO_2. For land use CO_2 emissions in the historical period, we use the values labeled Houghton/2 by Hansen et al (2008), which were shown in the latter publication to yield good agreement with observed CO_2. We use fossil fuel CO_2 emissions data for 1850-2013 from Boden et al. (2016). BP fuel consumption data for 2013-2015 are used for the fractional annual changes of each nation to allow extension of the Boden analysis through 2015. Emissions were almost flat from 2014 to 2015, due to economic slowdown and increased use of low-carbon energies, but, even if a peak in global emissions is near, substantial decline of emissions is dependent on acceleration in the transformation of energy production and use (Jackson et al., 2016).

The scenarios shown in Figs. 10a and 11a are the baseline cases without any anthropogenic CO_2 removal. We illustrate five cases with CO_2 removal in Fig. 11b that achieve atmospheric CO_2 targets of either 350 ppm or 450 ppm in 2100, with cumulative removal amounts listed in parentheses (Fig. 11b). The rate of CO_2 extraction in all cases increases linearly from zero in 2010 to the value in 2100 that achieves the atmospheric CO_2 target (350 ppm or 450 ppm). The amount of CO_2 that must be extracted from the system exceeds the difference between the atmospheric amount without extraction and the target amount, e.g., constant CO_2 emissions and no extraction yields 546 ppm for atmospheric CO_2 in 2100, but to achieve a target of 350 ppm the required extraction is 328 ppm, not 546 – 350 = 196 ppm. The well-known reason (Cao and Caldeira, 2010) is that ocean outgassing increases and vegetation productivity and ocean CO_2 uptake decrease with decreasing atmospheric CO_2, as explored in a wide range of Earth System models (Jones et al., 2016).

8 Simulations of Global Temperature Change

Analysis of future climate change, and policy options to alter that change, must address various uncertainties. One useful way to treat uncertainty is to use results of many models and construct probability distributions (Collins et al., 2013). Such distributions have been used to estimate the remaining budget for fossil fuel emissions for a specified likelihood of staying under a given global warming limit and to compare alternative policies for limiting climate forcing and global warming (Rogelj et al., 2016a,b).

Our aim here is a fundamental, transparent calculation that clarifies how future warming depends on the rate of fossil fuel emissions. We use best estimates for basic uncertain quantities such as climate sensitivity. If these estimates are accurate, actual temperature should have about equal chances of falling higher or lower than the calculated value. Important uncertainties in projections of future climate change include climate sensitivity, the effects of ocean mixing and dynamics on the climate response function discussed below, and aerosol climate forcing. We provide all defining data so that others can easily repeat calculations with alternative choices.

One clarification is important for our present paper. The climate calculations in this section include only fast-feedbacks, which is also true for most climate simulations by the scientific community for IPCC (2013). This is not a limitation for the past, i.e., for the period 1850-present, because we employ measured GHG changes, which include any GHG change due to slow feedbacks. Also we know that ice sheets did not change significantly in size in that period; there may have been some change in Greenland's albedo and expansion of forests in the Northern Hemisphere (Pearson et al., 2013), but those feedbacks so far have only a small global effect. However, this limitation to fast feedbacks may soon become important; it is only in the past few decades that global temperature rose above the prior Holocene range and only in the past two years that it shot far above that range. This limitation must be borne in mind when we consider the role of slow feedbacks in establishing the dangerous level of warming.

We calculate global temperature change T at time t in response to any climate forcing scenario using the Green's function (Hansen 2008)

$$T(t) = \int_{1850}^{t} R(t')\,[dF/dt']\,dt' \quad + \quad Fv \times R(t) \qquad (1)$$

where R(t') is the product of equilibrium global climate sensitivity and the dimensionless climate response function (percent of equilibrium response), dF(t')/dt' is the annual increment of the net forcing, and Fv is the negative of the average volcanic aerosol forcing during the few centuries preceding 1850. Fv ×R(t) is a small correction term that prevents average volcanic aerosol activity from causing a long-term cooling, i.e., it accounts for the fact that the ocean in 1850 has been slightly cooled by prior volcanoes. We take Fv = 0.3 W/m^2, the average stratospheric aerosol forcing for 1850-2015. Our response function reaches 75% response in 100 years, a rate that Hansen et al. (2011) conclude is representative of the real world, based on observations of Earth's energy imbalance; this imbalance is a consequence of the time required for the ocean surface temperature to respond to changing climate forcing. Our results can be exactly reproduced, or altered with alternative choices for climate forcings, climate sensitivity and response function, because we tabulate the forcings in Table A1 and the response function is exactly defined.[13]

We use equilibrium fast-feedback climate sensitivity 0.75°C per W/m^2 (3°C for 2×CO_2). This is consistent with climate models (Collins et al., 2013: Flato et al., 2013) and paleoclimate evidence (Rohling et al., 2012a; Masson-Delmotte et al., 2013; Bindoff and Stott, 2013).

CO_2 is the dominant forcing in scenarios for future climate. The growth of non-CO_2 GHG climate forcing is likely to be even smaller, relative to CO_2 forcing, than it has been in recent decades (Fig. 9), especially if there is a strong effort to limit climate change. Indeed, recent agreement to use the Montreal Protocol (2016) to phase down emissions of minor trace gases, the hydrofluorocarbons (HFCs), should cause added forcing of Montreal Protocol Trace Gases (MPTGs) + Other Trace Gases (OTGs) (red region in Fig. 9) to become near zero or slightly negative, thus at least partially off-setting growth of other non-CO_2 GHGs, especially N_2O.

Some N_2O increase may be inevitable, because its emissions are largely associated with food production (fertilizers and waste handling), and population is not expected to stabilize before mid-century at the earliest (Ciais et al., 2013; Kroeze and Bouwman, 2011). The net effect of these N_2O sources is complex because of potential cancelling secondary effects, e.g., fertilizers can increase uptake of carbon by the biosphere; but, in addition to emitting N_2O from soils, they also emit NO, an important precursor of tropospheric O_3, also an important GHG. It is expected that more efficient use of fertilizers can reduce emissions and N_2O growth (Liu and Zhang 2011).

CH_4 is responsible for the largest non-CO_2 GHG forcing, with potential to significantly exacerbate or alleviate the magnitude of global warming, so we address the range of CH_4 possibilities in Section 10. Here we use RCP6.0 for the non-CO_2 GHGs, a scenario in which warming by non-CO_2 GHGs is small compared to warming by CO_2.

We take tropospheric aerosol plus surface albedo forcing as −1.2 W/m^2 in 2015, presuming the aerosol and albedo contributions to be −1 W/m^2 and −0.2 W/m^2, respectively. We assume a small increase this century as global population rises and increasing aerosol emission controls in emerging economies tend to be offset by increasing development elsewhere, so aerosol + surface forcing is −1.5 W/m^2 in 2100. The temporal shape of the historic aerosol forcing curve (Table A1) is from Hansen et al. (2011), which in turn was based on the Novakov et al. (2003) analysis of how aerosol emissions have changed with technology change.

Historic stratospheric aerosol data (Table A1, annual version), an update of Sato et al. (1993), include moderate 21st century aerosol amounts (Bourassa et al., 2012). Future aerosols, for realistic variability, include three volcanic eruptions in the rest of this century with properties of the historic Agung, El Chichon and Pinatubo eruptions, plus a background stratospheric aerosol forcing −0.1 W/m^2. This leads to mean stratospheric aerosol climate forcing −0.3 W/m^2 for remainder of the 21st century, similar to the mean stratospheric aerosol forcing for 1850-2015 (Table A1). Reconstruction of historical solar forcing (Coddington et al., 2015; Kopp et al., 2016), based on data in Fig. A3, is extended with an 11-year cycle.

[13]We use the "intermediate" response function in Fig. 5 of Hansen et al. (2011), which gives best agreement with Earth's energy imbalance. Fractional response is 0.15, 0.55, 0.75 and 1 at years 1, 10, 100 and 2000 with these values connected linearly in log (year), cf. Fig. 5 of Hansen et al. (2011).

