CENTER for BIOLOGICAL DIVERSITY

Comments submitted via upload to www.regulations.gov
and via email to RegComments@fhfa.gov

March 26, 2012

Alfred M. Pollard
General Counsel
Federal Housing Finance Agency
Eighth Floor, 400 Seventh Street, S.W.
Washington, D.C. 20024

Attn: RIN 2590-AA53

Re: Federal Housing Finance Agency's Advance Notice of Proposed Rulemaking re Mortgage Assets Affected by Property Assessed Clean Energy Programs (RIN 2590-AA53); EIS Scoping Comments (RIN 2590-AA53)

Dear Mr. Pollard:

The Center for Biological Diversity ("The Center") submits the following comments regarding the Federal Housing Finance Agency's ("FHFA" or the "Agency") Advance Notice of Proposed Rulemaking re Mortgage Assets Affected by Property Assessed Clean Energy ("PACE") Programs, RIN 2590-AA53. The Center is a non-profit organization with more than 350,000 members and online activists and offices throughout the United States. The Center's mission is to ensure the preservation, protection and restoration of biodiversity, native species, ecosystems, public lands and waters and public health. In furtherance of these goals, the Center's Climate Law Institute seeks to reduce US greenhouse gas emissions and other air pollution to protect biological diversity, the environment, and human health and welfare.

The Center urges FHFA to withdraw its July 2010 statement and February 2011 directive restricting PACE programs and allow Fannie Mae and Freddie Mac to purchase mortgages secured by properties with PACE obligations or properties eligible for PACE obligations. The proposed rule bars homeowners from making essential energy related home improvements through the financing structure provided in PACE programs. Renewable energy and energy efficiency home improvements reduce greenhouse gas emissions, save homeowners money, and are critical tools to address climate change.

Through state run PACE programs, local governments finance renewable energy improvements for residents through assessment powers. Homeowners then pay for the energy retrofit costs on their property tax bill over time. More than twenty states have passed PACE legislation. On July 6, 2010, FHFA issued a "Statement on Certain Energy Retrofit Loan Programs," discussing its concerns with PACE programs. On February 28, 2011, FHFA issued a directive setting forth purported risks with PACE programs and instructing Fannie Mae and Freddie Mac to refrain from purchasing mortgages secured by properties with first-lien PACE obligations. FHFA's actions, the subject of the proposed rule, block homeowners from taking advantage of PACE programs, and, due to the high upfront costs of energy related home improvements, like residential solar power, effectively prevent many homeowners from making energy retrofits. Conversely, PACE programs remove the significant financial hurdle tied to energy related improvements and allow homeowners to undertake renewable energy and energy efficiency improvements.

PACE programs are critical tools in addressing climate change because energy related home improvements reduce greenhouse gas emissions. Reduction of greenhouse gas emissions protects biological diversity, the environment, and human health and welfare. The United States joined the rest of the world in 1992 in signing and ratifying the U.N. Framework Convention on Climate Change and agreed to take action to avoid dangerous anthropogenic interference with the climate system. The best available science now indicates that temperature increases must be held to, at most, 1.5 °C, corresponding to atmospheric CO_2 concentration levels of 350 ppm, if drastic and unacceptable consequences are to be avoided.[1] In fact, however, despite international efforts to reduce greenhouse gas pollution, global energy-related emissions rose to a new record high last year of 30.6 Gigatonnes (Gt), a 5% jump over the previous record year in 2008, when these emissions reached 29.3.[2] As stated by IEA's chief economist, it is now "becoming extremely challenging to remain below 2 degrees."[3] As calculated by the IEA, annual energy-related emissions should be no more than 32 Gt per year by 2020 to avoid exceeding the 2 °C goal; alarmingly, if emissions in 2011 have risen by the same 5% increase experienced in 2010 over 2008, the 32 Gt annual emission level may be reached nine years ahead of schedule.[4] Because emissions have continued to rise beyond expectations, the time frame for meaningful action has become even shorter.

The Middle Class Task Force's 2009 report entitled "Recovery Through Retrofit" found that the approximately 130 million homes in the US generate more than 20 percent of the nation's carbon dioxide emissions, significantly contributing to climate change. The report further found that energy efficient retrofitting can reduce home energy use by up to 40 percent

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[1] Hansen , J. et al., *Target Atmospheric CO2: Where Should Humanity Aim?* 2 OPEN ATMOSPHERIC SCI. J. 217, 218 (2008), *available at* http://pubs.giss.nasa.gov/abstracts/2008/Hansen_etal.html.; *see also* F. Harvey, *UN Chief Challenges World to Agree Tougher Target for Climate Change,* Guardian.co.uk (June 1, 2011), *available at* http://www.guardian.co.uk/environment/2011/jun/01/climate-change-target-christiana-figueres. Indeed, a more recent study holds that a margin of safety cannot be reached unless temperature increases are limited to 1 °C. J. Hansen et al., *The Case for Young People and Nature: A Path to a Healthy, Natural, Prosperous Future*, Draft paper (May 5, 2011), *available at* www.columbia.edu/~jeh1/mailings/.../20110505_CaseForYoungPeople.pdf.

[2] IEA, *Prospect of Limiting the Global Increase in Temperature To 2°C is Getting Bleaker* (May 30, 2011), *available at* http://www.iea.org/index_info.asp?id=1959 ("IEA Report").

[3] Harvey, F., *Worst Ever Carbon Emissions Leave Climate On the Brink*, Guardian.co.uk (May 29, 2011), *available at* http://www.guardian.co.uk/environment/2011/may/29/carbon-emissions-nuclearpower; *see also* Rogelj et al, *Emission Pathways Consistent with a 2 °C Global Temperature Limit*, Nature Climate Change Letters DOI:10.1033/NCIMATE1248 (Oct. 23, 2011), *available at www.nature.com/nclimate/journal/v1/n8/full/nclimate1258.html.*

[4] *Id.*

per home, reducing greenhouse gas emissions by up to 160 million metric tons by the year 2020. In addition to the environmental benefit, energy efficiency retrofits, according to the report, may reduce energy bills by $21 billion annually. Nevertheless, the report concluded that a key barrier to improving home energy efficiency is access to financing; the high upfront costs of energy related improvements bar many homeowners from making the improvements. The PACE programs serve as an incentive for homeowners to make energy related improvements and then pay the costs over time.

The FHFA should avoid creating barriers to renewable energy and energy efficiency home improvements. The proposed rule prevents homeowners from utilizing PACE programs to finance energy related home improvements. Such home improvements reduce the nation's greenhouse gas emissions and contribute to national and international efforts to address climate change. The Center believes FHFA should promote well-regulated PACE programs with appropriate standards, allowing homeowners to invest in energy improvements.

EIS Scoping Comments

As explained above, the agency's proposal will have significant and serious environmental impacts including increased greenhouse gas emissions and other air pollution. The agency must fully analyze the environmental impacts of its proposed rule in the upcoming NEPA analysis. We hope that full analysis and understanding of those impacts will convince the agency to alter its course.

We thank the Agency for the opportunity to provide our comments.

Sincerely,

Kassie Siegel
Center for Biological Diversity

The Open Atmospheric Science Journal, 2008, *2*, 217-231

Target Atmospheric CO_2: Where Should Humanity Aim?

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Abstract: Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica. Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. 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 current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.

Keywords: Climate change, climate sensitivity, global warming.

1. INTRODUCTION

Human activities are altering Earth's atmospheric composition. Concern about global warming due to long-lived human-made greenhouse gases (GHGs) led to the United Nations Framework Convention on Climate Change [1] with the objective of stabilizing GHGs in the atmosphere at a level preventing "dangerous anthropogenic interference with the climate system."

The Intergovernmental Panel on Climate Change [IPCC, [2]] and others [3] used several "reasons for concern" to estimate that global warming of more than 2-3°C may be dangerous. The European Union adopted 2°C above pre-industrial global temperature as a goal to limit human-made warming [4]. Hansen *et al*. [5] argued for a limit of 1°C global warming (relative to 2000, 1.7°C relative to pre-industrial time), aiming to avoid practically irreversible ice sheet and species loss. This 1°C limit, with nominal climate sensitivity of ¾°C per W/m^2 and plausible control of other GHGs [6], implies maximum CO_2 ~ 450 ppm [5].

Our current analysis suggests that humanity must aim for an even lower level of GHGs. Paleoclimate data and ongoing global changes indicate that 'slow' climate feedback processes not included in most climate models, such as ice sheet disintegration, vegetation migration, and GHG release from soils, tundra or ocean sediments, may begin to come into play on time scales as short as centuries or less [7]. Rapid on-going climate changes and realization that Earth is out of energy balance, implying that more warming is 'in the pipeline' [8], add urgency to investigation of the dangerous level of GHGs.

A probabilistic analysis [9] concluded that the long-term CO_2 limit is in the range 300-500 ppm for 25 percent risk tolerance, depending on climate sensitivity and non-CO_2 forcings. Stabilizing atmospheric CO_2 and climate requires that net CO_2 emissions approach zero, because of the long lifetime of CO_2 [10, 11].

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We use paleoclimate data to show that long-term climate has high sensitivity to climate forcings and that the present global mean CO_2, 385 ppm, is already in the dangerous zone. Despite rapid current CO_2 growth, ~2 ppm/year, we show that it is conceivable to reduce CO_2 this century to less than the current amount, but only *via* prompt policy changes.

1.1. Climate Sensitivity

A global climate forcing, measured in W/m^2 averaged over the planet, is an imposed perturbation of the planet's energy balance. Increase of solar irradiance (So) by 2% and doubling of atmospheric CO_2 are each forcings of about 4 W/m^2 [12].

Charney [13] defined an idealized climate sensitivity problem, asking how much global surface temperature would increase if atmospheric CO_2 were instantly doubled, assuming that slowly-changing planetary surface conditions, such as ice sheets and forest cover, were fixed. Long-lived GHGs, except for the specified CO_2 change, were also fixed, not responding to climate change. The Charney problem thus provides a measure of climate sensitivity including only the effect of 'fast' feedback processes, such as changes of water vapor, clouds and sea ice.

Classification of climate change mechanisms into fast and slow feedbacks is useful, even though time scales of these changes may overlap. We include as fast feedbacks aerosol changes, e.g., of desert dust and marine dimethylsulfide, that occur in response to climate change [7].

Charney [13] used climate models to estimate fast-feedback doubled CO_2 sensitivity of 3 ± 1.5°C. Water vapor increase and sea ice decrease in response to global warming were both found to be strong positive feedbacks, amplifying the surface temperature response. Climate models in the current IPCC [2] assessment still agree with Charney's estimate.

Climate models alone are unable to define climate sensitivity more precisely, because it is difficult to prove that models realistically incorporate all feedback processes. The Earth's history, however, allows empirical inference of both fast feedback climate sensitivity and long-term sensitivity to specified GHG change including the slow ice sheet feedback.

2. PLEISTOCENE EPOCH

Atmospheric composition and surface properties in the late Pleistocene are known well enough for accurate assessment of the fast-feedback (Charney) climate sensitivity. We first compare the pre-industrial Holocene with the last glacial maximum [LGM, 20 ky BP (before present)]. The planet was in energy balance in both periods within a small fraction of 1 W/m^2, as shown by considering the contrary: an imbalance of 1 W/m^2 maintained a few millennia would melt all ice on the planet or change ocean temperature an amount far outside measured variations [Table **S1** of 8]. The approximate equilibrium characterizing most of Earth's history is unlike the current situation, in which GHGs are rising at a rate much faster than the coupled climate system can respond.

Climate forcing in the LGM equilibrium state due to the ice age surface properties, i.e., increased ice area, different vegetation distribution, and continental shelf exposure, was -3.5 ± 1 W/m^2 [14] relative to the Holocene. Additional forcing due to reduced amounts of long-lived GHGs (CO_2, CH_4, N_2O), including the indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor (Fig. **S1**) was -3 ± 0.5 W/m^2. Global forcing due to slight changes in the Earth's orbit is a negligible fraction of 1 W/m^2 (Fig. **S3**). The total 6.5 W/m^2 forcing and global surface temperature change of 5 ± 1°C relative to the Holocene [15, 16] yield an empirical sensitivity ~¾ ± ¼ °C per W/m^2 forcing, i.e., a Charney sensitivity of 3 ± 1 °C for the 4 W/m^2 forcing of doubled CO_2. This empirical fast-feedback climate sensitivity allows water vapor, clouds, aerosols, sea ice, and all other fast feedbacks that exist in the real world to respond naturally to global climate change.

Climate sensitivity varies as Earth becomes warmer or cooler. Toward colder extremes, as the area of sea ice grows, the planet approaches runaway snowball-Earth conditions, and at high temperatures it can approach a runaway greenhouse effect [12]. At its present temperature Earth is on a flat portion of its fast-feedback climate sensitivity curve (Fig. **S2**). Thus our empirical sensitivity, although strictly the mean fast-feedback sensitivity for climate states ranging from the ice age to the current interglacial period, is also today's fast-feedback climate sensitivity.

2.1. Verification

Our empirical fast-feedback climate sensitivity, derived by comparing conditions at two points in time, can be checked over the longer period of ice core data. Fig. (**1a**) shows CO_2 and CH_4 data from the Antarctic Vostok ice core [17, 18] and sea level based on Red Sea sediment cores [18]. Gases are from the same ice core and have a consistent time scale, but dating with respect to sea level may have errors up to several thousand years.

We use the GHG and sea level data to calculate climate forcing by GHGs and surface albedo change as in prior calculations [7], but with two refinements. First, we specify the N_2O climate forcing as 12 percent of the sum of the CO_2 and CH_4 forcings, rather than the 15 percent estimated earlier [7] Because N_2O data are not available for the entire record, and its forcing is small and highly correlated with CO_2 and CH_4, we take the GHG effective forcing as

$$Fe\ (GHGs) = 1.12\ [Fa(CO_2) + 1.4\ Fa(CH_4)], \qquad (1)$$

using published formulae for Fa of each gas [20]. The factor 1.4 accounts for the higher efficacy of CH_4 relative to CO_2, which is due mainly to the indirect effect of CH_4 on tropospheric ozone and stratospheric water vapor [12]. The resulting GHG forcing between the LGM and late Holocene is 3 W/m^2, apportioned as 75% CO_2, 14% CH_4 and 11% N_2O.