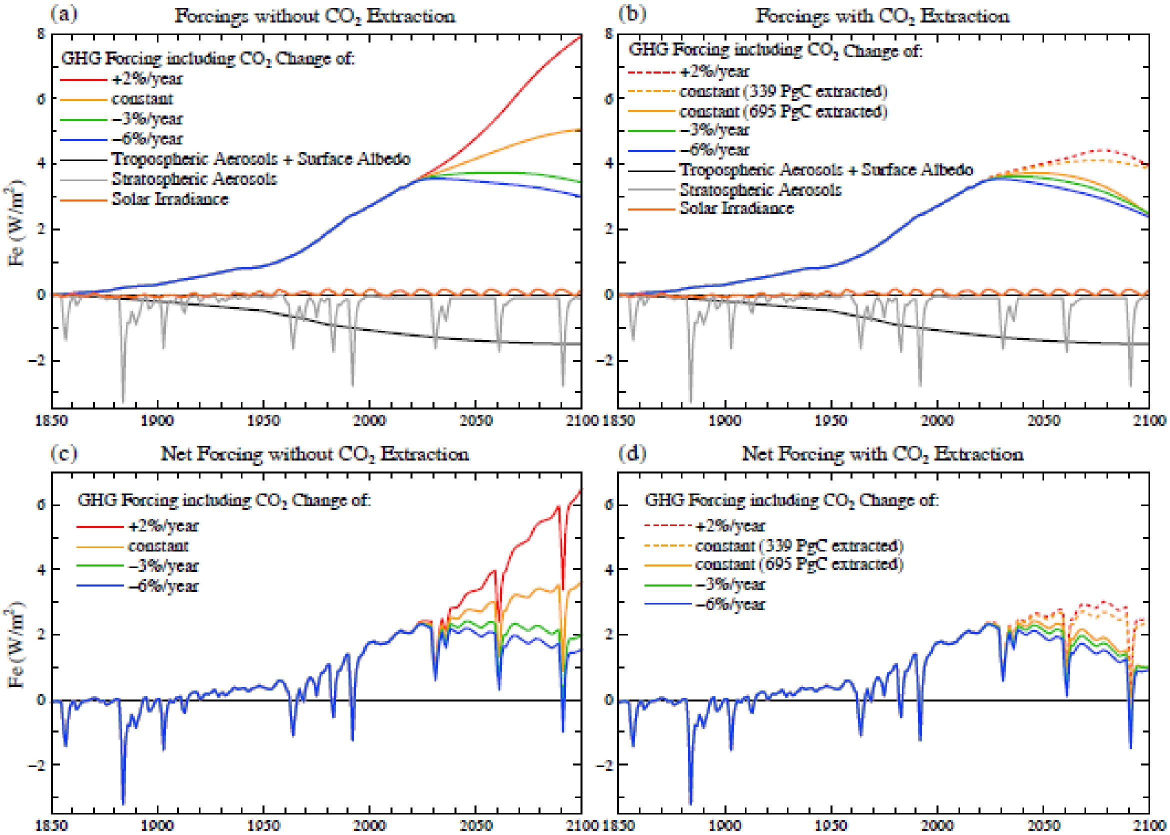

Figure 12. Climate forcings used in our climate simulations; Fe is effective forcing, as discussed in connection with Fig. 4. (a) Future GHG forcing uses four alternative fossil fuel emission growth rates. (b) GHG forcings are altered based on CO_2 extractions of Fig. 11.

Individual and net climate forcings for the several fossil fuel emission reduction rates are shown in Fig. 12a,c. Scenarios with linearly growing CO_2 extraction at rates required to yield 350 or 450 ppm airborne CO_2 in 2100 are in Fig. 12b,d. These forcings and the assumed climate response function define expected global temperature for the entire industrial era considered here (Fig. 13). We extended the global temperature calculations from 2100 to 2200 by continuing the %/year change of CO_2 emissions. In the cases with CO_2 extraction we kept the GHG climate forcing fixed in the 22nd century, which meant that large CO_2 extraction continued in cases with continuing high emissions, e.g., the case with constant emissions that required extraction of 695 PgC during 2020-2100 required further extraction of ~900 PgC during 2100-2200. Even the cases with annual emission reductions −6%/year and −3%/year required small extractions to compensate for back-flux of CO_2 from the ocean that accumulated there historically.

A stark summary of alternative futures emerges from Fig. 13a. If emissions grow 2%/ year, modestly slower than the 2.6%/year growth of 2000-2015, warming reaches ~3°C by 2100. Warming is about 2°C if emissions are constant until 2100. Furthermore, both scenarios launch Earth onto a course of more dramatic change well beyond the initial 2-3°C global warming, because: (1) warming continues beyond 2100 as the planet is still far from equilibrium with the climate forcing, and (2) warming of 2-3°C would unleash strong slow feedbacks, including melting of ice sheets and increases of GHGs.

The most important conclusion from Fig. 13a is the proximity of results for the cases with emission reductions of 6%/year and 3%/year. Although Hansen et al. (2013) called for reduction

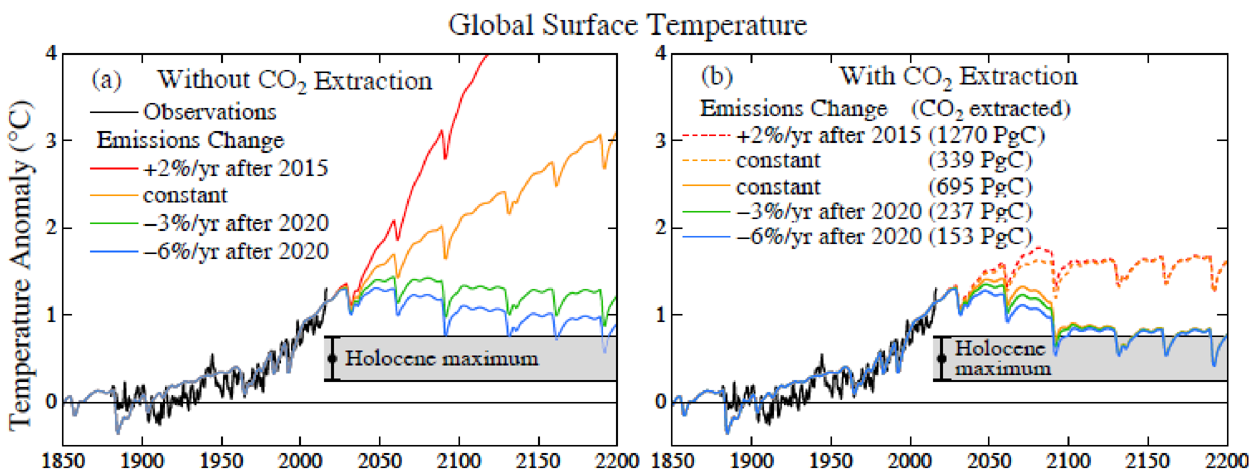

Figure 13. Simulated global temperature for Fig. 12 forcings. Observations as in Fig. 2. Temperature zero-point is the 1880-1920 mean temperature for both observations and model. Gray area is 2σ (95% confidence) range for centennially-smoothed Holocene maximum, but there is further uncertainty about the magnitude of the Holocene maximum, as noted in the text and discussed by Liu et al. (2014).

of 6%/year to restore CO_2 to 350 ppm by 2100, that rate of reduction was asserted to be implausibly rapid by the United States in the lawsuit Alec L vs. Jackson (2012), which was dismissed by the United States District Court, District of Columbia. That argument is more difficult to make for emission reductions of 3% per year, as discussed below with regard to mitigation alternatives. Reducing global emissions at a rate of 3%/year (or more steeply) maintains global warming at less than 1.5°C above preindustrial temperature.

However, end-of-century temperature is 0.5°C or more above the prior Holocene maximum with consequences for slow feedbacks that are difficult to foresee. Desire to minimize sea level rise spurs the need to get global temperature back into the Holocene range. That goal preferably should be achieved on the time scale of a century or less, because paleoclimate evidence indicates that the response time of sea level to climate change is 1-4 centuries (Grant et al., 2012, 2014) for natural climate change, and if anything the response should be faster to a stronger, more rapid human-made climate forcing. The scenarios that reduce CO_2 to 350 ppm succeed in getting temperature back close to the Holocene maximum by 2100 (Fig. 13b), but they require extractions of atmospheric CO_2 that range from 153 PgC in the scenario with 6%/year emission reductions to 1630 PgC in the scenario with +2%/year emission growth.

Scenarios ranging from constant emissions to +2%/year emissions growth can be made to yield 450 ppm in 2100 via extraction of 339-1270 PgC from the atmosphere (Fig. 11b). However, these scenarios still yield warming more than 1.5°C above the preindustrial level (more than 1°C above the early Holocene maximum). Consequences of such warming and the plausibility of extracting such huge amounts of atmospheric CO_2 are considered below.

9 CO_2 Extraction: Estimated Cost and Alternatives

Extraction of CO_2 from the air, also called negative emissions, is required if large, long-term excursion of global temperature above its Holocene range is to be averted, as shown above. In estimating the cost and plausibility of CO_2 extraction we differentiate between (1) carbon extracted from the air by improved agricultural and forestry practices, and (2) additional "technological extraction" by intensive negative emission technologies.

We assume that improved practices will aim at optimizing agricultural and forest carbon uptake via relatively natural approaches, compatible with the land delivering a range of ecosystem services (Smith 2016; Smith et al., 2016). In contrast, proposed technological extraction and storage of CO_2 generally does not have co-benefits and remains unproven at relevant scales (NAS, 2015a). Improved practices have local benefits in agricultural yields and forest products and services (Smith et al., 2016), which may help minimize net costs. The Intended Nationally Determined Contributions (INDCs) submitted by 189 countries include carbon drawdown through land use plans (United Nations, 2016) with aggregate removal rate of ~2 $PgCO_2$/year (~0.55 PgC/year) after 2020. These targets are not the maximum possible drawdown, as they are only about a third of amounts Smith (2016) estimated as "realistic".

Developed countries recognize a financial obligation to less developed countries that have done little to cause climate change (Paris Agreement 2015)[14]. We suggest that at least part of developed country support should be channeled through agricultural and forestry programs, with continual evaluation and adjustment to reward and encourage progress (Bustamante et al., 2014). Efforts to minimize non-CO_2 GHGs can be included in the improved practices program.

We do not estimate the cost of CO_2 extraction obtained via the "improved agricultural and forestry practices," because that would be difficult given the range of activities it is likely to entail, and because it is not necessary for reaching the conclusion that total CO_2 extraction costs will be high due to the remaining requirements for technological extraction. However, we do estimate the potential magnitude of CO_2 extraction that might be achievable via such improved practices, as that is needed to quantify the required amount of "technological extraction" of CO_2. Finally, we compare costs of extraction with estimated costs of mitigation measures that could limit the magnitude of required extraction, while admitting that there is large uncertainty in both extraction and mitigation cost estimates.

A comment is in order about the relation of "improved agricultural and forestry practices" with an increased role of biofuels in climate mitigation. Agriculture, forestry and other land use has potential for important contributions to climate change mitigation (Smith et al., 2014). However, first-generation biofuel production and use (which is usually based on edible portions of feedstocks, such as starch) is not inherently carbon neutral, indeed it is likely carbon-positive, as has been illustrated in specific quantitative analyses for corn ethanol in the United States (Searchinger et al., 2008; DeCicco et al., 2016). The need for caution regarding the role of biofuels in climate mitigation is discussed by Smith et al. (2014).