The second refinement in our calculations is to surface albedo. Based on models of ice sheet shape, we take the horizontal area of the ice sheet as proportional to the 4/5 power of volume. Fig. (**S4**) compares our present albedo forcing with prior use [7] of exponent 2/3, showing that this

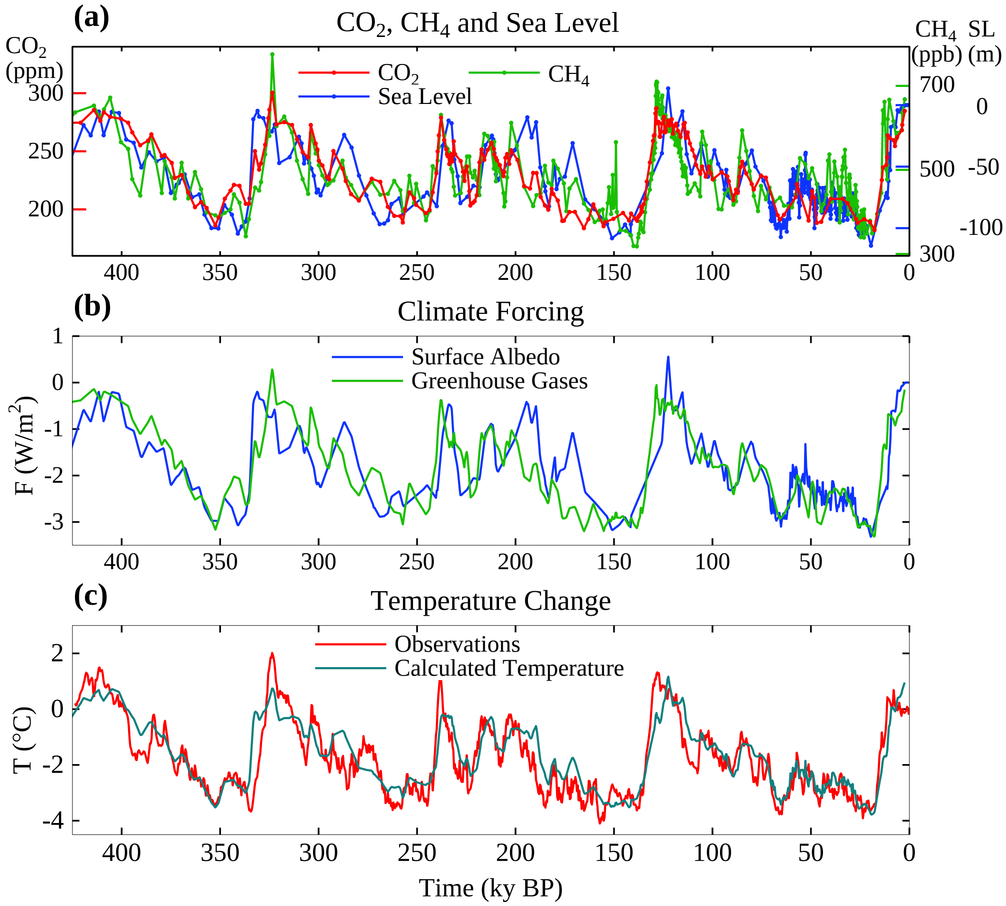

Fig. (1). (**a**) CO_2, CH_4 [17] and sea level [19] for past 425 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from sea level change. (**c**) Calculated global temperature change based on climate sensitivity of ¾°C per W/m^2. Observations are Antarctic temperature change [18] divided by two.

choice and division of the ice into multiple ice sheets has only a minor effect.

Multiplying the sum of GHG and surface albedo forcings by climate sensitivity ¾°C per W/m^2 yields the blue curve in Fig. (**1c**). Vostok temperature change [17] divided by two (red curve) is used to crudely estimate global temperature change, as typical glacial-interglacial global annual-mean temperature change is ~5°C and is associated with ~10°C change on Antarctica [21]. Fig. (**1c**) shows that fast-feedback climate sensitivity ¾°C per W/m^2 (3°C for doubled CO_2) is a good approximation for the entire period.

2.2. Slow Feedbacks

Let us consider climate change averaged over a few thousand years – long enough to assure energy balance and minimize effects of ocean thermal response time and climate change leads/lags between hemispheres [22]. At such temporal resolution the temperature variations in Fig. (**1**) are global, with high latitude amplification, being present in polar ice cores and sea surface temperature derived from ocean sediment cores (Fig. **S5**).

GHG and surface albedo changes are mechanisms causing the large global climate changes in Fig. (**1**), but they do not initiate these climate swings. Instead changes of GHGs and sea level (a measure of ice sheet size) lag temperature change by several hundred years [6, 7, 23, 24].

GHG and surface albedo changes are positive climate feedbacks. Major glacial-interglacial climate swings are instigated by slow changes of Earth's orbit, especially the tilt of Earth's spin-axis relative to the orbital plane and the precession of the equinoxes that influences the intensity of summer insolation [25, 26]. Global radiative forcing due to orbital changes is small, but ice sheet size is affected by changes of geographical and seasonal insolation (e.g., ice melts at both poles when the spin-axis tilt increases, and ice melts at one pole when perihelion, the closest approach to the sun, occurs in late spring [7]. Also a warming climate causes net release of GHGs. The most effective GHG feedback is release of CO_2 by the ocean, due partly to temperature dependence of CO_2 solubility but mostly to increased ocean mixing in a warmer climate, which acts to flush out

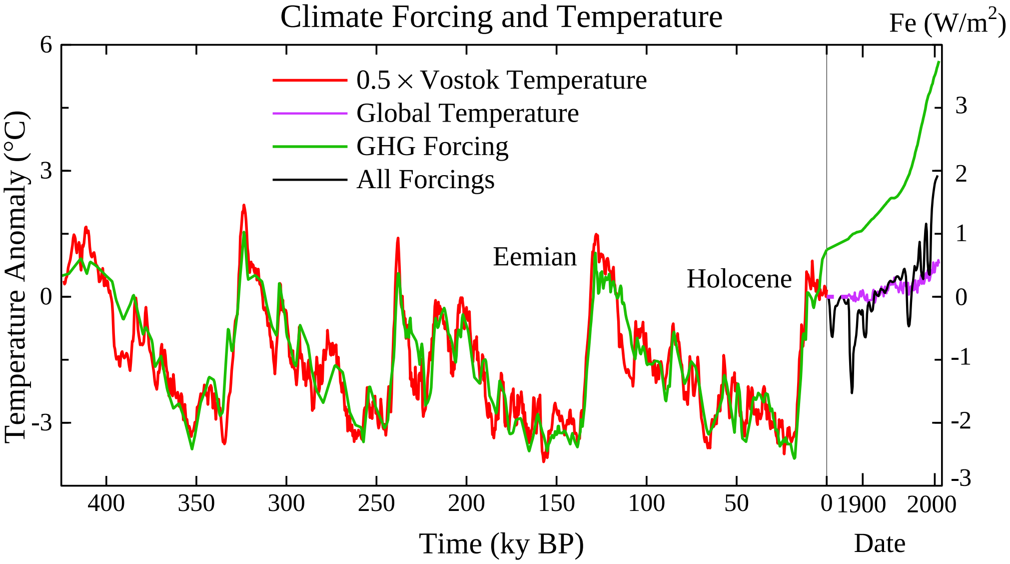

Fig. (2). Global temperature (left scale) and GHG forcing (right scale) due to CO_2, CH_4 and N_2O from the Vostok ice core [17, 18]. Time scale is expanded for the industrial era. Ratio of temperature and forcing scales is 1.5°C per W/m^2, i.e., the temperature scale gives the expected equilibrium response to GHG change including (slow feedback) surface albedo change. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky BP (Fig. **S6**). Zero point of modern temperature and net climate forcing was set at 1850 [5], but this is also the zero point for 10-8 ky BP, as shown by the absence of a trend in Fig. (**S6**) and by the discussion of that figure.

deep ocean CO_2 and alters ocean biological productivity [27].

GHG and surface albedo feedbacks respond and contribute to temperature change caused by any climate forcing, natural or human-made, given sufficient time. The GHG feedback is nearly linear in global temperature during the late Pleistocene (Fig. **7** of [6, 28]). Surface albedo feedback increases as Earth becomes colder and the area of ice increases. Climate sensitivity on

Pleistocene time scales includes slow feedbacks, and is larger than the Charney sensitivity, because the dominant slow feedbacks are positive. Other feedbacks, e.g., the negative feedback of increased weathering as CO_2 increases, become important on longer geologic time scales.

Paleoclimate data permit evaluation of long-term sensitivity to specified GHG change. We assume only that, to first order, the area of ice is a function of global temperature. Plotting GHG forcing [7] from ice core data [18] against temperature shows that global climate sensitivity including the slow surface albedo feedback is 1.5°C per W/m^2 or 6°C for doubled CO_2 (Fig. **2**), twice as large as the Charney fast-feedback sensitivity. Note that we assume the area of ice and snow on the planet to be predominately dependent on global temperature, but some changes of regional ice sheet properties occur as part of the Earth orbital climate forcing (see Supplementary Material).

This equilibrium sensitivity of 6°C for doubled CO_2 is valid for specified GHG amount, as in studies that employ emission scenarios and coupled carbon cycle/climate models to determine GHG amount. If GHGs are included as a feedback (with say solar irradiance as forcing) sensitivity is still larger on Pleistocene time scales (see Supplementary Material), but the sensitivity may be reduced by negative feedbacks on geologic time scales [29, 30]. The 6°C sensitivity reduces to 3°C when the planet has become warm enough to lose its ice sheets.

This long-term climate sensitivity is relevant to GHGs that remain airborne for centuries-to-millennia. The human-caused atmospheric GHG increase will decline slowly if anthropogenic emissions from fossil fuel burning decrease enough, as we illustrate below using a simplified carbon cycle model. On the other hand, if the globe warms much further, carbon cycle models [2] and empirical data [6, 28] reveal a positive GHG feedback on century-millennia time scales. This amplification of GHG amount is moderate if warming is kept within the range of recent interglacial periods [6], but larger warming would risk greater release of CH_4 and CO_2 from methane hydrates in tundra and ocean sediments [29]. On still longer, geological, time scales weathering of rocks causes a negative feedback on atmospheric CO_2 amount [30], as discussed in section 3, but this feedback is too slow to alleviate climate change of concern to humanity.

2.3. Time Scales

How long does it take to reach equilibrium temperature with specified GHG change? Response is slowed by ocean thermal inertia and the time needed for ice sheets to disintegrate.

Ocean-caused delay is estimated in Fig. (**S7**) using a coupled atmosphere-ocean model. One-third of the response occurs in the first few years, in part because of rapid response over land, one-half in ~25 years, three-quarters in 250 years, and nearly full response in a millennium. The ocean-caused delay is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of surface water and deep water [31], as discussed in the Supplementary Material Section.

Ice sheet response time is often assumed to be several millennia, based on the broad sweep of paleo sea level change (Fig. **1a**) and primitive ice sheet models designed to capture that change. However, this long time scale may reflect the slowly changing orbital forcing, rather than inherent inertia, as there is no discernable lag between maximum ice sheet melt rate and local insolation that favors melt [7]. Paleo sea level data with high time resolution reveal frequent ‘suborbital’ sea level changes at rates of 1 m/century or more [32-34].

Present-day observations of Greenland and Antarctica show increasing surface melt [35], loss of buttressing ice shelves [36], accelerating ice streams [37], and increasing overall mass loss [38]. These rapid changes do not occur in existing ice sheet models, which are missing critical physics of ice sheet disintegration [39]. Sea level changes of several meters per century occur in the paleoclimate record [32, 33], in response to forcings slower and weaker than the present human-made forcing. It seems likely that large ice sheet response will occur within centuries, if human-made forcings continue to increase. Once ice sheet disintegration is underway, decadal changes of sea level may be substantial.

2.4. Warming “in the Pipeline”

The expanded time scale for the industrial era (Fig. **2**) reveals a growing gap between actual global temperature (purple curve) and equilibrium (long-term) temperature response based on the net estimated climate forcing (black curve). Ocean and ice sheet response times together account for this gap, which is now 2.0°C.

The forcing in Fig. (**2**) (black curve, Fe scale), when used to drive a global climate model [5], yields global temperature change that agrees closely (Fig. **3** in [5]) with observations (purple curve, Fig. **2**). That climate model, which includes only fast feedbacks, has additional warming of ~0.6°C in the pipeline today because of ocean thermal inertia [5, 8].

The remaining gap between equilibrium temperature for current atmospheric composition and actual global temperature is ~1.4°C. This further 1.4°C warming still to come is due to the slow surface albedo feedback, specifically ice sheet disintegration and vegetation change.

One may ask whether the climate system, as the Earth warms from its present ‘interglacial’ state, still has the capacity to supply slow feedbacks that double the fast-feedback sensitivity. This issue can be addressed by considering longer time scales including periods with no ice.

3. CENOZOIC ERA

Pleistocene atmospheric CO_2 variations occur as a climate feedback, as carbon is exchanged among surface reservoirs: the ocean, atmosphere, soils and biosphere. The most effective feedback is increase of atmospheric CO_2 as climate warms, the CO_2 transfer being mainly from ocean to atmosphere [27, 28]. On longer time scales the total amount of CO_2 in the surface reservoirs varies due to exchange of carbon with the solid earth. CO_2 thus becomes a primary agent of long-term climate change, leaving orbital effects as ‘noise’ on larger climate swings.

The Cenozoic era, the past 65.5 My, provides a valuable complement to the Pleistocene for exploring climate sensitivity. Cenozoic data on climate and atmospheric composition are not as precise, but larger climate variations occur, including an ice-free planet, thus putting glacial-interglacial changes in a wider perspective.

Oxygen isotopic composition of benthic (deep ocean dwelling) foraminifera shells in a global compilation of ocean sediment cores [26] provides a starting point for analyzing Cenozoic climate change (Fig. **3a**). At times with negligible ice sheets, oxygen isotope change, $\delta^{18}O$, provides a direct measure of deep ocean temperature (T_{do}). Thus T_{do} (°C) ~ $-4\ \delta^{18}O + 12$ between 65.5 and 35 My BP.

Rapid increase of $\delta^{18}O$ at about 34 My is associated with glaciation of Antarctica [26, 40] and global cooling, as evidenced by data from North America [41] and Asia [42]. From then until the present, ^{18}O in deep ocean foraminifera is affected by both ice volume and T_{do}, lighter ^{16}O evaporating preferentially from the ocean and accumulating in ice sheets. Between 35 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3‰, change of T_{do} was ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Given that a 1.5‰ change of $\delta^{18}O$ is associated with a 6°C T_{do} change, we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75). Equal division of $\delta^{18}O$ between temperature and sea level yields sea level change in the late Pleistocene in reasonable accord with available sea level data (Fig. **S8**). Subtracting the ice volume portion of $\delta^{18}O$ yields deep ocean temperature T_{do} (°C) = $-2\ (\delta^{18}O - 4.25‰)$ after 35 My, as in Fig. (**3b**).

The large (~14°C) Cenozoic temperature change between 50 My and the ice age at 20 ky must have been forced by changes of atmospheric composition. Alternative drives could come from outside (solar irradiance) or the Earth’s surface (continental locations). But solar brightness increased ~0.4% in the Cenozoic [43], a linear forcing change of only +1 W/m^2 and of the wrong sign to contribute to the cooling trend. Climate forcing due to continental locations was < 1 W/m^2, because continents 65 My ago were already close to present latitudes (Fig. **S9**). Opening or closing of oceanic gateways might affect the timing of glaciation, but it would not provide the climate forcing needed for global cooling.

CO_2 concentration, in contrast, varied from ~180 ppm in glacial times to 1500 ± 500 ppm in the early Cenozoic [44]. This change is a forcing of more than 10 W/m^2 (Table **1** in [16]), an order of magnitude larger than other known forcings. CH_4 and N_2O, positively correlated with CO_2 and global temperature in the period with accurate data (ice cores), likely increase the total GHG forcing, but their forcings are much smaller than that of CO_2 [45, 46].