9.1 Estimated Cost of CO_2 Extraction

Hansen et al. (2013) suggested a goal of 100 PgC (47 ppm CO_2) extraction in the 21st century, which would be almost as large as estimated net emissions from historic deforestation and land use (Ciais et al., 2013). Hansen et al. (2013) assumed that 100 PgC was about as much as could be achieved via relatively natural reforestation and afforestation (Canadell and Raupach, 2008) and improved agricultural practices that increase soil carbon (Smith, 2016).

Here we first reexamine whether a concerted global effort on carbon storage in forests and soil might have potential to provide a carbon sink substantially larger than 100 PgC this century.

[14] Another conceivable source of financial support for CO_2 drawdown might be legal settlements with fossil fuel companies, analogous to penalties that courts have imposed on tobacco companies, but with the funds directed to the international "improved practices" program.

Smith et al. (2016) estimate that reforestation and afforestation together have carbon storage potential of about 1.1 PgC/year. However, as forests mature, their uptake of atmospheric carbon decreases (termed "sink saturation"), thereby limiting CO_2 drawdown. Taking 50 years as the average time for tropical, temperate and boreal trees to experience sink saturation yields 55 PgC as the potential storage in forests this century.

Smith (2016) shows that soil carbon sequestration and soil amendment with biochar compare favorably with other negative emission technologies with less impact on land use, water use, nutrients, surface albedo, and energy requirements, but understanding of and literature on biochar are limited (NAS, 2015a). Smith estimates that soil carbon sequestration has potential to store 0.7 PgC/year. However, as with carbon storage in forest, there is a saturation effect. A commonly used 20-year saturation time (IPCC 2006) would yield 14 PgC soil carbon storage, while an optimistic 50-year saturation time would yield 35 PgC. Use of biochar to improve soil fertility provides additional carbon storage with potential rate as high as 0.7-1.8 PgC/year (Woolf et al., 2010; Smith 2016). Larger industrial-scale biochar carbon storage is conceivable, but belongs in the category of intensive negative emission technologies, discussed below, whose environmental impacts and costs require scrutiny. We conclude that 100 PgC is an appropriate estimate for potential carbon extraction via an ambitious concerted global-scale effort to improve agricultural and forestry practices with carbon drawdown as a prime objective.

Intensive negative emission technologies that could yield greater CO_2 extraction include (1) burning of biomass in power plants with capture and sequestration of resulting CO_2 (Creutzig et al., 2015), and (2) direct air capture of CO_2 and sequestration (Keith, 2009; NAS, 2015a), and (3) grinding and spreading of minerals such as olivine to enhance the geological weathering process (Taylor et al., 2016). However, energy, land and water requirements of these technologies impose economic and biophysical limits on CO_2 extraction (Smith et al., 2016).

The popular concept of bioenergy with carbon capture and storage (BECCS) requires large areas, high fertilizer and water use, and may compete with other vital land use such as agriculture (Smith, 2016). Costs estimates are ~\$150-350/tC for crop-based BECCS (Smith et al., 2016).

Direct air capture has more limited area and water needs than BECCS and no fertilizer requirement, but it has high energy use, has not been demonstrated at scale, and cost estimates exceed those of BECCS (Socolow et al., 2011; Smith et al., 2016). Keith et al. (2006) have argued that, with strong research and development support and industrial-scale pilot projects sustained over decades, it may be possible to achieve costs ~\$200/tC, thus comparable to BECCS costs; however other assessments are higher, reaching \$1400-3700/tC (NAS, 2015a). Carbon capture and storage (CCS) from the stream of concentrated CO_2 at fossil fuel burning sites is more efficient and thus less expensive than direct air capture, but CCS at power plants is implicitly included in our scenarios as one of the mechanisms competing to achieve phase-down of fossil fuel emissions, along with energy efficiency, renewable energies, and nuclear power.

Enhanced weathering via soil amendment with crushed silicate rock is a candidate negative emission technology that also limits coastal ocean acidification as chemical products liberated by weathering increase land-ocean alkalinity flux (Kohler et al., 2010; Taylor et al., 2016). If two-thirds of global croplands were amended with basalt dust, as much as 1-3 PgC/year might be extracted, depending on application rate (Taylor et al., 2016), but energy costs of mining, grinding and spreading likely reduce this by 10-25% (Moosdorf et al., 2014). Such large-scale enhanced weathering is speculative, but potential co-benefits for temperate and tropical agroecosystems could affect its practicality, and may put some enhanced weathering into the category of improved agricultural and forestry practices. Benefits include crop fertilization that increases yield and reduces use and cost of other fertilizers, increasing crop protection from insect herbivores and pathogens thus decreasing pesticide use and cost, neutralizing soil acidification to improve yield, and suppression of GHG (N_2O and CO_2) emissions from soils (Edwards et al., 2016; Kantola et al., 2016). Against these benefits, we note potential negative impacts of air and water pollution caused by the mining, including downstream environmental consequences if silicates are washed into rivers and the ocean, causing increased turbidity, sedimentation, and pH, with unknown impacts on biodiversity (Edwards et al., 2016). Cost of enhanced weathering might be reduced by deployment with reforestation and afforestation and with crops used for BECCS; this could significantly enhance the combined carbon sequestration potential of these methods.

For cost estimates, we first consider restoration of airborne CO_2 to 350 ppm in 2100 (Fig. 11b), which would keep global warming below 1.5°C and bring global temperature back close to the Holocene maximum by end-of-century (Fig. 13b). This scenario keeps the temperature excursion above the Holocene level small enough and brief enough that it has the best chance of avoiding ice sheet instabilities and multi-meter sea level rise (Hansen et al., 2016). If fossil fuel emission phasedown of 6%/year had begun in 2013, as proposed by Hansen et al. (2013), this scenario would have been achieved via the hypothesized 100 PgC carbon extraction from improved agricultural and forestry practices.

However, global emission reduction beginning in 2013 was not achieved. Attainment of policy changes needed for rapid emission reduction and their implementation will require time. Thus to define more realistic scenarios, we assume that average global emissions through 2020 will be comparable to today's level. We then examine (Figs. 11b and 13b) scenarios with 6%/year and 3%/year emission reduction starting in 2021, as well as scenarios with constant emissions and +2%/year emission growth starting in 2016. The −6%/year and −3%/year scenarios leave a requirement to extract 153 and 237 PgC from the air during this century. Constant emission and +2%/year emission scenarios yield extraction requirements of 695 and 1630 PgC to reach 350 ppm CO_2 in 2100.

In the following cost estimates we assume that 100 PgC will be stored in the biosphere via improved agricultural and forestry practices, and we do not include a cost estimate for that activity. Thus any shortfall of that 100 PgC goal will increase the following cost estimates accordingly, as will the cost of the improved agricultural and forestry program.

Given a CO_2 extraction cost of $150-350/tC for intensive negative emission technologies (Fig. 3f of Smith et al., 2016), the 53 PgC additional extraction required for the scenario with 6%/year emission reduction would cost $8-18.5 trillion, thus $100-230 billion per year if spread uniformly over 80 years.

In contrast, continued high emissions, between constant emissions and +2%/year, would require additional extraction of 595-1530 PgC (Fig. 11b) at a cost $89-535 trillion or $1.1-6.7 trillion per year over 80 years.[15] Such extraordinary cost, along with the land area, fertilizer and water requirements (Smith et al., 2016) suggest that, rather than the world being able to buy its way out of climate change, continued high emissions would likely force humanity to live with climate change running out of control with all the consequences that would entail.

[15] For reference, the United Nations global peacekeeping budget is about $10B/year. National military budgets are larger: the 2015 USA military budget was $596B and the global military budget was $1.77 trillion (SIPRI 2016).

9.2 Mitigation Alternative

High costs of CO_2 extraction raise the question of how these costs compare to the alternative: taking actions to mitigate climate change by reducing fossil fuel CO_2 emissions. The Stern Review (Stern, 2006; Stern and Taylor, 2007) used expert opinion to produce an estimate for the cost of reducing emissions to limit global warming to about 2°C. Their central estimate was 1% of gross domestic product (GDP) per year, thus about $800 billion per year. They argued that this cost was much less than likely costs of future climate damage if high emissions continue, unless we apply a high "discount rate" to future damage, which has ethical implications in its treatment of today's young people and future generations. However, their estimated uncertainty of the cost is ±3%, i.e., the uncertainty is so large as to encompass GDP gain.

Hsu (2011) and Ackerman and Stanton (2012) argue that economies are more efficient if the price of fossil fuels better reflects costs to society, and thus GDP gain is likely with an increasing carbon price. Mankiw (2009) similarly suggests that a revenue-neutral carbon tax is economically beneficial. Hansen (2009, 2014) advocates an approach in which a gradually rising carbon fee is collected from the fossil fuel industry with the funds distributed uniformly to citizens. This approach provides incentives to business and the public that drive the economy toward energy efficiency, conservation, renewable energies and nuclear power. An economic study of this carbon-fee-and-dividend in the United States (Nystrom and Luckow, 2014) supports the conclusion that GDP increases as the fee rises steadily. These studies refute the common argument that environmental protection is damaging to economic prosperity.