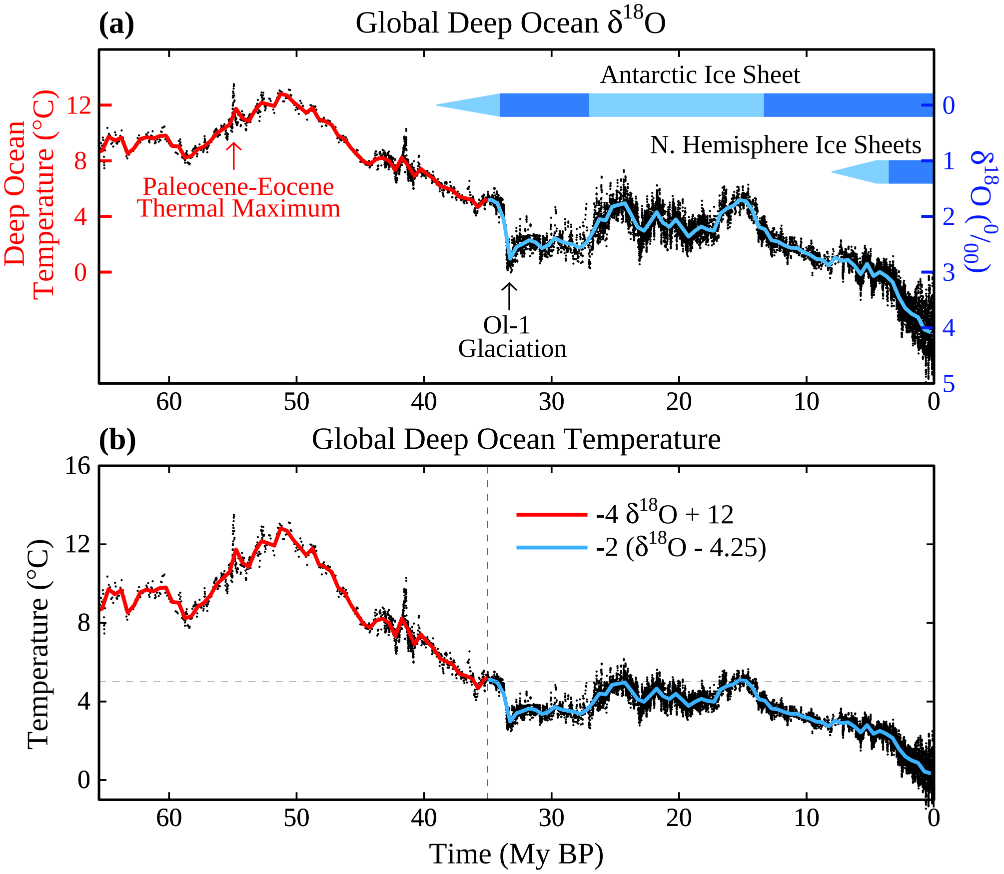

Fig. (3). Global deep ocean (**a**) $\delta^{18}O$ [26] and (**b**) temperature. Black curve is 5-point running mean of $\delta^{18}O$ original temporal resolution, while red and blue curves have 500 ky resolution.

3.1. Cenozoic Carbon Cycle

Solid Earth sources and sinks of CO_2 are not, in general, balanced at any given time [30, 47]. CO_2 is removed from surface reservoirs by: (1) chemical weathering of rocks with deposition of carbonates on the ocean floor, and (2) burial of organic matter; weathering is the dominant process [30]. CO_2 returns primarily *via* metamorphism and volcanic outgassing at locations where carbonate-rich oceanic crust is being subducted beneath moving continental plates.

Outgassing and burial of CO_2 are each typically 10^{12}-10^{13} mol C/year [30, 47-48]. At times of unusual plate tectonic activity, such as rapid subduction of carbon-rich ocean crust or strong orogeny, the imbalance between outgassing and burial can be a significant fraction of the one-way carbon flux. Although negative feedbacks in the geochemical carbon cycle reduce the rate of surface reservoir perturbation [49], a net imbalance ~10^{12} mol C/year can be maintained over thousands of years. Such an imbalance, if confined to the atmosphere, would be ~0.005 ppm/year, but as CO_2 is distributed among surface reservoirs, this is only ~0.0001 ppm/year. This rate is negligible compared to the present human-made atmospheric CO_2 increase of ~2 ppm/year, yet over a million years such a crustal imbalance alters atmospheric CO_2 by 100 ppm.

Between 60 and 50 My ago India moved north rapidly, 18-20 cm/year [50], through a region that long had been a depocenter for carbonate and organic sediments. Subduction of carbon-rich crust was surely a large source of CO_2 outgassing and a prime cause of global warming, which peaked 50 My ago (Fig. **3b**) with the Indo-Asian collision. CO_2 must have then decreased due to a reduced subduction source and enhanced weathering with uplift of the Himalayas/Tibetan Plateau [51]. Since then, the Indian and Atlantic Oceans have been major depocenters for carbon, but subduction of carbon-rich crust has been limited mainly to small regions near Indonesia and Central America [47].

Thus atmospheric CO_2 declined following the Indo-Asian collision [44] and climate cooled (Fig. **3b**) leading to Antarctic glaciation by ~34 My. Antarctica has been more or less glaciated ever since. The rate of CO_2 drawdown declines as atmospheric CO_2 decreases due to negative feedbacks, including the effect of declining atmospheric temperature and plant growth rates on weathering [30]. These negative feedbacks tend to create a balance between crustal outgassing and drawdown of CO_2, which have been equal within 1-2 percent over the past 700 ky [52]. Large fluctuations in the size of the Antarctic ice sheet have occurred in the past 34 My, possibly related to temporal variations of plate tectonics [53] and outgassing rates. The relatively constant atmospheric CO_2 amount of the past 20 My (Fig. **S10**) implies a near balance of outgassing and weathering rates over that period.

Knowledge of Cenozoic CO_2 is limited to imprecise proxy measures except for recent ice core data. There are discrepancies among different proxy measures, and even between different investigators using the same proxy method, as discussed in conjunction with Fig. (**S10**). Nevertheless, the proxy data indicate that CO_2 was of the order of 1000 ppm in the early Cenozoic but <500 ppm in the last 20 My [2, 44].

3.2. Cenozoic Forcing and CO_2

The entire Cenozoic climate forcing history (Fig. **4a**) is implied by the temperature reconstruction (Fig. **3b**), assuming a fast-feedback sensitivity of ¾°C per W/m^2. Subtracting the solar and surface albedo forcings (Fig. **4b**), the latter from Eq. S2 with ice sheet area *vs* time from $\delta^{18}O$, we obtain the GHG forcing history (Fig. **4c**).

We hinge our calculations at 35 My for several reasons. Between 65 and 35 My ago there was little ice on the planet, so climate sensitivity is defined mainly by fast feedbacks. Second, we want to estimate the CO_2 amount that precipitated Antarctic glaciation. Finally, the relation between global surface air temperature change (ΔT_s) and deep ocean temperature change (ΔT_{do}) differs for ice-free and glaciated worlds.

Climate models show that global temperature change is tied closely to ocean temperature change [54]. Deep ocean temperature is a function of high latitude ocean surface temperature, which tends to be amplified relative to global mean ocean surface temperature. However, land temperature change exceeds that of the ocean, with an effect on global temperature that tends to offset the latitudinal variation of ocean temperature. Thus in the ice-free world (65-35 My) we take $\Delta T_s \sim \Delta T_{do}$ with generous (50%) uncertainty. In the glaciated world ΔT_{do} is limited by the freezing point in the deep ocean. ΔT_s between the last ice age (20 ky) and the present

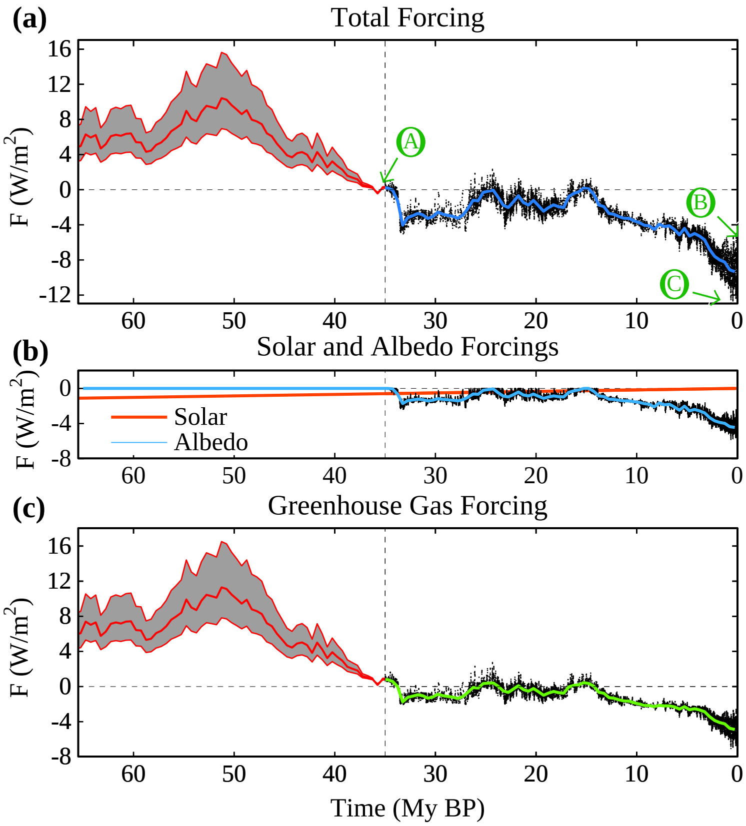

Fig. (4). (**a**) Total climate forcing, (**b**) solar and surface albedo forcings, and (**c**) GHG forcing in the Cenozoic, based on T_{do} history of Fig. (**3b**) and assumed fast-feedback climate sensitivity ¾°C per W/m^2. Ratio of T_s change and T_{do} change is assumed to be near unity in the minimal ice world between 65 and 35 My, but the gray area allows for 50% uncertainty in the ratio. In the later era with large ice sheets we take $\Delta T_s/\Delta T_{do} = 1.5$, in accord with Pleistocene data.

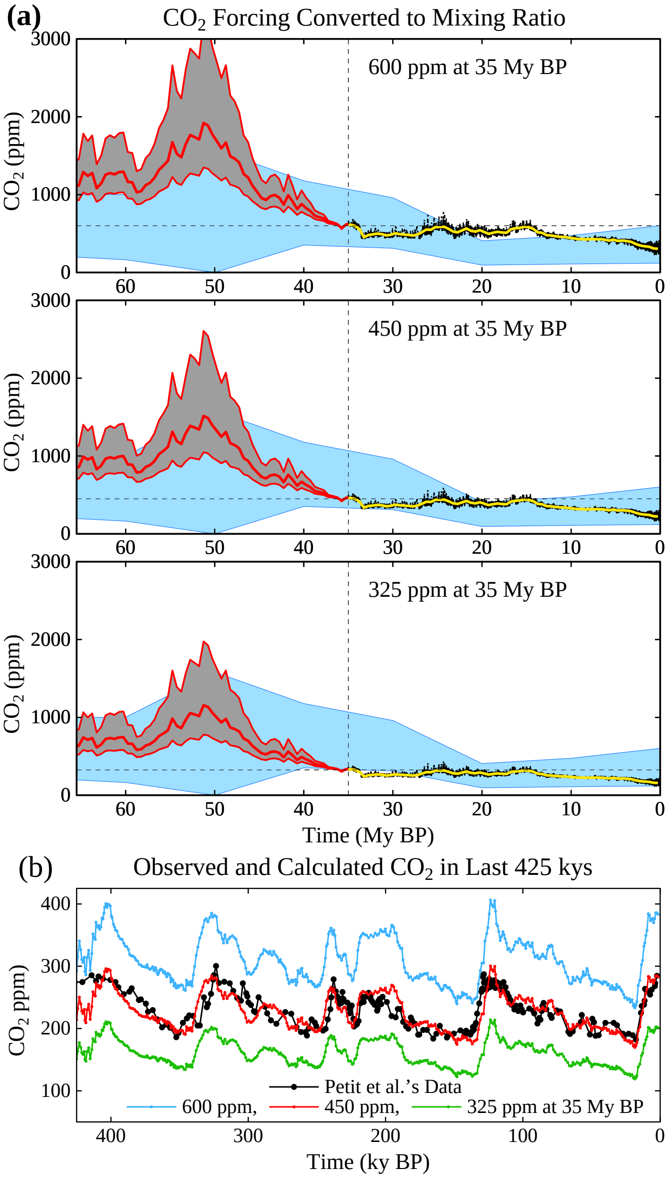

Fig. (5). (**a**) Simulated CO_2 amounts in the Cenozoic for three choices of CO_2 amount at 35 My (temporal resolution of black and colored curves as in Fig. (**3**); blue region: multiple CO_2 proxy data, discussed with Fig. (**S10**); gray region allows 50 percent uncertainty in ratio of global surface and deep ocean temperatures). (**b**) Expanded view of late Pleistocene, including precise ice core CO_2 measurements (black curve).

interglacial period (~5°C) was ~1.5 times larger than ΔT_{do}. In Fig. (**S5**) we show that this relationship fits well throughout the period of ice core data.

If we specify CO_2 at 35 My, the GHG forcing defines CO_2 at other times, assuming CO_2 provides 75% of the GHG forcing, as in the late Pleistocene. CO_2 ~450 ppm at 35 My keeps CO_2 in the range of early Cenozoic proxies (Fig. **5a**) and yields a good fit to the amplitude and mean CO_2 amount in the late Pleistocene (Fig. **5b**). A CO_2 threshold for Antarctic glaciation of ~500 ppm was previously inferred from proxy CO_2 data and a carbon cycle model [55].

Individual CO_2 proxies (Fig. **S10**) clarify limitations due to scatter among the measurements. Low CO_2 of some early Cenozoic proxies, if valid, would suggest higher climate sensitivity. However, in general the sensitivities inferred from the Cenozoic and Phanerozoic [56, 57, 58] agree well with our analysis, if we account for the ways in which sensitivity is defined and the periods emphasized in each empirical derivation (Table **S1**).

Our CO_2 estimate of ~450 ppm at 35 My (Fig. **5**) serves as a prediction to compare with new data on CO_2 amount. Model uncertainties (Fig. **S10**) include possible changes of non-CO_2 GHGs and the relation of ΔT_s to ΔT_{do}. The model fails to account for cooling in the past 15 My if CO_2 increased, as several proxies suggest (Fig. **S10**). Changing ocean currents, such as the closing of the Isthmus of Panama, may have contributed to climate evolution, but models find little effect on temperature [59]. Non-CO_2 GHGs also could have played a role, because little forcing would have been needed to cause cooling due to the magnitude of late Cenozoic albedo feedback.

3.3. Implication

We infer from Cenozoic data that CO_2 was the dominant Cenozoic forcing, that CO_2 was ~450 ± 100 ppm when Antarctica glaciated, and that glaciation is reversible. Together these inferences have profound implications.

Consider three points marked in Fig. (**4**): point A at 35 My, just before Antarctica glaciated; point B at recent interglacial periods; point C at the depth of recent ice ages. Point B is about half way between A and C in global temperature (Fig. **3b**) and climate forcings (Fig. **4**). The GHG forcing from the deepest recent ice age to current interglacial warmth is ~3.5 W/m^2. Additional 4 W/m^2 forcing carries the planet, at equilibrium, to the ice-free state. Thus equilibrium climate sensitivity to GHG change, including the surface albedo change as a slow feedback, is almost as large between today and an ice-free world as between today and the ice ages.

The implication is that global climate sensitivity of 3°C for doubled CO_2, although valid for the idealized Charney definition of climate sensitivity, is a considerable understatement of expected equilibrium global warming in response to imposed doubled CO_2. Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity.

Equilibrium sensitivity 6°C for doubled CO_2 is relevant to the case in which GHG changes are specified. That is appropriate to the anthropogenic case, provided the GHG amounts are estimated from carbon cycle models including climate feedbacks such as methane release from tundra and ocean sediments. The equilibrium sensitivity is even higher if the GHG feedback is included as part of the climate response, as is appropriate for analysis of the climate response to Earth orbital perturbations. The very high sensitivity with both albedo and GHG slow feedbacks included accounts for the huge magnitude of glacial-interglacial fluctuations in the Pleistocene (Fig. **3**) in response to small forcings (section 3 of Supplementary Material).

Equilibrium climate response would not be reached in decades or even in a century, because surface warming is slowed by the inertia of the ocean (Fig. **S7**) and ice sheets. However, Earth's history suggests that positive feedbacks, especially surface albedo changes, can spur rapid global warmings, including sea level rise as fast as several meters per century [7]. Thus if humans push the climate system sufficiently far into disequilibrium, positive climate feedbacks may set in motion dramatic climate change and climate impacts that cannot be controlled.

4. ANTHROPOCENE ERA

Human-made global climate forcings now prevail over natural forcings (Fig. **2**). Earth may have entered the Anthropocene era [60, 61] 6-8 ky ago [62], but the net human-made forcing was small, perhaps slightly negative [7], prior to the industrial era. GHG forcing overwhelmed natural and negative human-made forcings only in the past quarter century (Fig. **2**).

Human-made climate change is delayed by ocean (Fig. **S7**) and ice sheet response times. Warming 'in the pipeline', mostly attributable to slow feedbacks, is now about 2°C (Fig. **2**). No additional forcing is required to raise global temperature to at least the level of the Pliocene, 2-3 million years ago, a degree of warming that would surely yield 'dangerous' climate impacts [5].

4.1. Tipping Points

Realization that today's climate is far out of equilibrium with current climate forcings raises the specter of 'tipping points', the concept that climate can reach a point where, without additional forcing, rapid changes proceed practically out of our control [2, 7, 63, 64]. Arctic sea ice and the West Antarctic Ice Sheet are examples of potential tipping points. Arctic sea ice loss is magnified by the positive feedback of increased absorption of sunlight as global warming initiates sea ice retreat [65]. West Antarctic ice loss can be accelerated by several feedbacks, once ice loss is substantial [39].

We define: (1) the *tipping level*, the global climate forcing that, if long maintained, gives rise to a specific consequence, and (2) the *point of no return*, a climate state beyond which the consequence is inevitable, even if climate forcings are reduced. A point of no return can be avoided, even if the tipping level is temporarily exceeded. Ocean and ice sheet inertia permit overshoot, provided the climate forcing is returned below the tipping level before initiating irreversible dynamic change.

Points of no return are inherently difficult to define, because the dynamical problems are nonlinear. Existing models are more lethargic than the real world for phenomena now unfolding, including changes of sea ice [65], ice streams [66], ice shelves [36], and expansion of the subtropics [67, 68].

The tipping level is easier to assess, because the paleoclimate quasi-equilibrium response to known climate forcing is relevant. The tipping level is a measure of the long-term climate forcing that humanity must aim to stay beneath to avoid large climate impacts. The tipping level does not define the magnitude or period of tolerable overshoot. However, if overshoot is in place for centuries, the thermal perturbation will so penetrate the ocean [10] that recovery without dramatic effects, such as ice sheet disintegration, becomes unlikely.

4.2. Target CO_2

Combined, GHGs other than CO_2 cause climate forcing comparable to that of CO_2 [2, 6], but growth of non-CO_2 GHGs is falling below IPCC [2] scenarios. Thus total GHG climate forcing change is now determined mainly by CO_2 [69]. Coincidentally, CO_2 forcing is similar to the net human-made forcing, because non-CO_2 GHGs tend to offset negative aerosol forcing [2, 5].

Thus we take future CO_2 change as approximating the net human-made forcing change, with two caveats. First, special effort to reduce non-CO_2 GHGs could alleviate the CO_2 requirement, allowing up to about +25 ppm CO_2 for the same climate effect, while resurgent growth of non-CO_2 GHGs could reduce allowed CO_2 a similar amount [6]. Second, reduction of human-made aerosols, which have a net cooling effect, could force stricter GHG requirements. However, an emphasis on reducing black soot could largely off-set reductions of high albedo aerosols [20].

Our estimated history of CO_2 through the Cenozoic Era provides a sobering perspective for assessing an appropriate target for future CO_2 levels. A CO_2 amount of order 450 ppm or larger, if long maintained, would push Earth toward the ice-free state. Although ocean and ice sheet inertia limit the rate of climate change, such a CO_2 level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity's control.

The climate system, because of its inertia, has not yet fully responded to the recent increase of human-made climate forcings [5]. Yet climate impacts are already occurring that allow us to make an initial estimate for a target atmospheric CO_2 level. No doubt the target will need to be adjusted as climate data and knowledge improve, but the urgency and difficulty of reducing the human-made forcing will be less, and more likely manageable, if excess forcing is limited soon.

Civilization is adapted to climate zones of the Holocene. Theory and models indicate that subtropical regions expand poleward with global warming [2, 67]. Data reveal a 4-degree latitudinal shift already [68], larger than model predictions, yielding increased aridity in southern United States [70, 71], the Mediterranean region, Australia and parts of Africa. Impacts of this climate shift [72] support the conclusion that 385 ppm CO_2 is already deleterious.

Alpine glaciers are in near-global retreat [72, 73]. After a one-time added flush of fresh water, glacier demise will yield summers and autumns of frequently dry rivers, including rivers originating in the Himalayas, Andes and Rocky Mountains that now supply water to hundreds of millions of people. Present glacier retreat, and warming in the pipeline, indicate that 385 ppm CO_2 is already a threat.

Equilibrium sea level rise for today's 385 ppm CO_2 is at least several meters, judging from paleoclimate history [19, 32-34]. Accelerating mass losses from Greenland [74] and West Antarctica [75] heighten concerns about ice sheet stability. An initial CO_2 target of 350 ppm, to be reassessed as effects on ice sheet mass balance are observed, is suggested.

Stabilization of Arctic sea ice cover requires, to first approximation, restoration of planetary energy balance. Climate models driven by known forcings yield a present planetary energy imbalance of +0.5-1 W/m^2 [5]. Observed heat increase in the upper 700 m of the ocean [76] confirms the planetary energy imbalance, but observations of the entire ocean are needed for quantification. CO_2 amount must be reduced to 325-355 ppm to increase outgoing flux 0.5-1 W/m^2, if other forcings are unchanged. A further imbalance reduction, and thus CO_2 ~300-325 ppm, may be needed to restore sea ice to its area of 25 years ago.

Coral reefs are suffering from multiple stresses, with ocean acidification and ocean warming principal among them [77]. Given additional warming 'in-the-pipeline', 385 ppm CO_2 is already deleterious. A 300-350 ppm CO_2 target would significantly relieve both of these stresses.

4.3. CO_2 Scenarios

A large fraction of fossil fuel CO_2 emissions stays in the air a long time, one-quarter remaining airborne for several centuries [11, 78, 79]. Thus moderate delay of fossil fuel use will not appreciably reduce long-term human-made climate change. Preservation of a climate resembling that to which humanity is accustomed, the climate of the Holocene, requires that most remaining fossil fuel carbon is never emitted to the atmosphere.

Coal is the largest reservoir of conventional fossil fuels (Fig. **S12**), exceeding combined reserves of oil and gas [2, 79]. The only realistic way to sharply curtail CO_2 emissions is to phase out coal use except where CO_2 is captured and sequestered.

Phase-out of coal emissions by 2030 (Fig. **6**) keeps maximum CO_2 close to 400 ppm, depending on oil and gas reserves and reserve growth. IPCC reserves assume that half of readily extractable oil has already been used (Figs. **6**, **S12**). EIA [80] estimates (Fig. **S12**) have larger reserves and reserve growth. Even if EIA estimates are accurate, the IPCC case remains valid if the most difficult to extract oil and gas is left in the ground, *via* a rising price on carbon emissions that discourages remote exploration and environmental regulations that place some areas off-limit. If IPCC gas reserves (Fig. **S12**) are underestimated, the IPCC case in Fig. (**6**) remains valid if the additional gas reserves are used at facilities where CO_2 is captured.

However, even with phase-out of coal emissions and assuming IPCC oil and gas reserves, CO_2 would remain above 350 ppm for more than two centuries. Ongoing Arctic and ice sheet changes, examples of rapid paleoclimate change, and other criteria cited above all drive us to consider scenarios that bring CO_2 more rapidly back to 350 ppm or less.

4.4. Policy Relevance

Desire to reduce airborne CO_2 raises the question of whether CO_2 could be drawn from the air artificially. There are no large-scale technologies for CO_2 air capture now, but

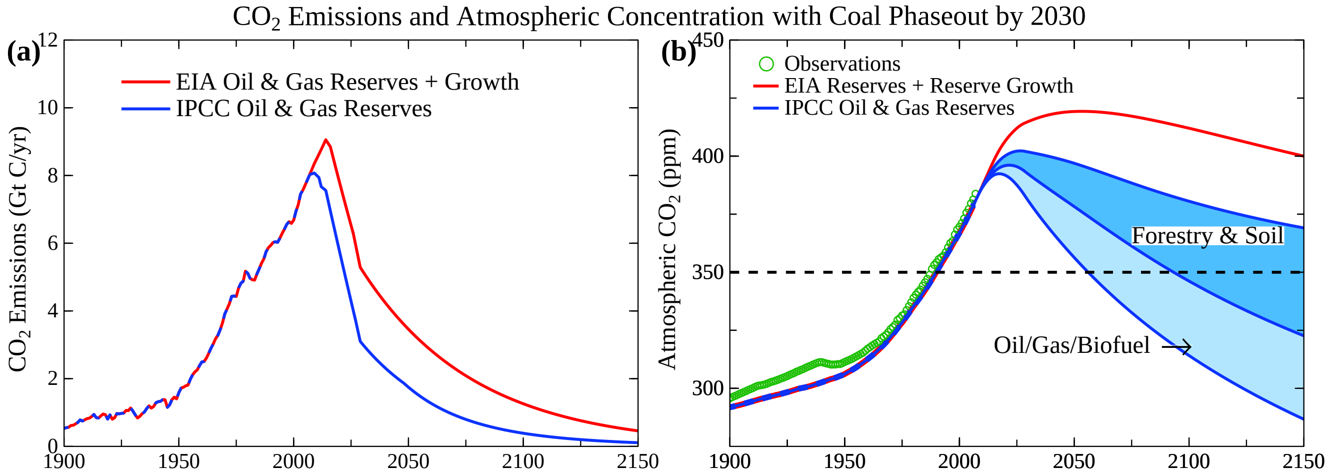

Fig. (6). (**a**) Fossil fuel CO$_2$ emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. (**b**) Resulting atmospheric CO$_2$ based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

with strong research and development support and industrial-scale pilot projects sustained over decades it may be possible to achieve costs ~\$200/tC [81] or perhaps less [82]. At \$200/tC, the cost of removing 50 ppm of CO$_2$ is ~\$20 trillion.

Improved agricultural and forestry practices offer a more natural way to draw down CO$_2$. Deforestation contributed a net emission of 60±30 ppm over the past few hundred years, of which ~20 ppm CO$_2$ remains in the air today [2, 83] (Figs. (**S12**, **S14**). Reforestation could absorb a substantial fraction of the 60±30 ppm net deforestation emission.

Carbon sequestration in soil also has significant potential. Biochar, produced in pyrolysis of residues from crops, forestry, and animal wastes, can be used to restore soil fertility while storing carbon for centuries to millennia [84]. Biochar helps soil retain nutrients and fertilizers, reducing emissions of GHGs such as N$_2$O [85]. Replacing slash-and-burn agriculture with slash-and-char and use of agricultural and forestry wastes for biochar production could provide a CO$_2$ drawdown of ~8 ppm or more in half a century [85].

In the Supplementary Material Section we define a forest/soil drawdown scenario that reaches 50 ppm by 2150 (Fig. **6b**). This scenario returns CO$_2$ below 350 ppm late this century, after about 100 years above that level.

More rapid drawdown could be provided by CO$_2$ capture at power plants fueled by gas and biofuels [86]. Low-input high-diversity biofuels grown on degraded or marginal lands, with associated biochar production, could accelerate CO$_2$ drawdown, but the nature of a biofuel approach must be carefully designed [85, 87-89].

A rising price on carbon emissions and payment for carbon sequestration is surely needed to make drawdown of airborne CO$_2$ a reality. A 50 ppm drawdown *via* agricultural and forestry practices seems plausible. But if most of the CO$_2$ in coal is put into the air, no such "natural" drawdown of CO$_2$ to 350 ppm is feasible. Indeed, if the world continues on a business-as-usual path for even another decade without initiating phase-out of unconstrained coal use, prospects for avoiding a dangerously large, extended overshoot of the 350 ppm level will be dim.

4.5. Caveats: Climate Variability, Climate Models, and Uncertainties

Climate has great variability, much of which is unforced and unpredictable [2, 90]. This fact raises a practical issue: what is the chance that climate variations, e.g., a temporary cooling trend, will affect public recognition of climate change, making it difficult to implement mitigation policies? Also what are the greatest uncertainties in the expectation of a continued global warming trend? And what are the impacts of climate model limitations, given the inability of models to realistically simulate many aspects of climate change and climate processes?

The atmosphere and ocean exhibit coupled nonlinear chaotic variability that cascades to all time scales [91]. Variability is so large that the significance of recent decadal global temperature change (Fig. **7a**) would be very limited, if the data were considered simply as a time series, without further information. However, other knowledge includes information on the causes of some of the temperature variability, the planet's energy imbalance, and global climate forcings.

The El Nino Southern Oscillation (ENSO) [94] accounts for most low latitude temperature variability and much of the global variability. The global impact of ENSO is coherent from month to month, as shown by the global-ocean-mean SST (Fig. **7b**), for which the ocean's thermal inertia minimizes the effect of weather noise. The cool anomaly of 2008 coincides with an ENSO minimum and does not imply a change of decadal temperature trend.

Decadal time scale variability, such as predicted weakening of the Atlantic overturning circulation [95], could interrupt global warming, as discussed in section 18 of the Supplementary Material. But the impact of regional dynamical effects on global temperature is opposed by the planet's energy imbalance [96], a product of the climate system's thermal inertia, which is confirmed by increasing ocean heat

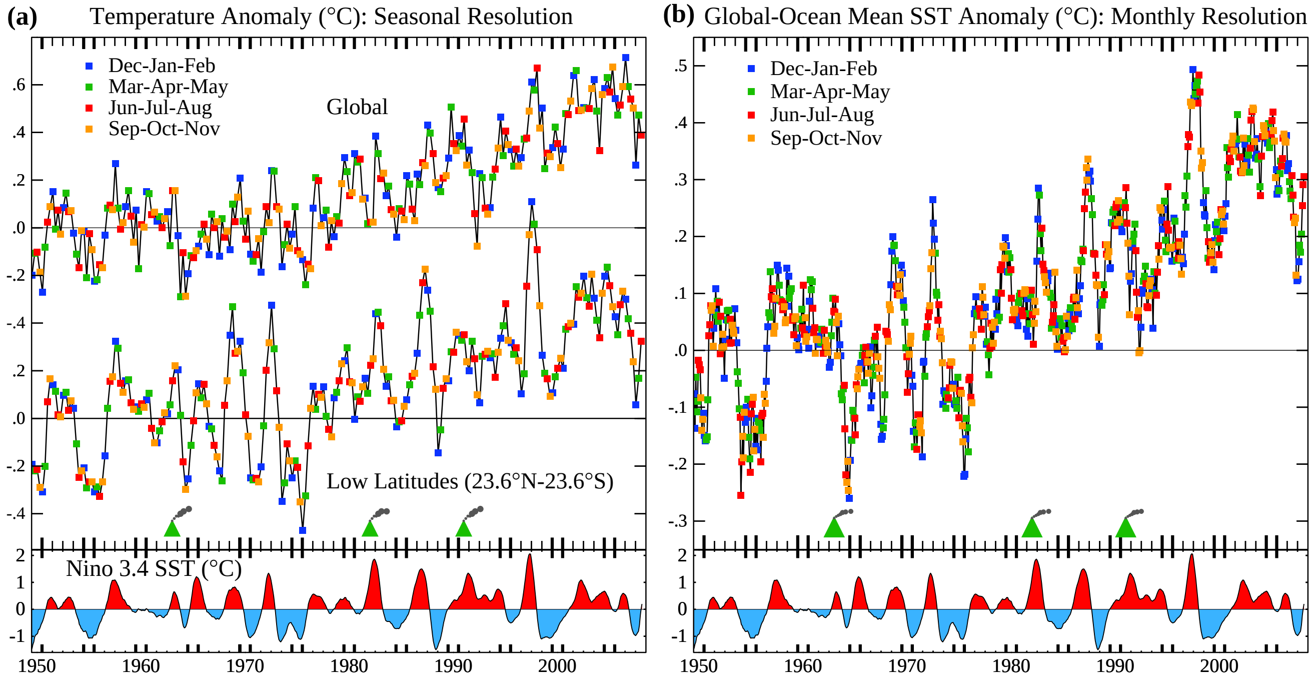

Fig. (7). (**a**) Seasonal-mean global and low-latitude surface temperature anomalies relative to 1951-1980, an update of [92], (**b**) global-ocean-mean sea surface temperature anomaly at monthly resolution. The Nino 3.4 Index, the temperature anomaly (12-month running mean) in a small part of the tropical Pacific Ocean [93], is a measure of ENSO, a basin-wide sloshing of the tropical Pacific Ocean [94]. Green triangles show major volcanic eruptions.

storage [97]. This energy imbalance makes decadal interruption of global warming, in the absence of a negative climate forcing, improbable [96].