We can also compare CO_2 extraction cost with the cost of carbon-free energy infrastructure. Global energy consumption in 2015 was 12.9 Gtoe,[16] with coal providing 30% of global energy and almost 45% of global fossil fuel CO_2 emissions (BP, 2016). Most coal use, and its increases, are in Asia, especially China and India. Carbon-free replacement for coal energy is expected to be some combination of renewables (including hydropower) and nuclear power. China is leading the world in installation of wind, solar and nuclear power, with new nuclear power in 2015 approximately matching the sum of new solar and wind power (BP, 2016). For future decarbonization of electricity it is easiest to estimate the cost of the nuclear power component, because nuclear power can replace coal for baseload electricity without the need for energy storage or major change to national electric grids. Recent costs of Chinese and South Korean light water reactors are in the range $2000-3000 per kilowatt (Chinese Academy of Engineering, 2015; Lovering et al., 2016), and it has been shown that reactor costs stabilize or decline with repeated construction of the same reactor design (Lovering et al., 2016). Using $2500 per kilowatt as reactor cost and assuming 85% capacity factor (percent uptime for reactors) yields a cost of $10 trillion to produce 20% of present global energy use (12.9 Gtoe). Note that 20% of current global energy use is a huge amount (Fig. 14), exceeding the sum of present hydropower (6.8%), nuclear (4.4%), wind (1.4%), solar (0.4%), and other renewable energies (0.9%).

[16] Gtoe is gigatons oil equivalent. 1 Gtoe is 41.868 EJ (Exajoule = 10^{18} Joules) or 11,630 TWh (terawatt hours).

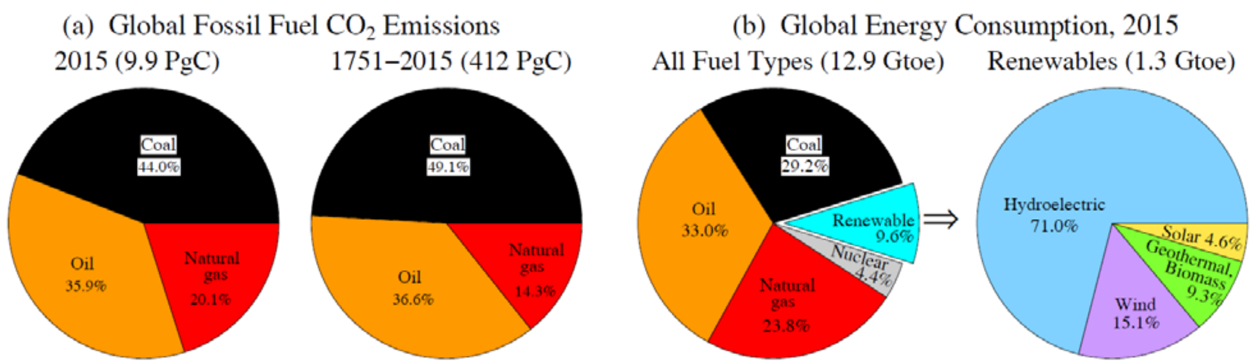

Figure 14. (a) Global fossil fuel emissions data from Boden et al. (2016) for 1751-2013 are extended to 2014-2015 using BP (2016) data. (b) Global energy consumption data from BP (2016).

We do not suggest that new nuclear power plants on this scale will or necessarily should be built. Rather we use this calculation to show that mitigation costs are not large in comparison to costs of extracting CO_2 from the air. Renewable energy costs have fallen rapidly in the past 2-3 decades with the help of government subsidies, especially renewable portfolio standards that require utilities to achieve a specified fraction of their power from renewable sources. Yet fossil fuel use continues to be high, at least in part because fossil fuel prices do not include their full cost to society. Rapid and economic movement to non-fossil energies would surely be aided by a rising carbon price, with the composition of future energy sources determined by competition among all non-fossil energy sources, as well as energy efficiency and conservation. Sweden provides a prime example: it cut per capita emissions by two-thirds since the 1970s while doubling per capita income in a capitalistic framework that embodies free-market principles (Pierrehumbert, 2016).

Mitigation of climate change deserves urgent priority. We disagree with assessments such as “The world will probably have only two choices if it wants to stay below 1.5°C of warming. It must either deploy carbon dioxide removal on an enormous scale or use solar geoengineering” (Parker and Geden, 2016). While we reject 1.5°C as a safe target – it is warmer than the Eemian and far above the Holocene range – Figure 13 shows that fossil fuel emission reduction of 3%/year beginning in 2021 yields maximum global warming ~1.5°C for climate sensitivity 3°C for 2×CO_2, with neither CO_2 removal nor geoengineering. These calculations show that mitigation – reduction of fossil fuel emissions – is very effective. We know no persuasive scientific reason to au priori reject as implausible rapid phasedown of fossil fuel emissions.

10 Non-CO_2 GHGs, Aerosols and Purposeful Climate Intervention

10.1 Non-CO_2 GHGs

GHG climate forcing is surging, not declining, the annual rate having increased more than 20% in just the past five years (Fig. A5). This recent surge in the growth rate of the GHG climate forcing is led by increasing growth of CH_4, but CO_2 is by far the largest cause of continued growth of the GHG climate forcing (Fig. 9). Given the difficulty and cost of reducing CO_2, we must ask about the alternative of reducing non-CO_2 GHGs. Could realistic reductions of these other gases substantially alter the CO_2 abundance required to meet a target climate forcing?

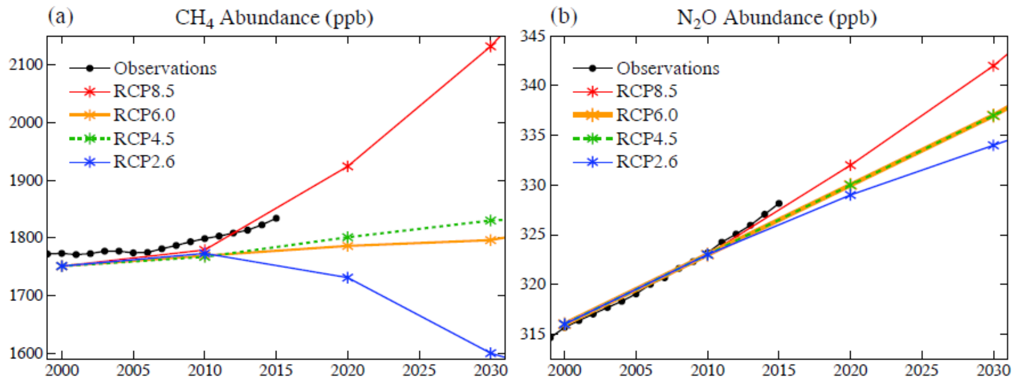

Figure 15. Comparison of observed CH_4 and N_2O amounts with RCP scenarios. RCP 6.0 and 4.5 scenarios for N_2O overlap. Observations are from NOAA/ESRL Global Monitoring Division.

Methane (CH_4) is the largest climate forcing other than CO_2 (Fig. 4). The CH_4 atmospheric lifetime is only about 10 years (Prather et al., 2012), so there is potential to reduce this climate forcing rapidly if CH_4 sources are reduced. Our climate simulations, employing the RCP6.0 chemistry model for emissions of non-CO_2 gases, make an optimistic assumption that future CH_4, after a moderate increase in the next few decades, will decrease from its present ~1800 ppb to 1650 ppb in 2100, yielding a forcing −0.1 W/m^2. However, the IPCC (Kirtman et al., 2013) recommended chemical projections of the RCP emissions gives a less beneficial view with a decrease to only 1734 ppb and a forcing change of −0.03 W/m^2. RCP2.6 makes a more optimistic assumption: that CH_4 will decline monotonically to 1250 ppb in 2100, yielding a forcing of −0.3 W/m^2 (relative to today's 1800 ppb CH_4), based on radiation equations identified in section 6, but again the IPCC chemical model projections reduce this to −0.2 W/m^2.

Actual (observed) atmospheric CH_4 amount (Fig. 15) is diverging well on the high side of these optimistic scenarios. The downward offset (~20 ppb) of CH_4 scenarios relative to observations (Fig. 15) is due to the fact that RCP scenarios did not include a data adjustment that was made in 2005 to match a revised CH_4 standard scale (E. Dlugokencky, pers. comm.), but observed CH_4 is also increasing more rapidly than in most scenarios. Reversal of CH_4 growth is made difficult by increasing global population, the diverse and widely distributed nature of agricultural sources, and global warming "in the pipeline," as these trends create an underlying tendency for increasing CH_4. Evidence for increased natural sources in a warmer climate are suggested by glacial-interglacial CH_4 increases of the order of 300 ppb.

Methane emissions from rice agriculture and ruminants potentially could be mitigated by changing rice growing methods (Epule et al., 2011) and inoculating ruminants (Eckard et al., 2010; Beil, 2015)], but that would require widespread adoption of new technologies at the farmer level. California, in implementing a state law to reduce GHG emissions, hopes to dramatically cut agricultural CH_4 emissions (see www.arb.ca.gov/cc/scopingplan/scopingplan.htm), but California has one of the most technological and regulated agricultural sectors in the world. It is not clear that this level of management can occur in the top agricultural CH_4 emitters like China, India and Brazil. Methane leaks from fossil fuel mining, transportation and use can be reduced, indeed, percentage leakage from conventional fossil fuel mining and fuel use has declined substantially in recent decades (Schwietzke et al, 2016), but there is danger of increased leakage with expanded shale gas extraction (Caulton et al., 2014; Petron et al., 2013; Howarth, 2015; Kang et al., 2016).

Prospects for reducing atmospheric CH_4 depend upon whether fossil fuel use is phased down. High fossil fuel use not only contributes CH_4 leakage, it also helps assure continued increase of global temperature and the amplifying effects of climate change on CH_4 biogenic emissions. Thus high fossil fuel use implies that CH_4 is likely to continue to increase. On the other hand, if global fossil fuel use is phased down, at least moderate reduction of CH_4 by 2100 seems feasible. For example, in that case a focus on agricultural emissions including adoption of new practices and technology at the farm level conceivably could reduce CH_4 climate forcing as much as 0.1-0.2 W/m^2. However, CH_4 reductions, should they be achieved, may be needed to offset growth of N_2O, which is projected to increase by 0.1-0.3 W/m^2.