Volcanoes and the sun can cause significant negative forcings. However, even if the solar irradiance remained at its value in the current solar minimum, this reduced forcing would be offset by increasing CO_2 within seven years (Supplementary Material section 18). Human-made aerosols cause a greater negative forcing, both directly and through their effects on clouds. The first satellite observations of aerosols and clouds with accuracy sufficient to quantify this forcing are planned to begin in 2009 [98], but most analysts anticipate that human-made aerosols will decrease in the future, rather than increase further.

Climate models have many deficiencies in their abilities to simulate climate change [2]. However, model uncertainties cut both ways: it is at least as likely that models underestimate effects of human-made GHGs as overestimate them (Supplementary Material section 18). Model deficiencies in evaluating tipping points, the possibility that rapid changes can occur without additional climate forcing [63, 64], are of special concern. Loss of Arctic sea ice, for example, has proceeded more rapidly than predicted by climate models [99]. There are reasons to expect that other nonlinear problems, such as ice sheet disintegration and extinction of interdependent species and ecosystems, also have the potential for rapid change [39, 63, 64].

5. SUMMARY

Humanity today, collectively, must face the uncomfortable fact that industrial civilization itself has become the principal driver of global climate. If we stay our present course, using fossil fuels to feed a growing appetite for energy-intensive life styles, we will soon leave the climate of the Holocene, the world of prior human history. The eventual response to doubling pre-industrial atmospheric CO_2 likely would be a nearly ice-free planet, preceded by a period of chaotic change with continually changing shorelines.

Humanity's task of moderating human-caused global climate change is urgent. Ocean and ice sheet inertias provide a buffer delaying full response by centuries, but there is a danger that human-made forcings could drive the climate system beyond tipping points such that change proceeds out of our control. The time available to reduce the human-made forcing is uncertain, because models of the global system and critical components such as ice sheets are inadequate. However, climate response time is surely less than the atmospheric lifetime of the human-caused perturbation of CO_2. Thus remaining fossil fuel reserves should not be exploited without a plan for retrieval and disposal of resulting atmospheric CO_2.

Paleoclimate evidence and ongoing global changes imply that today's CO_2, about 385 ppm, is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted. Realization that we must reduce the current CO_2 amount has a bright side: effects that had begun to seem inevitable, including impacts of ocean acidification, loss of fresh water supplies, and shifting of climatic zones, may be averted by the necessity of finding an energy course beyond fossil fuels sooner than would otherwise have occurred.

We suggest an initial objective of reducing atmospheric CO_2 to 350 ppm, with the target to be adjusted as scientific understanding and empirical evidence of climate effects accumulate. Although a case already could be made that the eventual target probably needs to be lower, the 350 ppm target is sufficient to qualitatively change the discussion and drive fundamental changes in energy policy. Limited opportunities for reduction of non-CO_2 human-caused forcings are important to pursue but do not alter the initial 350 ppm CO_2 target. This target must be pursued on a timescale of decades, as paleoclimate and ongoing changes, and the ocean response time, suggest that it would be foolhardy to allow CO_2 to stay in the dangerous zone for centuries.

A practical global strategy almost surely requires a rising global price on CO_2 emissions and phase-out of coal use except for cases where the CO_2 is captured and sequestered. The carbon price should eliminate use of unconventional fossil fuels, unless, as is unlikely, the CO_2 can be captured. A reward system for improved agricultural and forestry practices that sequester carbon could remove the current CO_2 overshoot. With simultaneous policies to reduce non-CO_2 greenhouse gases, it appears still feasible to avert catastrophic climate change.

Present policies, with continued construction of coal-fired power plants without CO_2 capture, suggest that decision-makers do not appreciate the gravity of the situation. We must begin to move now toward the era beyond fossil fuels. Continued growth of greenhouse gas emissions, for just another decade, practically eliminates the possibility of near-term return of atmospheric composition beneath the tipping level for catastrophic effects.

The most difficult task, phase-out over the next 20-25 years of coal use that does not capture CO_2, is Herculean, yet feasible when compared with the efforts that went into World War II. The stakes, for all life on the planet, surpass those of any previous crisis. The greatest danger is continued ignorance and denial, which could make tragic consequences unavoidable.

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REFERENCES

[1] Framework Convention on Climate Change, United Nations 1992; http://www.unfccc.int/

[2] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007, Solomon S, Dahe Q, Manning M, *et al.* (eds), Cambridge Univ Press: New York 2007; pp. 996.

[3] Mastrandrea MD, Schneider SH. Probabilistic integrated assessment of "dangerous" climate change. Science 2004; 304: 571-5.

[4] European Council, Climate change strategies 2005; http://register.consilium.europa.eu/pdf/en/05/st07/st07242.en05.pdf

[5] Hansen J, Sato M, Ruedy, *et al.* Dangerous human-made interference with climate: a GISS modelE study. Atmos Chem Phys 2007; 7: 2287-312.

[6] Hansen J, Sato M. Greenhouse gas growth rates. Proc Natl Acad Sci 2004; 101: 16109-14.

[7] Hansen J, Sato M, Kharecha P, Russell G, Lea DW, Siddall M. Climate change and trace gases. Phil Trans R Soc A 2007; 365: 1925-54.

[8] Hansen J, Nazarenko L, Ruedy R, *et al.* Earth's energy imbalance: Confirmation and implications. Science 2005; 308: 1431-35.

[9] Harvey LDD. Dangerous anthropogenic interference, dangerous climatic change, and harmful climatic change: non-trivial distinctions with significant policy implications. Clim Change 2007; 82: 1-25.

[10] Matthews HD, Caldeira K. Stabilizing climate requires near-zero emissions. Geophys Res Lett 2008; 35: L04705.

[11] Archer D. Fate of fossil fuel CO_2 in geologic time. J Geophys Res 2005; 110: C09S05.

[12] Hansen J, Sato M, Ruedy R, *et al.* Efficacy of climate forcings. J Geophys Res 2005; 110: D18104.

[13] Charney J. Carbon Dioxide and Climate: A Scientific Assessment. National Academy of Sciences Press: Washington DC 1979; pp. 33.

[14] Hansen J, Lacis A, Rind D, *et al.* J Climate sensitivity: Analysis of feedback mechanisms. In Climate Processes and Climate Sensitivity, Geophys Monogr Ser 29. Hansen JE, Takahashi T, Eds. American Geophysical Union: Washington, DC 1984; pp. 130-63.

[15] Braconnot P, Otto-Bliesner BL, Harrison S, *et al.* Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features. Clim Past 2007; 3: 261-77.

[16] Farrera I, Harrison SP, Prentice IC, *et al.* Tropical climates at the last glacial maximum: a new synthesis of terrestrial paeleoclimate data. I. Vegetation, lake-levels and geochemistry. Clim Dyn 1999; 15: 823-56

[17] Petit JR, Jouzel J, Raynaud D, *et al.* 420,000 years of climate and atmospheric history revealed by the Vostok deep Antarctic ice core. Nature 1999; 399: 429-36.

[18] Vimeux F, Cuffey KM, Jouzel J. New insights into Southern Hemisphere temperature changes from Vostok ice cores using deuterium excess correction. Earth Planet Sci Lett 2002; 203: 829-43.

[19] Siddall M, Rohling EJ, Almogi-Labin A, *et al.* Sea-level fluctuations during the last glacial cycle. Nature 2003; 423: 853-58.

[20] Hansen J, Sato M, Ruedy R, Lacis A, Oinas V. Global warming in the twenty-first century: An alternative scenario. Proc Natl Acad Sci 2000; 97: 9875-80.

[21] Masson-Delmotte V, Kageyama M, Braconnot P. Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. Clim Dyn 2006; 26: 513-29.

[22] EPICA community members. One-to-one coupling of glacial climate variability in Greenland and Antarctica. Nature 2006; 444: 195-8.

[23] Caillon N, Severinghaus JP, Jouzel J, Barnola JM, Kang J, Lipenkov VY. Timing of atmospheric CO_2 and Antarctic temperature changes across Termination III. Science 2003; 299: 1728-31.

[24] Mudelsee M. The phase relations among atmospheric CO_2 content, temperature and global ice volume over the past 420 ka. Quat Sci Rev 2001; 20: 583-9.

[25] Hays JD, Imbrie J, Shackleton NJ. Variations in the Earth's orbit: pacemaker of the ice ages. Science 1976; 194: 1121-32.

[26] Zachos J, Pagani M, Sloan L, Thomas E, Billups K. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 2001; 292: 686-93.

[27] Kohler P, Fischer H. Simulating low frequency changes in atmospheric CO_2 during the last 740 000 years. Clim Past 2006; 2: 57-78.

[28] Siegenthaler U, Stocker TF, Monnin E, *et al.* Stable carbon cycle – climate relationship during the late Pleistocene. Science 2005; 310: 1313-7.

[29] Archer D. Methane hydrate stability and anthropogenic climate change. Biogeoscience 2007; 4: 521-44.

[30] Berner RA. The Phanerozoic Carbon Cycle: CO_2 and O_2; Oxford Univ Press: New York 2004; p. 150.

[31] Hansen J, Russell G, Lacis A, *et al.* Climate response times: Dependence on climate sensitivity and ocean mixing. Science 1985; 229: 857-9.

[32] Thompson WG, Goldstein SL. Open-system coral ages reveal persistent suborbital sea-level cycles. Science 2005; 308: 401-4.

[33] Hearty PJ, Hollin JT, Neumann AC, O'Leary MJ, McCulloch M. Global sea-level fluctuations during the last interglaciation (MIS 5e). Quat Sci Rev 2007; 26: 2090-112.

[34] Rohling EJ, Grant K, Hemleben Ch, *et al* . High rates of sea-level rise during the last interglacial period. Nat Geosci 2008; 1: 38-42.

[35] Tedesco M. Snowmelt detection over the Greenland ice sheet from SSM/I brightness temperature daily variations. Geophys Res Lett 2007; 34: L02504, 1-6.

[36] Rignot E, Jacobs SS. Rapid bottom melting widespread near Antarctic ice sheet grounding lines. Science 2002; 296: 2020-3.

[37] Zwally HJ, Abdalati W, Herring T, Larson K, Saba J, Steffen K. Surface melt-induced acceleration of Greenland ice-sheet flow. Science 2002; 297: 218-22.

[38] Chen JL, Wilson CR, Tapley BD. Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet. Science 2006; 313: 1958-60.

[39] Hansen J. A slippery slope: how much global warming constitutes "dangerous anthropogenic interference"? Clim Change 2005; 68: 269-79.

[40] DeConto RM, Pollard D. Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2. Nature 2003; 421: 245-9.

[41] Zanazzi A, Kohn MJ, MacFadden BJ, Terry DO. Large temperature drop across the Eocene-Oligocene transition in central North America. Nature 2007; 445: 639-42.

[42] Dupont-Nivet G, Krijgsman W, Langereis CG, Abeld HA, Dai S, Fang X. Tibetan plateau aridification linked to global cooling at the Eocene–Oligocene transition. Nature 2007; 445: 635-8.

[43] Sackmann IJ, Boothroyd AI, Kraemer KE. Our sun III Present and future. Astrophys J 1993; 418: 457-68.

[44] Pagani M, Zachos J, Freeman KH, Bohaty S, Tipple B. Marked change in atmospheric carbon dioxide concentrations during the Oligocene. Science 2005; 309: 600-3.

[45] Bartdorff O, Wallmann K, Latif M, Semenov V. Phanerozoic evolution of atmospheric methane. Global Biogeochem Cycles 2008; 22: GB1008.

[46] Beerling D, Berner RA, Mackenzie FT, Harfoot MB, Pyle JA. Methane and the CH_4 greenhouse during the past 400 million years. Am J Sci 2008; (in press).

[47] Edmond JM, Huh Y. Non-steady state carbonate recycling and implications for the evolution of atmospheric P_{CO2}. Earth Planet Sci Lett 2003; 216: 125-39.

[48] Staudigel H, Hart SR, Schmincke H-U, Smith BM. Cretaceous ocean crust at DSDP Sites 417 and 418: Carbon uptake from weathering versus loss by magmatic outgassing. Geochim Cosmochim Acta 1989; 53: 3091-4.

[49] Berner R, Caldeira K. The need for mass balance and feedback in the geochemical carbon cycle. Geology 1997; 25: 955-6.

[50] Kumar P, Yuan X, Kumar MR, Kind R, Li X, Chadha RK. The rapid drift of the Indian tectonic plate. Nature 2007; 449: 894-97.

[51] Raymo ME, Ruddiman WF. Tectonic forcing of late Cenozoic climate. Nature 1992; 359: 117-22.

[52] Zeebe RE, Caldeira K. Close mass balance of long-term carbon fluxes from ice-core CO_2 and ocean chemistry records. Nat Geosci 2008; 1: 312-5.

[53] Patriat P, Sloan H, Sauter D. From slow to ultraslow: a previously undetected event at the Southwest Indian Ridge at ca. 24 Ma. Geology 2008; 36: 207-10.

[54] Joshi MM, Gregory JM, Webb MJ, Sexton DMH, Johns TC. Mechanisms for the land/sea warming contrast exhibited by simulations of climate change. Clim Dyn 2008; 30: 455-65.

[55] Royer DL. CO_2-forced climate thresholds during the Phanerozoic. Geochim Cosmochim Acta 2006; 70: 5665-75.

[56] Royer DL, Berner RA, Park J. Climate sensitivity constrained by CO_2 concentrations over the past 420 million years. Nature 2007; 446: 530-2.

[57] Higgins JA, Schrag DP. Beyond methane: Towards a theory for Paleocene-Eocene thermal maximum. Earth Planet Sci Lett 2006; 245: 523-37.

[58] Pagani M, Caldeira K, Archer D, Zachos JC. An ancient carbon mystery. Science 2006; 314: 1556-7.

[59] Lunt DJ, Valdes PJ, Haywood A, Rutt IC. Closure of the Panama Seaway during the Pliocene: implications for climate and Northern Hemisphere glaciation. Clim Dyn 2008; 30: 1-18.

[60] Crutzen PJ, Stoermer EF. The "Anthropocene". Glob Change Newslett 2000; 41: 12-3.

[61] Zalasiewicz J, Williams M, Smith A, *et al.* Are we now living in the Anthropocene? GSA Today 2008; 18: 4-8.

[62] Ruddiman WF. The anthropogenic greenhouse era began thousands of years ago. Clim Change 2003; 61: 261-93.

[63] Hansen J. Tipping point: perspective of a climatologist. In State of the Wild: A Global Portrait of Wildlife, Wildlands, and Oceans. Woods W, Ed. Wildlife Conservation Society/Island Press 2008; pp. 6-15.

[64] Lenton TM, Held H, Kriegler E, *et al.* Tipping elements in the Earth's climate system. Proc Natl Acad Sci USA 2008; 105: 1786-93.

[65] Stroeve J, Serreze M, Drobot S, *et al.* Arctic sea ice extent plummets in 2007. Eos Trans, AGU 2008; 89(2): 13.

[66] Howat IM, Joughin I, Scambos TA. Rapid changes in ice discharge from Greenland outlet glaciers. Science 2007; 315: 1559-61.

[67] Held IM, Soden BJ. Robust responses of the hydrological cycle to global warming. J Clim 2006; 19: 5686-99.

[68] Seidel DJ, Randel WJ. Variability and trends in the global tropopause estimated from radiosonde data. J Geophys Res 2006; 111: D21101.

[69] Hansen J, Sato M. Global warming: East-West connections. Open Environ J 2008; (in press).

[70] Barnett TP, Pierce DW, Hidalgo HG, *et al.* Human-induced changes in the hydrology of the Western United States. Science 2008; 319: 1080-3.

[71] Levi BG. Trends in the hydrology of the western US bear the imprint of manmade climate change. Phys Today 2008; April: 16-8.

[72] Intergovernmental Panel on Climate Change (IPCC), Impacts, Adaptation and Vulnerability. Parry M, Canziani O, Palutikof J, van der Linden P, Hanson C, Eds. Cambridge Univ. Press: New York 2007; pp. 978.

[73] Barnett TP, Adam JC, Lettenmaler DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 2005; 438: 303-9.

[74] Steffen K, Clark PU, Cogley JG, Holland D, Marshall S, Rignot E, Thomas R. Rapid changes in glaciers and ice sheets and their impacts on sea level. Chap. 2 in Abrupt Climate Change, U.S. Climate Change Science Program, SAP-3.4 2008; pp. 452.

[75] Rignot E, Bamber JL, van den Broeke MR, *et al.* Recent Antarctic ice mass loss from radar interferometry and regional climate modeling. Nat Geosci 2008; 1: 106-10.

[76] Domingues CM, Church JA, White NJ, *et al.* Rapid upper-ocean warming helps explain multi-decadal sea-level rise. Nautre 2008; (in press).

[77] Stone R. A world without corals? Science 2007; 316: 678-81.

[78] Joos F, Bruno M, Fink R, *et al*. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus B 1996; 48: 397-17.

[79] Kharecha P, Hansen J. Implications of "peak oil" for atmospheric CO_2 and climate. Global Biogeochem Cycles 2008; 22: GB3012.

[80] Energy Information Administration (EIA), U.S. DOE, International Energy Outlook 2006, http://www.eia.doe.gov/oiaf/archive/ieo06/index.html

[81] Keith DW, Ha-Duong M, Stolaroff JK. Climate strategy with CO_2 capture from the air. Clim Change 2006; 74: 17-45.

[82] Lackner KS. A guide to CO_2 sequestration. Science 2003; 300: 1677-8.

[83] Houghton RA. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus B 2003; 55: 378-90.

[84] Lehmann J. A handful of carbon. Nature 2007; 447: 143-4.

[85] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems – a review. Mitig Adapt Strat Glob Change 2006; 11: 403-27.

[86] Hansen J. Congressional Testimony 2007; http://arxiv.org/abs/0706.3720v1

[87] Tilman D, Hill J, Lehman C. Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 2006; 314: 1598-600.

[88] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008; 319: 1235-8.

[89] Searchinger T, Heimlich R, Houghton RA, *et al* . Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 2008; 319: 1238-40.
[90] Palmer TN. Nonlinear dynamics and climate change: Rossby's legacy. Bull Am Meteorol Soc 1998; 79: 1411-23.
[91] Hasselmann K. Ocean circulation and climate change. Tellus B 2002; 43: 82-103.
[92] Hansen J, Ruedy R, Glascoe J, Sato M. GISS analysis of surface temperature change. J Geophys Res 1999; 104: 30997-1022.
[93] NOAA National Weather Service, Climate prediction Center 2008; http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices
[94] Cane MA. Nino E. Ann Rev Earth Planet Sci 1986; 14: 43-70.
[95] Keenlyside NS, Latif M, Jungclaus J, Kornblueh L, Roeckner E. Advancing decadal-scale climate prediction in the North Atlantic sector. Nature 2008; 453: 84-8.
[96] Hansen J, Sato M, Ruedy R, *et al.* Forcings and chaos in interannual to decadal climate change. J Geophys Res 1997; 102: 25679-720.
[97] Domingues CM, Church JA, White NJ, *et al*. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 2008; 453: 1090-3.
[98] Mishchenko MI, Cairns B, Kopp G, *et al* . Precise and accurate monitoring of terrestrial aerosols and total solar irradiance: introducing the Glory mission. Bull Am Meteorol Soc 2007; 88: 677-91.
[99] Lindsay RW, Zhang J. The Thinning of Arctic Sea Ice, 1988–2003: Have we passed a tipping point? J Clim 2005; 18: 4879-94.

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Supplementary Material

1. ICE AGE CLIMATE FORCINGS

Fig. (**S1**) shows the climate forcings during the depth of the last ice age, 20 ky BP, relative to the Holocene [14]. The largest contribution to the uncertainty in the calculated 3.5 W/m^2 forcing due to surface changes (ice sheet area, vegetation distribution, shoreline movements) is due to uncertainty in the ice sheet sizes [14, S1]. Formulae for the GHG forcings [20] yield 2.25 W/m^2 for CO_2 (185 ppm → 275 ppm), 0.43 W/m^2 for CH_4 (350 → 675 ppb) and 0.32 W/m^2 for N_2O (200 → 270 ppb). The CH_4 forcing includes a factor 1.4 to account for indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor [12].

The climate sensitivity inferred from the ice age climate change (~¾°C per W/m^2) includes only fast feedbacks, such as water vapor, clouds, aerosols (including dust) and sea ice. Ice sheet size and greenhouse gas amounts are specified boundary conditions in this derivation of the fast-feedback climate sensitivity.

It is permissible, alternatively, to specify aerosol changes as part of the forcing and thus derive a climate sensitivity that excludes the effect of aerosol feedbacks. That approach was used in the initial empirical derivation of climate sensitivity from Pleistocene climate change [14]. The difficulty with that approach is that, unlike long-lived GHGs, aerosols are distributed heterogeneously, so it is difficult to specify aerosol changes accurately. Also the forcing is a sensitive function of aerosol single scatter albedo and the vertical distribution of aerosols in the atmosphere, which are not measured. Furthermore, the aerosol indirect effect on clouds also depends upon all of these poorly known aerosol properties.

One recent study [S2] specified an arbitrary glacial-interglacial aerosol forcing slightly larger than the GHG glacial-interglacial forcing. As a result, because temperature, GHGs, and aerosol amount, overall, are positively correlated in glacial-interglacial changes, this study inferred a climate sensitivity of only ~2°C for doubled CO_2. This study used the correlation of aerosol and temperature in the Vostok ice core at two specific times to infer an aerosol forcing for a given aerosol amount. The conclusions of the study are immediately falsified by considering the full Vostok aerosol record (Fig. **2** of [17]), which reveals numerous large aerosol fluctuations without any corresponding temperature change. In contrast, the role of GHGs in climate change is confirmed when this same check is made for GHGs (Fig. **2**), and the fast-feedback climate sensitivity of 3°C for doubled CO_2 is confirmed (Fig. **1**).

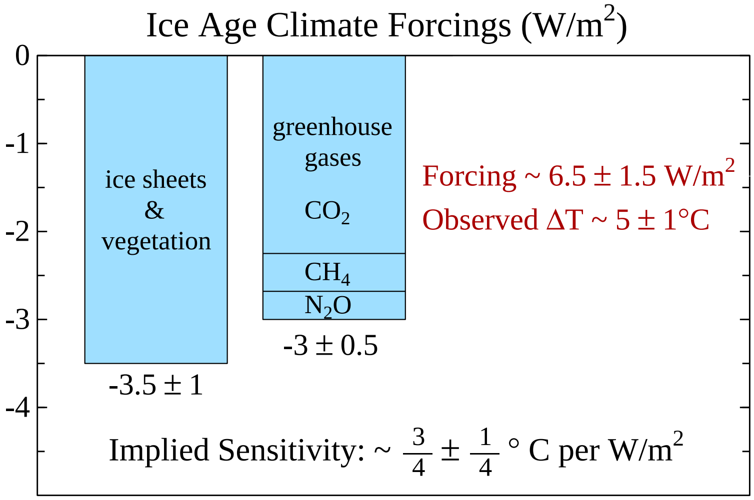


Fig. (S1). Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

All the problems associated with imprecise knowledge of aerosol properties become moot if, as is appropriate, aerosols are included in the fast feedback category. Indeed, soil dust, sea salt, dimethylsulfide, and other aerosols are expected to vary (in regional, inhomogeneous ways) as climate changes. Unlike long-lived GHGs, global aerosol amounts cannot be inferred from ice cores. But the effect of aerosol changes is fully included in observed global temperature change. The climate sensitivity that we derive in Fig. (**S1**) includes the aerosol effect accurately, because both the climate forcings and the global climate response are known. The indirect effect of aerosol change on clouds is, of course, also included precisely.

2. CLIMATE FORCINGS AND CLIMATE FEEDBACKS

The Earth's temperature at equilibrium is such that the planet radiates to space (as heat, i.e., infrared radiation) the same amount of energy that it absorbs from the sun, which is ~240 W/m^2. A blackbody temperature of ~255°K yields a heat flux of 240 W/m^2. Indeed, 255°K is the temperature in the mid-troposphere, the mean level of infrared emission to space.

A climate forcing is a perturbation to the planet's energy balance, which causes the Earth's temperature to change as needed to restore energy balance. Doubling atmospheric CO_2 causes a planetary energy imbalance of ~4 W/m^2, with more energy coming in than going out. Earth's temperature would need to increase by ΔT_O = 1.2-1.3°C to restore planetary energy balance, if the temperature change were uniform throughout the atmosphere and if nothing else changed.

Actual equilibrium temperature change in response to any forcing is altered by feedbacks that can amplify or diminish the response, thus the mean surface temperature change is [14]

$$\begin{aligned}\Delta T_{eq} &= f\ \Delta T_O \\ &= \Delta T_O + \Delta T_{feedbacks} \\ &= \Delta T_O + \Delta T_1 + \Delta T_2 + \ldots,\end{aligned}$$

where f is the net feedback factor and the ΔT_i are increments due to specific feedbacks.

The role of feedback processes is clarified by defining the gain, g,

$$\begin{aligned}g &= \Delta T_{feedbacks}/\Delta T_{eq} \\ &= (\Delta T_1 + \Delta T_2 + \ldots)/\Delta T_{eq} \\ &= g_1 + g_2 + \ldots\end{aligned}$$

g_i is positive for an amplifying feedback and negative for a feedback that diminishes the response. The additive nature of the g_i, unlike f_i, is a useful characteristic of the gain. Evidently

$$f = 1/(1 - g)$$

The value of g (or f) depends upon the climate state, especially the planetary temperature. For example, as the planet becomes so warm that land ice disappears, the land ice albedo feedback diminishes, i.e. $g_{\text{land ice albedo}} \rightarrow 0$.

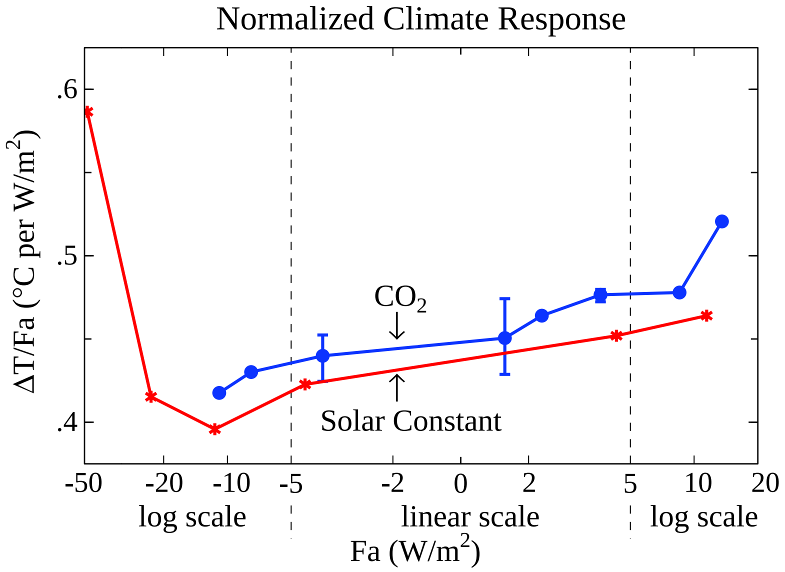


Fig. (S2). Global surface air temperature change [12] after 100 years in simulations with the Goddard Institute for Space Studies modelE [S3, 5] as a function of climate forcing for changes of solar irradiance and atmospheric CO_2. Fa is the standard adjusted climate forcing [12]. Results are extracted from Fig. (**25a**) of [12]. Curves terminate because the climate model 'bombs' at the next increment of forcing due to failure of one or more of the parameterizations of processes in the model as extreme conditions are approached.

'Fast feedbacks', such as water vapor, clouds and sea ice, are the mechanisms usually included in the 'Charney' [13] climate sensitivity. Climate models yield a Charney (fast feedback) sensitivity of about 3°C for doubled CO_2 [2, 12], a conclusion that is confirmed and tightened by empirical evidence from the Pleistocene (Section 2.1). This sensitivity implies

$$g_{\text{fast feedbacks}} \sim 0.5\text{-}0.6.$$

This fast feedback gain and climate sensitivity apply to the present climate and climate states with global temperatures that are not too different than at present.

If g approaches unity, f → ∞, implying a runaway climate instability. The possibility of such instability is anticipated for either a very warm climate (runaway greenhouse effect [S4]) or a very cold climate (snowball Earth [S5]). We can investigate how large a climate forcing is needed to cause g → 1 using a global climate model that includes the fast feedback processes, because both of these instabilities are a result of the temperature dependence of 'fast feedbacks' (the water vapor and ice/snow albedo feedbacks, respectively).

Fig. (**S2**) suggests that climate forcings ~10-25 W/m^2 are needed to approach either runaway snowball-Earth conditions or the runaway greenhouse effect. More precise quantification requires longer simulations and improved parameterizations of physical processes as extreme climates are approached. The processes should include slow feedbacks that can either amplify or diminish the climate change.

Earth has experienced snowball conditions [S5], or at least a ‘slushball’ state [S6] with ice reaching sea level in the tropics, on at least two occasions, the most recent ~640 My BP, aided by reduced solar irradiance [43] and favorable continental locations. The mechanism that allowed Earth to escape the snowball state was probably reduced weathering in a glaciated world, which allowed CO_2 to accumulate in the atmosphere [S5]. Venus, but not Earth, has experienced the runaway greenhouse effect, a state from which there is no escape.