There is less leverage with N_2O, whose growth is exceeding all scenarios (Fig. 15b). Major quantitative gaps remain in our understanding of the nitrogen cycle (Kroeze and Bouwman, 2011), but fertilizers are clearly a principal cause of N_2O growth (Röckmann and Levin 2005; Park et al., 2012). More efficient use of fertilizers could reduce N_2O emissions (Liu and Zhang, 2011), but considering the scale of global agriculture, and the fact that fixed N is an inherent part of feeding people, there will be pressure for continued emissions at least comparable to present emissions. In contrast, agricultural CH_4 emissions are inadvertent and not core to food production. Given the current imbalance [emissions exceeding atmospheric losses by about 30% (Prather et al., 2012)] and the long N_2O atmospheric lifetime (116 ± 9 years; Prather et al., 2015) it is nearly inevitable that N_2O will continue to increase this century, even if emissions growth is checked. There can be no expectation of an N_2O decline that offsets the need to reduce CO_2.

The Montreal Protocol has stifled and even reversed growth of specific trace gases that destroy ozone and cause global warming (Prather et al., 1996; Newman et al., 2009). The anticipated benefit over the 21st century is a drop in climate forcing of −0.23 W/m^2. Protocol amendments that add other gases such as HFCs are important; forcings of these gases are small today, but without the Protocol their potential for growth is possibly as large as +0.2 W/m^2.

In summary, a net decrease of climate forcing by non-CO_2 GHGs of perhaps −0.25 W/m^2 relative to today is plausible, but we must note that this is a dramatic change from the growing abundances, indeed accelerating growth, of these gases today. Achievement of this suggested negative forcing requires (i) successful completion of planned phase-out of MPTGs (−0.23 W/m^2), (ii) absolute reductions of CH_4 forcing by 0.12 W/m^2 from its present value, and (iii) N_2O forcing increases by only 0.1 W/m^2. Overall, this is an optimistic scenario because the RCP scenarios do not include known climate feedbacks that amplify biogenic emissions. Achieving this net negative forcing of −0.25 W/m^2 for non-CO_2 gases would allow CO_2 to be 365 ppm, rather than 350 ppm, while yielding the same total GHG forcing. Absolute reduction of non-CO_2 gases is thus helpful, but does not alter the requirement for rapid fossil fuel emission reductions. Indeed, the hypothesized non-CO_2 reduction does not seem plausible without a reduction of CO_2, which is needed to limit global warming and thus avoid amplifying GHG feedbacks.

10.2 Aerosols and Purposeful Climate Intervention

Human-made aerosols today cause a large, albeit poorly measured, negative climate forcing (Fig. 3), of the order of −1 W/m^2. Fossil fuel burning is only one of several human-caused aerosol sources (Boucher et al., 2013). Given that human population continues to grow, and that human-caused climate effects such as increased desertification can lead to increased aerosols, we do not anticipate a large reduction in the aerosol cooling effect, even if fossil fuel use declines.

Recognition that human-caused aerosols have a cooling effect, combined with the difficulty of restoring CO_2 to 350 ppm or less, inevitably raises the issue of purposeful climate intervention, also called geoengineering. The cooling mechanism receiving greatest attention is injection of SO_2 into the stratosphere (Budyko, 1974; Crutzen, 2006), thus creating sulfuric acid aerosols that mimic the effect of volcanic aerosol cooling. That idea and others are discussed in a report of the U.S. National Academy of Sciences (NAS, 2015b) and references therein. We limit our discussion to the following summary comments.

Such purposeful intervention in nature, an attempt to mitigate effects of one human-made pollutant with another, raises additional practical and ethical issues. Stratospheric aerosols, e.g., could deplete stratospheric ozone and/or modify climate and precipitation patterns in ways that are difficult to predict with confidence, while doing nothing to alleviate ocean acidification caused by rising CO_2; we note that Keith et al. (2016) suggest alternative aerosols that would limit the impact on ozone. However, climate intervention also raises issues of global governance, and introduces the possibility of sudden global consequences if aerosol injection is interrupted (Boucher at al., 2013). Despite these issues, it is apparent that cooling by aerosols, or other methods that alter the amount of sunlight absorbed by Earth, could be effective more quickly than the difficult process of removing CO_2 from the air. Thus we agree with the NAS (2015b) conclusion that research is warranted to better define the climate, economic, political, ethical, legal and other dimensions of potential climatic interventions.

In summary, although research on climate interventions is warranted, the possibility of geoengineering can hardly be seen as alleviating the overall burden being placed on young people by continued high fossil fuel emissions. We concur with the assessment (NAS, 2015b) that such climate interventions are no substitute for the reduction of carbon dioxide emissions needed to stabilize climate and avoid deleterious consequences of rapid climate change.

11. Discussion

Slow amplifying feedbacks and consequent climate impacts, including ice sheet melt and sea level rise, are probably the most threatening aspect of global warming. The inertia and slow initial response of the climate system to human-caused climate forcing allows large future climate response to build up “in the pipeline,” potentially creating a system with continuing change out of humanity’s control. As stated presciently by E. E. David, Jr. (1983), then President of EXXON Research and Engineering Company: “A look at the theory of feedback systems shows that where there is such a long delay the system breaks down unless there is anticipation built into the system.”

The question now is whether we have been too slow with anticipation. Certainly some effects of human-caused global warming are now unavoidable, but is it inevitable that sea level rise of many meters is locked in, and, if so, on what time scale? Precise unequivocal answers to such questions are not possible. However, useful statements can be made.

First, the inertia and slow response of the climate system also allow the possibility of actions to limit the climate response by reducing human-caused climate forcing in coming years and decades. Second, the response time itself depends on how strongly the system is being forced, specifically, the response can be much delayed with a weaker forcing.

For example, Hansen et al. (2016) conclude that continued high fossil fuel emissions this century would yield such a huge climate forcing that multi-meter sea level rise would be likely on a time scale of 50-150 years, with change continuing long thereafter. Ice sheet modeling reveals that ice sheet response time decreases rapidly as the magnitude of the forcing increases, because processes such as hydrofracturing of buttressing ice shelves and structural collapse of marine-terminating ice cliffs spur rapid ice sheet disintegration (Pollard et al., 2015). Paleoclimate analyses and climate modeling concur that both fast-feedback climate sensitivity and long-term climate sensitivity are dominated by amplifying feedbacks. All amplifying feedbacks, ranging from fast feedbacks, such as atmospheric water vapor and sea ice cover, to soil carbon release and ice sheet melt could be reduced by rapid emissions phasedown. This would reduce the risk of climate change running out of humanity's control and provide time to assess the climate response, develop relevant technologies, and consider further purposeful actions to limit and/or adapt to climate change.

Concern exists that large sea level rise may be inevitable, because of numerous ice streams on Antarctica and Greenland with inward-sloping beds (beds that deepen upstream) subject to runaway marine ice sheet instability (Mercer, 1978; Schoof, 2007, 2010). Some of these ice stream instabilities may already have been triggered (Rignot et al., 2014). However, the number of ice streams affected and the time scale of their response may differ strongly depending on the magnitude of the forcing (DeConto and Pollard, 2016). Sea level rise this century of say half a meter to a meter, which may be inevitable even if emissions decline, would have consequences, yet these are dwarfed by the humanitarian and economic disasters that would accompany sea level rise of several meters (McGranahan et al., 2007). Given the increasing proportion of global population living in coastal areas (Hallegatte et al., 2013), there is potential for forced migrations of hundreds of millions of people, dwarfing prior refugee humanitarian crises, challenging global governance (Biermann and Boas, 2010) and security (Gemenne et al., 2014).

Global temperature is a useful metric, because increasing temperature drives amplifying feedbacks. Global ocean temperature is a major factor affecting ice sheet size, as indicated by both model studies (Pollard et al., 2015) and paleoclimate analyses (Overpeck et al., 2006; Hansen et al., 2016). Eemian ocean warmth, probably not more than about +0.7°C warmer than pre-industrial conditions (McKay et al., 2011; Masson-Delmotte et al., 2013; Section 2.2 above), corresponding to global warmth about +1°C relative to preindustrial, led to sea level 6-9 m higher than today. This implies that, on the long run, the El Niño-elevated 2016 temperature of +1.3°C relative to preindustrial temperature, and even the (+1.05°C) underlying trend to date without the El Niño boost, are probably too high for maintaining our present coastlines.

We conclude that the world has already overshot appropriate targets for GHG amount and global temperature, and we thus infer an urgent need for both (1) rapid phasedown of fossil fuel emissions, (2) actions that draw down atmospheric CO_2, and (3) actions that, at minimum, eliminate net growth of non-CO_2 climate forcings. These tasks are formidable and, with the exception of the Montreal Protocol agreement on HFCs that will halt the growth of their climate forcing, they are not being pursued globally. Actions at citizen, city, state and national levels to reduce GHG emissions provide valuable experience and spur technical developments, but without effective global policies the impact of these local efforts is reduced by the negative feedback caused by reduced demand for and price of fossil fuels.

Our conclusion that the world has overshot appropriate targets is sufficiently grim to compel us to point out that pathways minimizing climate impacts are feasible and have other benefits.

The underlying policy required to spur rapid reduction of fossil fuel emissions is a transparent steadily rising carbon fee that makes fossil fuels include their costs to society (Ackerman and Stanton, 2012; Hsu, 2011; Hansen, 2014), which encourages energy conservation (reduced consumption), energy efficiency, and technology development of carbon-free energies. Rising awareness that such a policy is needed to secure a livable future has led to the formation of ad hoc citizen groups advocating for a carbon fee (https://citizensclimatelobby.org/) on every continent (http://engage4climate.org/marrakech; http://engage4climate.org/inteq). Although a rising global carbon fee, which could be achieved by agreement of a few major powers (Hsu, 2011), is the crucial underlying policy needed to spur investments, innovations and consumer choices, it will not obviate the need for government energy planning, energy efficiency and pollution regulations, and support for energy research and development.