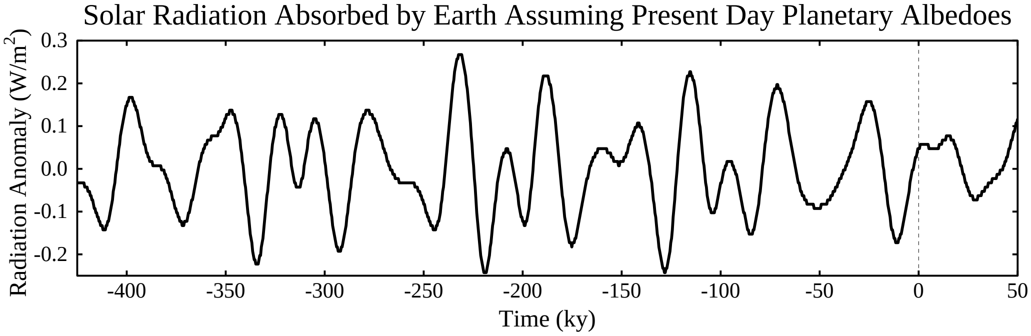


Fig. (S3). Annual-mean global-mean perturbation of the amount of solar radiation absorbed by the Earth, calculated by assuming present-day seasonal and geographical distribution of albedo.

3. PLEISTOCENE FORCINGS AND FEEDBACKS

Fig. (**S3**) shows the perturbation of solar radiation absorbed by the Earth due to changes in Earth orbital elements, i.e., the tilt of the Earth’s spin axis relative to the orbital plane, the eccentricity of the Earth’s orbit, and the time of year at which the Earth is closest to the sun (precession of equinoxes). This perturbation is calculated using fixed (present day) seasonal and geographical distribution of planetary albedo.

The global-mean annual-mean orbital (Milankovitch) forcing is very weak, at most a few tenths of 1 W/m^2. Our procedure in calculating the forcing, keeping ice sheet properties (size and albedo) fixed, is appropriate for ‘instantaneous’ and ‘adjusted’ radiative forcings [12].

Further, successive, definitions of the orbital ‘forcing’, e.g., allowing some regional response to the seasonal insolation perturbations, may be useful for the purpose of understanding glacial-interglacial climate change. For example, it may be informative to calculate the ‘forcing’ due to insolation-induced changes of ice-she*et al*bedo, because increased insolation can ‘age’ (increase snow crystal size and thus darken) an ice surface and also spur the date of first snow-melt [7]. However, one merit of the standard forcing definition is the insight that glacial-interglacial climate swings are almost entirely due to feedbacks.

Indeed, the gain during the Pleistocene is close to unity. Climate models and empirical evaluation from the climate change between the last ice age (Section 2.1 above) yield $g_{\text{fast feedbacks}}$ ~0.5-0.6 (the gain corresponding to fast feedback climate sensitivity 3°C for doubled CO_2). GHGs and surface albedo contribute about equally to glacial-interglacial ‘forcings’ and temperature change, with each having gain ~0.2 [14]. Thus

$$\begin{aligned} g &= g_{\text{fast feedbacks}} + g_{\text{surface albedo}} + g_{\text{GHG}} \\ &= {\sim}0.5\text{-}0.6 + {\sim}0.2 + {\sim}0.2. \end{aligned}$$

Thus climate gain in the Pleistocene was greater than or of the order of 0.9. It is no wonder that late Cenozoic climate fluctuated so greatly (Fig. **3b**). When substantial ice is present on the planet, g is close to unity, climate is sensitive, and large climate swings occur in response to small orbital forcings. Indeed, with g near unity any forcing or climate noise can cause large climate change, consistent with the conclusion that much of climate variability is not due to orbital forcings [S7]. In the early Cenozoic there was little ice, $g_{\text{surface albedo}}$ was small, and thus climate oscillations due to insolation perturbations were smaller.

It may be useful to divide inferences from Pleistocene climate change into two categories: (1) well-defined conclusions about the nature of the climate change, (2) less certain suggestions about the nature and causes of the climate change. The merit of identifying well-defined conclusions is that they help us predict likely consequences of human-made climate forcings. Less certain aspects of Pleistocene climate change mainly concern the small forcings that instigated climate swings. The small forcings are of great interest to paleoclimatologists, but they need not prevent extraction of practical implications from Pleistocene climate change.

Two fundamental characteristics of Pleistocene climate change are clear. First, there is the high gain, at least of the order of 0.9, i.e., the high sensitivity to a climate forcing, when the planet is in the range of climates that existed during the Pleistocene. Second, we have a good knowledge of the amplifying feedbacks that produce this high gain. Fast feedbacks, including water vapor, clouds, aerosols, sea ice and snow, contribute at least half of this gain. The remainder of the amplification is provided almost entirely by two factors: surface albedo (mainly ice sheets) and GHGs (mainly CO_2).

Details beyond these basic conclusions are less certain. The large glacial-interglacial surface albedo and GHG changes should lag global temperature, because they are feedbacks on global temperature on the global spatial scale and millennial time scale. The lag of GHGs after temperature change is several hundred years (Fig. **6** of [6]), perhaps determined by the ocean overturning time. Ice sheet changes may lag temperature by a few millennia [24], but it has been argued that there is no discernible lag between insolation forcing and the maximum rate of change of ice sheet volume [7].

A complication arises from the fact that some instigating factors (forcing mechanisms) for Pleistocene climate change also involve surface albedo and GHG changes. Regional anomalies of seasonal insolation are as much as many tens of W/m^2. The global forcing is small (Fig. **S3**) because the local anomalies are nearly balanced by anomalies of the opposite sign in either the opposite hemisphere or the opposite season. However, one can readily imagine climate change mechanisms that operate in such a way that cancellation does not occur.

For example, it has been argued [7] that a positive insolation anomaly in late spring is most effective for causing ice sheet disintegration because early ‘albedo flip’, as the ice becomes wet, yields maximum extension of the melt season. It is unlikely that the strong effect of albedo flip on absorbed solar energy could be offset by a negative insolation anomaly at other times of year.

A second example is non-cancellation of hemispheric insolation anomalies. A hemispheric asymmetry occurs when Earth is cold enough that ice sheets extend to Northern Hemisphere middle latitudes, due to absence of similar Southern Hemisphere land. It has been argued [7] that this hemispheric asymmetry is the reason that the orbital periodicities associated with precession of the equinoxes and orbit eccentricity became substantial about 1 million years ago.

Insolation anomalies also may directly affect GHG amounts, as well as surface albedo. One can readily imagine ways in which insolation anomalies affect methane release from wetlands or carbon uptake through biological processes.

Surface albedo and GHG changes that result immediately from insolation anomalies can be defined as climate forcings, as indirect forcings due to insolation anomalies. The question then becomes: what fractions of the known paleo albedo and GHG changes are immediate indirect forcings due to insolation anomalies and what fractions are feedbacks due to global temperature change?

It is our presumption that most of the Pleistocene GHG changes are a slow feedback in response to climate change. This interpretation is supported by the lag of several hundred years between temperature change and greenhouse gas amount (Fig. **6** of [6]). The conclusion that most of the ice area and surface albedo change is also a feedback in response to global temperature change is supported by the fact that the large climate swings are global (Section 5 of Appendix).

Note that our inferred climate sensitivity is not dependent on detailed workings of Pleistocene climate fluctuations. The fast feedback sensitivity of 3°C for doubled CO_2, derived by comparing glacial and interglacial states, is independent of the cause and dynamics of glacial/interglacial transitions.

Climate sensitivity including surface albedo feedback (~6°C for doubled CO_2) is the average sensitivity for the climate range from 35 My ago to the present and is independent of the glacial-interglacial ‘wiggles’ in Fig. (**3**). Note that climate and albedo changes occurred mainly at points with ‘ready’ [63] feedbacks: at Antarctic glaciation and (in the past three million years) with expansion of Northern Hemisphere glaciation, which are thus times of high climate sensitivity.

The entire ice albedo feedback from snowball-Earth to ice-free planet (or vice versa) can be viewed as a response to changing global temperature, with wiggles introduced by Milankovitch (orbital) forcings. The average $g_{\text{surface albedo}}$ for the range from today’s climate through Antarctic deglaciation is close to $g_{\text{surface albedo}} \sim 0.2$, almost as large as in the Pleistocene. Beyond Antarctic deglaciation (i.e., for an ice-free planet) $g_{\text{surface albedo}} \rightarrow 0$, except for vegetation effects.

For the sake of specificity, let us estimate the effect of slow feedbacks on climate sensitivity. If we round ΔT_O to 1.2°C for doubled CO_2 and the fast feedback gain to $g_{\text{fast feedbacks}} = 0.6$, then for fast feedbacks alone $f = 2.5$ and the equilibrium warming is $\Delta T_{eq} = 3°C$. Inclusion of $g_{\text{surface albedo}} = 0.2$ makes $f = 5$ and $\Delta T_{eq} = 6°C$, which is the sensitivity if the GHG amount is specified from observations or from a carbon cycle model.

The feedback factor f can approach infinity, i.e., the climate can become unstable. However, instabilities are limited except at the snowball Earth and runaway greenhouse extremes. Some feedbacks have a finite supply, e.g., as when Antarctica becomes fully deglaciated. Also climate change can cause positive feedbacks to decrease or negative feedbacks to come into play.

For example, Fig. (**S2**) suggests that a cooling climate from the present state first reduces the fast feedback gain. This and reduced weathering with glaciation may be reasons that most ice ages did not reach closer to the iceball state. Also there may be limitations on the ranges of GHG (CO_2, CH_4, N_2O) feedbacks. Empirical values g_{GHG} ~ 0.2 and $g_{surface\ albedo}$ ~ 0.2 were derived as averages relevant to the range of climates that existed in the past several hundred thousand years, and they may not be valid outside that range.

On the other hand, if the forcing becomes large enough, global instabilities are possible. Earth did become cold enough in the past for the snowball-Earth instability. Although the runaway greenhouse effect has not occurred on Earth, solar irradiance is now at its highest level so far, and Fig. (**S2**) suggests that the required forcing for runaway may be only 10-20 W/m^2. If all conventional and unconventional fossil fuels were burned, with the CO_2 emitted to the atmosphere, it is possible that a runaway greenhouse effect could occur, with incineration of life and creation of a permanent Venus-like hothouse Earth. It would take time for the ice sheets to melt, but the melt rate may accelerate as ice sheet disintegration proceeds.

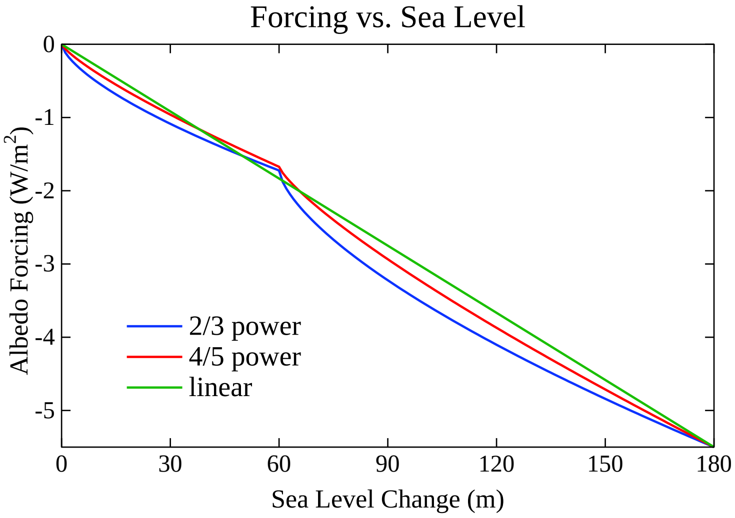


Fig. (S4). Surface albedo climate forcing as a function of sea level for three approximations of the ice sheet area as a function of sea level change, from an ice free planet to the last glacial maximum. For sea level between 0 and 60 m only Antarctica contributes to the albedo change. At the last glacial maximum Antarctica contains 75 m of sea level and the Northern Hemisphere contains 105 m.

4. ICE SHE*ET AL*BEDO

In the present paper we take the surface area covered by an ice sheet to be proportional to the 4/5 power of the volume of the ice sheet, based on ice sheet modeling of one of us (VM-D). We extend the formulation all the way to zero ice on the planet, with separate terms for each hemisphere. At 20 ky ago, when the ice sheets were at or near their maximum size in the Cenozoic era, the forcing by the Northern Hemisphere ice sheet was -3.5 W/m^2 and the forcing by the Southern Hemisphere ice sheet was -2 W/m^2, relative to the ice-free planet [14]. It is assumed that the first 60 m of sea level fall went entirely into growth of the Southern Hemisphere ice sheet. The water from further sea level fall is divided proportionately between hemispheres such that when sea level fall reaches -180 m there is 75 m in the ice sheet of the Southern Hemisphere and 105 m in the Northern Hemisphere.

The climate forcing due to sea level changes in the two hemispheres, SL_S and SL_N, is

$$F_{Albedo}\ (W/m^2) = -\ 2\ (SL_S/75\ m)^{4/5} - 3.5\ (SL_N/105\ m)^{4/5}, \qquad (S1)$$

where the climate forcings due to fully glaciated Antarctica (-2 W/m^2) and Northern Hemisphere glaciation during the last glacial maximum (-3.5 W/m^2) were derived from global climate model simulations [14].

Fig. (**S4**) compares results from the present approach with results from the same approach using exponent 2/3 rather than 4/5, and with a simple linear relationship between the total forcing and sea level change. Use of exponent 4/5 brings the results close to the linear case, suggesting that the simple linear relationship is a reasonably good approximation. The similarity of Fig. (**1c**) in our present paper and Fig. (**2c**) in [7] indicates that change of exponent from 2/3 to 4/5 did not have a large effect.

5. GLOBAL NATURE OF MAJOR CLIMATE CHANGES

Climate changes often begin in a specific hemisphere, but the large climate changes are invariably global, in part because of the global GHG feedback. Even without the GHG feedback, forcings that are located predominately in one hemisphere, such as ice sheet changes or human-made aerosols, still evoke a global response [12], albeit with the response being larger in the hemisphere of the forcing. Both the atmosphere and ocean transmit climate response between hemispheres. The deep ocean can carry a temperature change between hemispheres with little loss, but because of the ocean's thermal inertia there can be a hemispheric lag of up to a millennium (see Ocean Response Time, below).

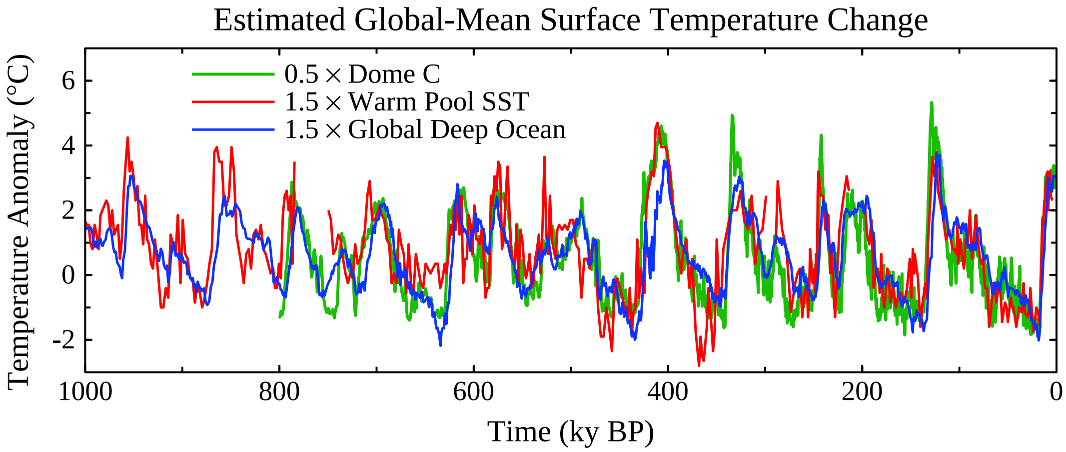


Fig. (S5). Estimated global temperature change based on measurements at a single point or, in the case of the deep ocean, a near-global stack of ocean drilling sites: Antarctica Dome C [S8], Warm Pool [S9], deep ocean [26].