Governments have shown the ability to achieve high rates of emissions reduction, e.g., Peters et al. (2013) note that Belgium, France and Sweden achieved emission reductions of 4-5%/year sustained over 10 or more years in response to the oil crisis of 1973. These rates were primarily a result of nuclear power build programs, which historically has been the fastest route to carbon-free energy (Fig. 2 of Cao et al., 2016). Peters et al. (2013) also note that a continuous shift from coal to natural gas led to sustained reductions of 1-2%/year in the UK in the 1970s and in the 2000s, 2%/year in Denmark in 1990-2000s, and 1.4%/year in the USA since 2005. None of these examples were aided by the broad economy-wide effect of a rising carbon fee, although high oil prices in the 1970s partially simulated that effect. What is needed to achieve rates presently demanded by the climate crisis is a combination of a rising carbon fee along with government support of technological advances, which has historically received the smallest share of total research budgets in OECD countries.

In addition to CO_2 emission phase-out, there must be large CO_2 extraction from the air and a net halt of growth of non-CO_2 GHG climate forcings to achieve the temperature stabilization of our scenarios. Success with both CO_2 extraction and non-CO_2 GHG controls requires a major role for developing countries. Ancillary benefits of the agricultural and forestry practices needed to achieve CO_2 drawdown, such as improved soil fertility, advanced agricultural practices, forest products, and species preservation, are of interest to all nations. Developed nations have a recognized obligation to assist nations that have done little to cause climate change yet suffer some of the largest climate impacts. If economic assistance is made partially dependent on verifiable success in carbon drawdown and non-CO_2 mitigation, this will provide incentives that maximize success in carbon storage. Some activities, such as soil amendments that enhance weathering, might be designed to support both CO_2 and other GHG drawdown.

Considering our conclusion that the world has overshot the appropriate target for global temperature, and the difficulty and perhaps implausibility of negative emissions scenarios, we would be remiss if we did not point out the potential contribution of demand-side mitigation that can be achieved by individual actions as well as by government policies. Numerous studies (e.g. Hedenhus et al., 2014; Popp et al., 2010) have shown that reduced ruminant meat and dairy products is needed to reduce GHG emissions from agriculture, even if technological improvements increase food yields per unit farmland. Such climate-beneficial dietary shifts have also been linked to co-benefits that include improved sustainability and public health (Bajzelj et al., 2014; Tilman and Clark, 2014). Similarly, Working Group 3 of IPCC (2014) finds “robust evidence and high agreement” that demand-side measures in the agriculture and land use sectors, especially dietary shifts, reduced food waste, and changes in wood use have substantial mitigation potential, but they remain under-researched and poorly quantified.

There is no time to delay. CO_2 extraction required to achieve 350 ppm CO_2 in 2100 was ~100 PgC if 6%/year emission reductions began in 2013 (Hansen et al., 2013). Required extraction is ~150 PgC in our updated scenarios, which incorporate growth of emissions in the past four years and assume that emissions will continue at approximately current levels until a global program of emission reductions begins in four years (in 2021 relative to 2020). The difficulty of stabilizing climate was thus markedly increased by a delay in emission reductions of eight years, from 2013 to 2021. Nevertheless, if rapid emission reductions are initiated soon, it is still possible that at least a large fraction of required CO_2 extraction can be achieved via relatively natural agricultural and forestry practices with other benefits. On the other hand, if large fossil fuel emissions are allowed to continue, the scale and cost of industrial CO_2 extraction, occurring in conjunction with a deteriorating climate and costly dislocations, may become unmanageable. Simply put, the burden placed on young people and future generations may become too heavy to bear.

Appendix A: Additional figures and tables

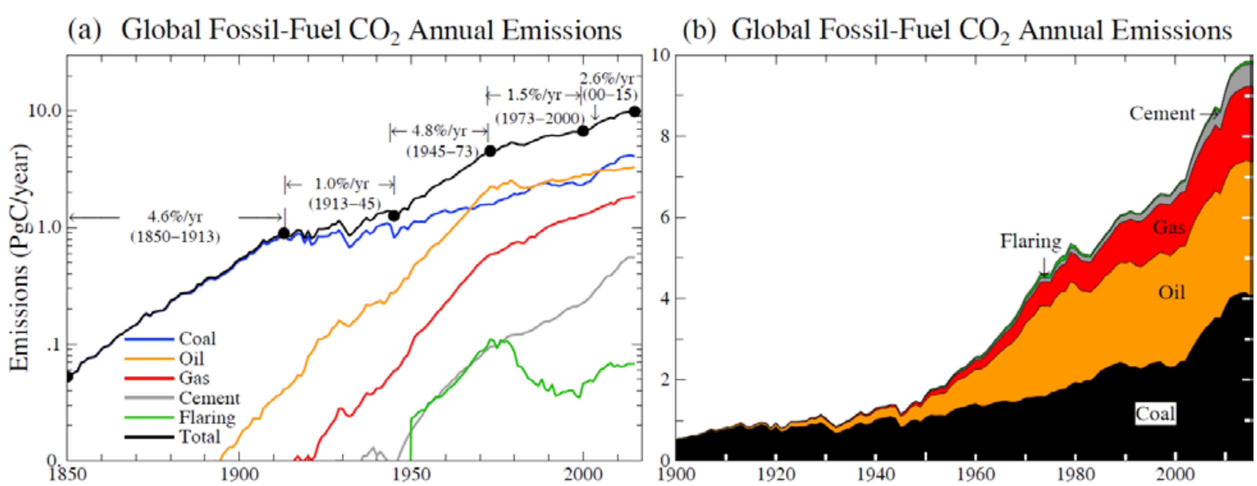

Figure A1. CO_2 emissions from fossil fuel use and cement manufacture, based on data of Boden et al. (2016) through 2013, with results extended using BP(2016) energy consumption data. (a) is log scale and (b) is linear. Growth rates r in (a) for an n year interval from $(1+r)^n$ with end-year amount the mean for three years to minimize noise.

A1. Fossil Fuel CO_2 Emissions

CO_2 emissions from fossil fuels in 2015, based on preliminary data from BP (2016), were only slightly higher than in 2014 (Fig. A1). Such slowdowns are common, and usually reflect the global economic situation. Given rising global population and the fact that many nations, including soon-to-be-most-populous India, are still at early stages of development, the potential exists for continued growth of emissions. Fundamental changes in energy technology will be needed if the world is to rapidly change energy course and phase down fossil fuel emissions.

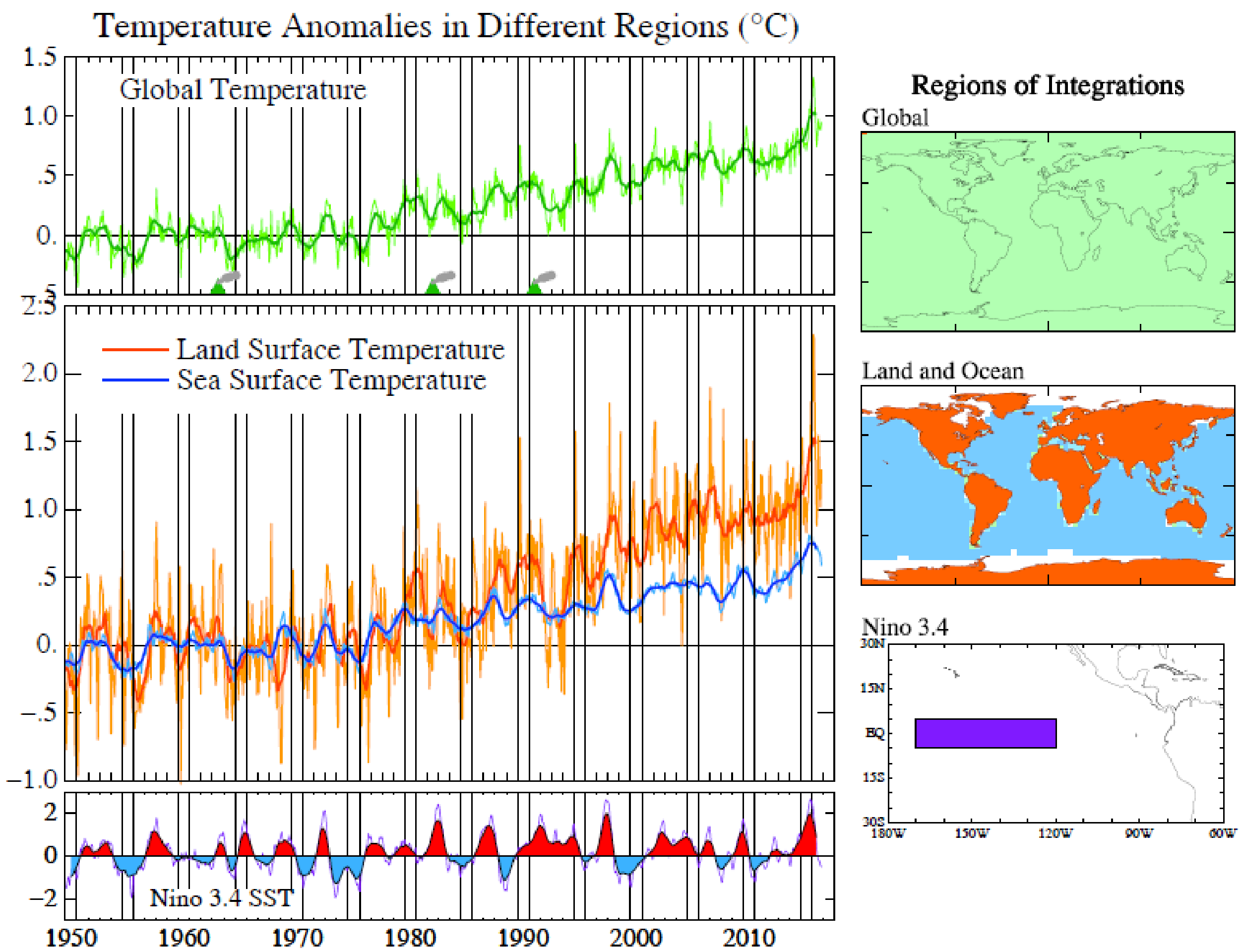

Figure A2a. Monthly (thin lines) and 12-month running mean (thick lines or filled colors for Niño 3.4) global, global land, sea surface, and Niño 3.4 temperatures. Temperatures are relative to 1951-1980 base period for the current GISTEMP analysis, which uses NOAA ERSST.v4 for sea surface temperature.

A2. Temperature Data and Analysis Method

We use the current Goddard Institute for Space Studies global temperature analysis (GISTEMP), which is the analysis method described by Hansen et al. (2010) but with updated input data. The analysis combines data from three sources: (1) monthly mean meteorological station data of the Global Historical Climatology Network (GHCN) described by Peterson and Vose (1997) and Menne et al. (2012), (2) monthly mean data from Antarctic research stations of the Scientific Committee on Antarctic Research (SCAR), as reported by the SCAR Reference Antarctic Data for Environmental Research project (http://www.antarctica.ac.uk/met/READER), and (3) ocean surface temperature measurements from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) (Smith et al., 2008; Huang et al., 2015).

Monthly and 12-month running mean temperatures relative to 1951-1980 base period (Fig. A2a) show that land temperature change is about twice SST change, and thus global SST change is about ¾ of global temperature change. Note that the Arctic Ocean and parts of the Southern Ocean are excluded in the calculations because of inadequate observations, but these regions are also not sampled in most paleo analyses and the excluded areas are small. Land area included covers 29% of the globe and ocean area included covers 65% of the globe.

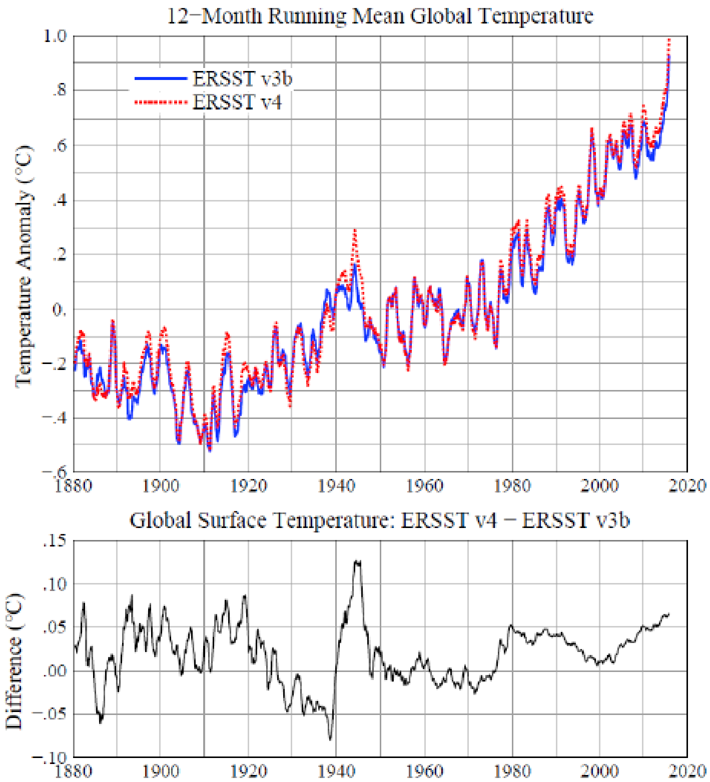

Figure A2b. Global surface temperature (12-month running mean) relative to 1951-1980 in the GISTEMP analysis, comparing the current analysis using NOAA ERSST.v4 for sea surface temperature with results using the prior ERSST.v3b.

The present analysis uses GHCN.v3.3.0 (Menne et al., 2012) for land data and ERSST.v4 for sea surface temperature (Huang et al., 2015). Update from GHCN.v2 used in our 2010 analysis to GHCN.v3 had negligible effect on global temperature change over the past century (see graph on http://www.columbia.edu/~mhs119/Temperature/GHCN_V3vsV2/). However, the adjustments to SST to produce ERSST.v4 have a noticeable effect, especially in the period 1939-1945, as shown by the difference between the two data sets (lower graph in Fig. A2b). This change is of interest mainly because it increases the magnitude of an already unusual global temperature fluctuation in the 1940s, making the 1939-1945 global temperature maximum even more pronounced than it was in ERSST.v3 data. Thompson et al. (2008) show that two natural sources of variability, the El Niño/Southern Oscillation and (possibly related) unusual winter Arctic warmth associated with advection over high Northern Hemisphere latitudes, partly account for global warmth of 1939-1945, and they suggest that the sharp cooling after 1945 is a data flaw, due to a rapid change in the mix of data sources (bucket measurements and engine room intake measurements) and a bias between these that is not fully accounted for.

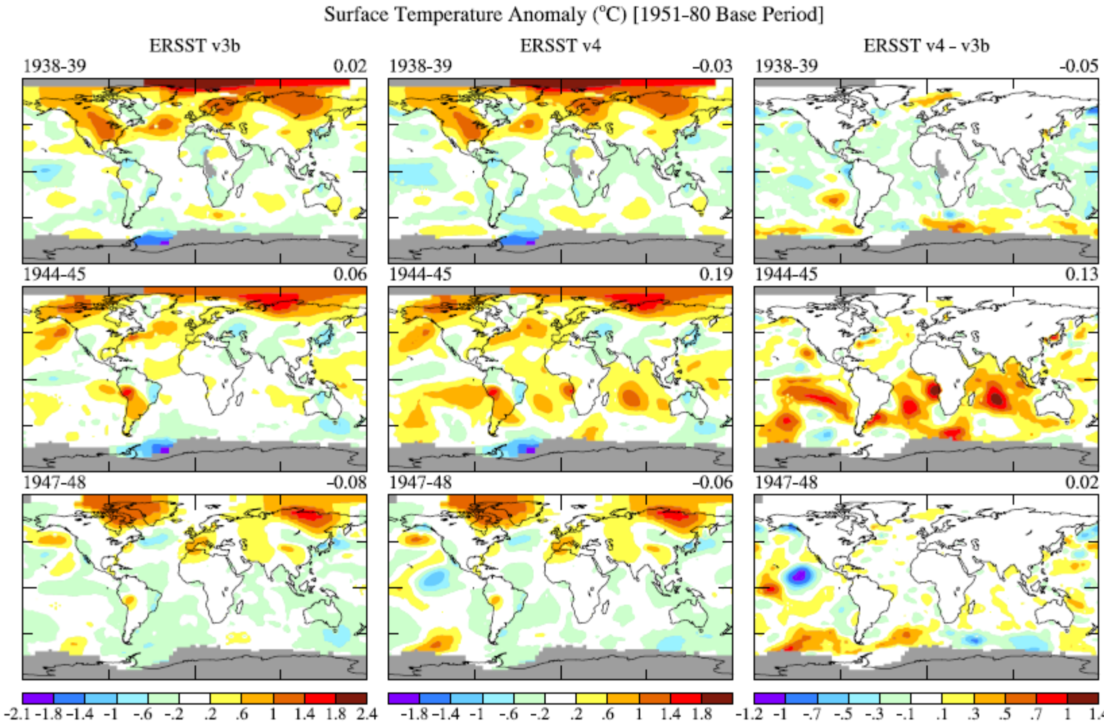

Figure A2c. Temperature anomalies in three periods relative to 1951-1980 comparing results obtained using ERSST.v3b (left column), ERSST.v4 (center column), and their difference (right column).

Huang et al. (2015) justify the changes made to obtain version 4 of ERSST, the changes including more complete input data in ICOADS Release 2.5, buoy SST bias adjustments not present in version 3, updated ship SST bias adjustments using Hadley Nighttime Marine Air Temperature version 2 (HadNMat2), and revised low-frequency data filling in data sparse regions using nearby observations. ERSST.v4 is surely an improvement in the record during the past half century when spatial and temporal data coverages are best. On the other hand, the largest changes between v3 and v4 are in 1939-1945, coinciding with World War II and changes in the mix of data sources. Several hot spots appear in the Southern Hemisphere ocean during WW II in the v4 data, and then disappear after the war (Fig. A2c). These hot spots coincide with the locations of large SST changes between v3 and v4 (Fig. A2c), which leads us to suspect that the magnitude of the 1940s global warming maximum (Fig. 2) is exaggerated; i.e., it is partly spurious. We suggest that this warming spike warrants scrutiny in the next version of the SST analysis. However, the important point is that these data adjustments and uncertainties are small in comparison with the long-term warming. Adjustments between ERSST.v3b and ERSST.v4 increase global warming over the period 1950-2015 by about 0.05°C, which is small compared with the ~1°C global warming during that period. The effect of the adjustments on total global warming between the beginning of the 20^{th} century and 2015 is even smaller (Fig. A2b).

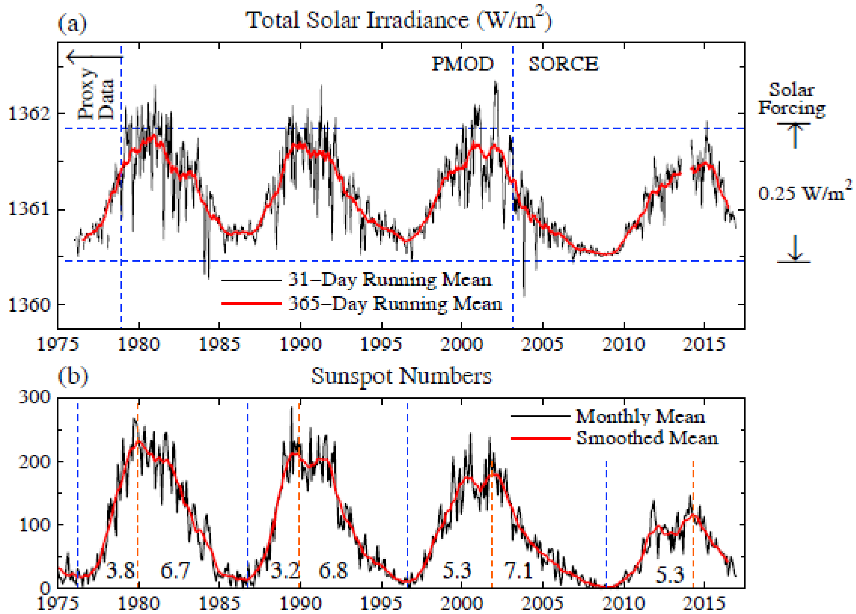

Figure A3. Solar irradiance and sunspot number in the era of satellite data. Left scale is the energy passing through an area perpendicular to Sun-Earth line. Averaged over Earth's surface the absorbed solar energy is ~240 W/m^2, so the full amplitude of the measured solar variability is ~0.25 W/m^2.

A3. Solar Irradiance

Solar irradiance has been measured from satellites since the late 1970s. Fig. A3 is a composite of several satellite-measured time series. Data through 28 February 2003 are an update of Frohlich and Lean (1998) obtained from Physikalisch Meteorologisches Observatorium Davos, World Radiation Center. Subsequent update is from University of Colorado Solar Radiation & Climate Experiment (SORCE). Historical total solar irradiance reconstruction is available at http://lasp.colorado.edu/home/sorce/data/tsi-data/ Data sets are concatenated by matching the means over the first 12 months of SORCE data. Monthly sunspot numbers support the conclusion that the solar irradiance in the current solar cycle is significantly lower than in the three preceding solar cycles.

The magnitude of the change of solar irradiance from the prior solar cycle to the current solar cycle is of the order of −0.1 W/m^2, which is not negligible but is small compared with greenhouse gas climate forcing. On the other hand, the variation of solar irradiance from solar minimum to solar maximum is of the order of 0.25 W/m^2, so the high solar irradiance in 2011 - 2015 contributes to the increase of Earth's energy imbalance between 2005-2010 and 2010-2015.

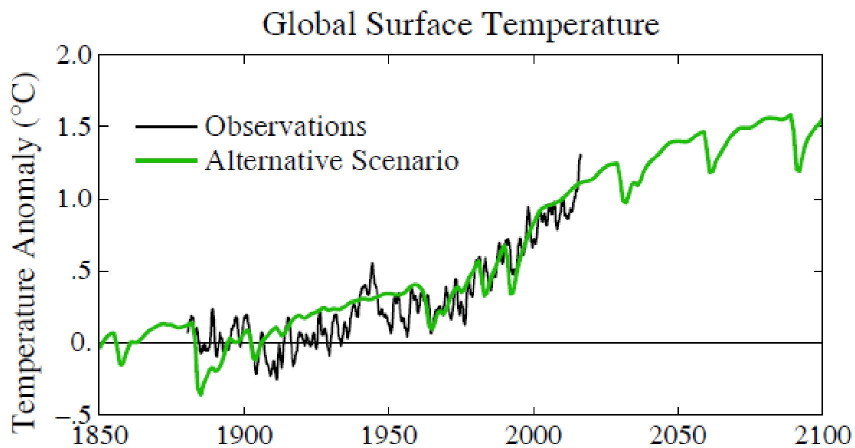

Figure A4. Simulated global temperature with historical climate forcings to 2000 followed by the alternative scenario. Historical climate forcings are discussed in the main text.

A4. Alternative Scenario

Simulated global temperature for the climate forcings of the "alternative scenario" discussed in Section 6 are shown in Fig. A4. Climate model, with sensitivity 3°C for doubled CO_2, is the same as used for Fig. 13.

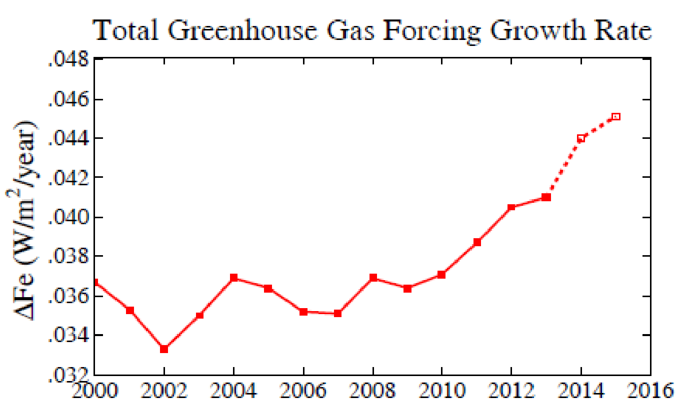

Figure A5. Recent growth rate of total GHG climate forcing; see Fig. 9 for individual gases.

A5. Growth Rate of Total GHG Climate Forcing

In the past several years the growth rate of climate forcing by GHGs has accelerated sharply, in contrast to most scenarios, which presumed that the GHG climate forcing would be declining. Ozone is not well-mixed, so its changes are not well-measured and are not fully accounted for in Fig.5. However, the effective CH_4 forcing, which is included, includes about half of the tropospheric O_3 change.

Table A1. Effective Forcing (W/m2) Relative to 1850 except Volcanic Aerosols

Year	CO_2	CH_4[a]	CFCs	N_2O	O_3[b]	TA+SA	Volcano	Solar	Net
1850	0.000	0.000	0.000	0.000	0.000	0.000	-0.083	0.000	-0.083
1860	0.024	0.012	0.000	0.004	0.004	-0.029	-0.106	0.032	-0.059
1870	0.048	0.025	0.000	0.007	0.009	-0.058	-0.014	0.048	0.065
1880	0.109	0.039	0.000	0.010	0.014	-0.097	-0.026	-0.049	-0.001
1890	0.179	0.054	0.000	0.013	0.018	-0.146	-0.900	-0.070	-0.850
1900	0.204	0.073	0.001	0.016	0.023	-0.195	-0.040	-0.063	0.018
1910	0.287	0.109	0.002	0.020	0.026	-0.250	-0.072	-0.043	0.079
1920	0.348	0.150	0.003	0.027	0.032	-0.307	-0.215	-0.016	0.022
1930	0.425	0.194	0.004	0.035	0.036	-0.364	-0.143	0.014	0.200
1940	0.494	0.232	0.005	0.041	0.045	-0.424	-0.073	0.037	0.356
1950	0.495	0.274	0.009	0.049	0.056	-0.484	-0.066	0.055	0.387
1960	0.599	0.342	0.027	0.057	0.078	-0.621	-0.106	0.102	0.478
1970	0.748	0.433	0.076	0.071	0.097	-0.742	-0.381	0.093	0.395
1980	0.976	0.532	0.185	0.091	0.115	-0.907	-0.108	0.169	1.054
1990	1.227	0.618	0.303	0.118	0.117	-0.997	-0.141	0.154	1.399
2000	1.464	0.651	0.347	0.141	0.117	-1.084	-0.048	0.173	1.761
2005	1.619	0.651	0.356	0.153	0.123	-1.125	-0.079	0.019	1.716
2010	1.766	0.665	0.364	0.167	0.129	-1.163	-0.082	0.028	1.874
2015	1.927	0.684	0.373	0.183	0.129	-1.199	-0.100	0.137	2.134

[a]CH_4:CH_4-induced changes of tropospheric O_3 and stratospheric H_2O are included.
[b]O_3 half of tropospheric O_3 forcing + stratospheric O_3 forcing from IPCC (2013)
Annual data are available in a longer version of the table available at
http://www.columbia.edu/~mhs119/Burden/.

Table A2. Effective Forcing (W/m^2) Relative to 1850 except Volcanic Aerosols

Year	CO_2	CH_4[c]	CFCs	N_2O	O_3[d]	TA+SA	Volcano	Solar	Net
2016	1.942	0.654	0.367	0.180	0.130	-1.207	-0.100	0.097	2.062
2020	2.074	0.658	0.373	0.189	0.130	-1.234	-0.100	-0.008	2.082
2030	2.347	0.663	0.343	0.212	0.130	-1.296	-1.057	-0.008	1.335
2040	2.580	0.688	0.301	0.238	0.123	-1.350	-0.100	0.027	2.507
2050	2.803	0.717	0.267	0.271	0.117	-1.396	-0.100	0.062	2.741
2060	3.017	0.740	0.243	0.302	0.111	-1.433	-1.208	0.097	1.870
2070	3.222	0.753	0.229	0.337	0.105	-1.462	-0.100	0.132	3.215
2080	3.421	0.741	0.215	0.367	0.098	-1.484	-0.100	0.167	3.425
2090	3.614	0.676	0.199	0.401	0.091	-1.495	-1.240	0.167	2.413
2100	3.801	0.580	0.191	0.428	0.085	-1.500	-0.100	0.167	3.652

[c]CH_4: CH_4-induced changes of tropospheric O_3 and stratospheric H_2O are included
[d]O_3: Half of tropospheric O_3 forcing + stratospheric O_3 forcing from IPCC 2013
Annual data are available in a longer version of the table available at
http://www.columbia.edu/~mhs119/Burden/.

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