Fig. (**S5**) compares temperature change in Antarctica [S8], the tropical sea surface [S9], and the global deep ocean [26]. Temperature records are multiplied by factors that convert the temperature record to an estimate of global temperature change. Based on paleoclimate records, polar temperature change is typically twice the global average temperature change, and tropical temperature change is about two-thirds of the global mean change. This polar amplification of the temperature change is an expected consequence of feedbacks [14], especially the snow-ice albedo feedback. The empirical result that deep ocean temperature changes are only about two-thirds as large as global temperature change is obtained from data for the Pleistocene epoch, when deep ocean temperature change is limited by its approach to the freezing point.

6. HOLOCENE CLIMATE FORCINGS

The GHG zero-point for the paleo portion of Fig. (**2**) is the mean for 10-8 ky BP, a time that should precede any significant anthropogenic effect on GHG amount. It has been suggested that the increase of CO_2 that began 8000 years ago is due to deforestation and the increase of CH_4 that began 6000 years ago is caused by rice agriculture [62]. This suggestion has proven to be controversial, but regardless of whether late Holocene CO_2 and CH_4 changes are human-made, the GHG forcing is anomalous in that period relative to global temperature change estimated from ocean and ice cores. As discussed elsewhere [7], the late Holocene is the only time in the ice core record in which there is a clear deviation of temperature from that expected due to GHG and surface albedo forcings.

The GHG forcing increase in the second half of the Holocene is ~3/4 W/m^2. Such a large forcing, by itself, would create a planetary energy imbalance that could not be sustained for millennia without causing a large global temperature increase, the expected global warming being about 1°C. Actual global temperature change in this period was small, perhaps a slight cooling. Fig. (**S6**) shows estimates of global temperature change obtained by dividing polar temperature change by two or multiplying tropical and deep ocean temperatures by 1.5. Clearly the Earth has not been warming rapidly in the latter half of the Holocene. Thus a substantial (negative) forcing must have been operating along with the positive GHG forcing.

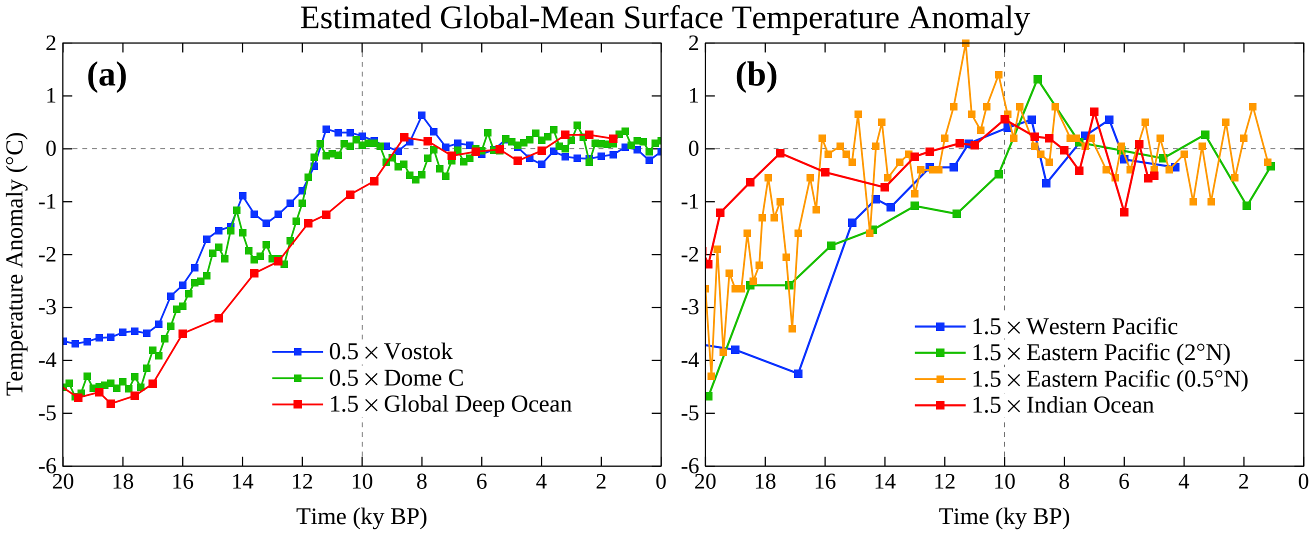


Fig. (S6). Estimates of global temperature change inferred from Antarctic ice cores [18, S8] and ocean sediment cores [S9-S13], as in Fig. (**S5**) but for a period allowing Holocene temperature to be apparent.

Deforestation causes a negative climate forcing [12], but an order of magnitude too small to balance GHG positive forcing. A much larger negative forcing is expected from human-made aerosols. Aerosol forcing is non-linear, especially the indirect effect on clouds, with aerosols added to a pristine atmosphere being more effective than those added to the current highly polluted atmosphere. Given estimates of a negative forcing of 1-2 W/m^2 for today's anthropogenic aerosols [2, 5, 12], a negative aerosol forcing at least of the order of 0.5 W/m^2 in 1850 is expected. We conclude that aerosols probably were the predominant negative forcing that opposed the rapid increase of positive GHG forcing in the late Holocene.

7. OCEAN RESPONSE TIME

Fig. (**S7**) shows the climate response function, defined as the fraction of equilibrium global warming that is obtained as a function of time. This response function was obtained [7] from a 3000-year simulation after instant doubling of atmospheric CO_2, using GISS modelE [S3, 12] coupled to the Russell ocean model [S14]. Note that although 40% of the equilibrium solution is obtained within several years, only 60% is achieved after a century, and nearly full response requires a millennium. The long response time is caused by slow uptake of heat by the deep ocean, which occurs primarily in the Southern Ocean.

This delay of the surface temperature response to a forcing, caused by ocean thermal inertia, is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of water into the deep ocean [31]. The ocean model used for Fig. (**S7**) may mix somewhat too rapidly in the waters around Antarctica, as judged by transient tracers [S14], reducing the simulated surface response on the century time scale. However, this uncertainty does not qualitatively alter the shape of the response function (Fig. **S7**).

When the climate model used to produce Fig. (**S7**) is driven by observed changes of GHGs and other forcings it yields good agreement with observed global temperature and ocean heat storage [5]. The model has climate sensitivity ~3°C for doubled CO_2, in good agreement with the fast-feedback sensitivity inferred from paleoclimate data.

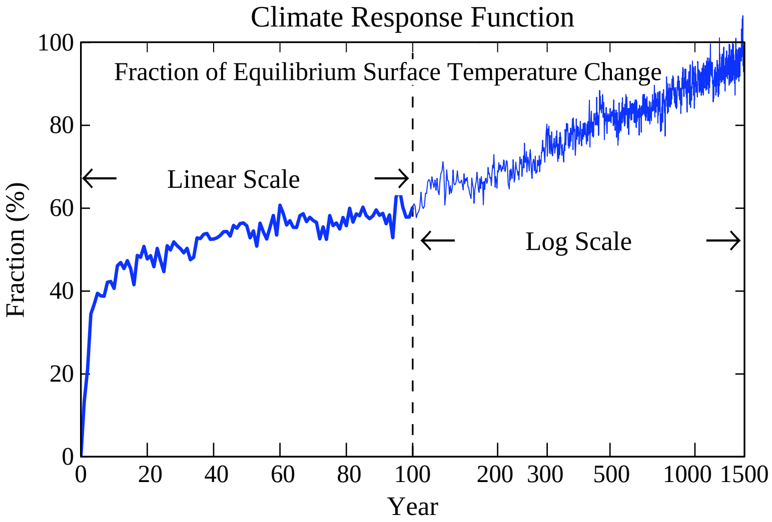


Fig. (S7). Fraction of equilibrium surface temperature response versus time in the GISS climate model [7, 12, S3] with the Russell [S14] ocean. The forcing was doubled atmospheric CO_2. The ice sheets, vegetation distribution and other long-lived GHGs were fixed.

8. SEPARATION OF Δ^{18}O INTO ICE VOLUME AND TEMPERATURE

$\delta^{18}O$ of benthic (deep ocean dwelling) foraminifera is affected by both deep ocean temperature and continental ice volume. Between 34 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3, with T_{do} change ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Based on the rate of change of $\delta^{18}O$ with deep ocean temperature in the prior period without land ice, ~ 1.5 of $\delta^{18}O$ is associated with the T_{do} change of ~ 6°C, and we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75).

Thus we assume that ice sheets were absent when $\delta^{18}O < 1.75$ with sea level 75 msl higher than today. Sea level at smaller values of $\delta^{18}O$ is given by

$$SL\ (m) = 75 - 60 \times (\delta^{18}O - 1.75). \qquad (S2)$$

Fig. (**S8**) shows that the division of $\delta^{18}O$ equally into sea level change and deep ocean temperature captures well the magnitude of the major glacial to interglacial changes.

9. CONTINENTAL DRIFT AND ATMOSPHERIC CO_2

At the beginning of the Cenozoic era 65 My ago the continents were already close to their present latitudes, so the effect of continental location on surface albedo had little direct effect on the planet's energy balance (Fig. **S9**). However, continental drift has a major effect on the balance, or imbalance, of outgassing and uptake of CO_2 by the solid Earth and thus a major effect on atmospheric composition and climate. We refer to the carbon in the air, ocean, soil and biosphere as the combined surface reservoir of carbon, and carbon in ocean sediments and the rest of the crust as the carbon in the 'solid' Earth. Sloshing of CO_2 among the surface reservoirs, as we have shown, is a primary mechanism for glacial-interglacial climate fluctuations. On longer time scales the total amount of carbon in the surface reservoirs can change as a result of any imbalance between outgassing and uptake by the solid Earth.

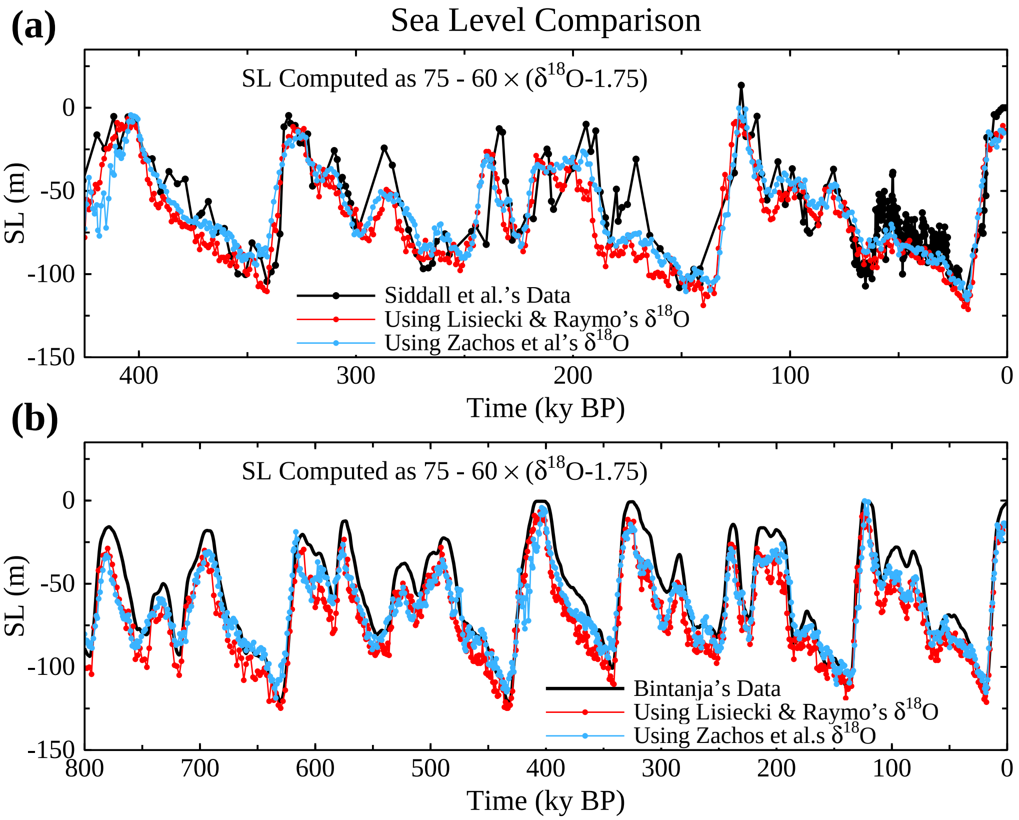
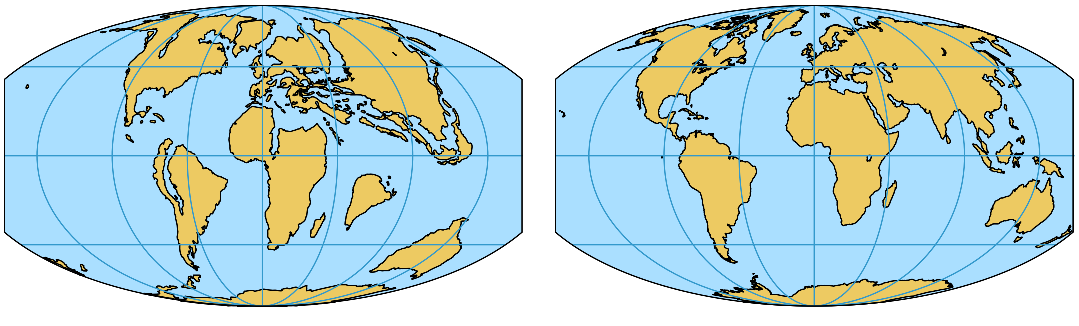


Fig. (S8). (**a**) Comparison of Siddall *et al*. [19] sea level record with sea level computed from $\delta^{18}O$ *via* Eq. S2 using two alternative global benthic stacks [26, S15]. (**b**) Comparison of Bintanja *et al*. [S16] sea level reconstruction with the same global benthic stacks as in (**a**).



End of Cretaceous (65 My BP)

Present Day

Fig. (S9). Continental locations at the beginning and end of the Cenozoic era [S17].

Outgassing, which occurs mainly in regions of volcanic activity, depends upon the rate at which carbon-rich oceanic crust is subducted beneath moving continental plates [30, 47]. Drawdown of CO_2 from the surface reservoir occurs with weathering of rocks exposed by uplift, with the weathering products carried by rivers to the ocean and eventually deposited as carbonates on the ocean floor [30] and by burial of organic matter. Both outgassing and drawdown of CO_2 are affected by changes in plate tectonics, which thus can alter the amount of carbon in the surface reservoir. The magnitude of the changes of carbon in the surface reservoir, and thus in the atmosphere, is constrained by a negative weathering feedback on the time scale of hundreds of thousands of years [30, 52], but plate tectonics can evoke changes of the surface carbon reservoir by altering the rates of outgassing and weathering.

At the beginning of the Cenozoic the African plate was already in collision with Eurasia, pushing up the Alps. India was still south of the equator, but moving north rapidly through a region with fresh carbonate deposits. It is likely that subduction of carbon rich crust of the Tethys Ocean, long a depocenter for sediments, caused an increase of atmospheric CO_2 and the early Cenozoic warming that peaked ~50 My ago. The period of rapid subduction terminated with the collision of India with Eurasia, whereupon uplift of the Himalayas and the Tibetan Plateau increased weathering rates and drawdown of atmospheric CO_2 [51].

Since 50 My ago the world's major rivers have emptied into the Indian and Atlantic Oceans, but there is little subduction of oceanic crust of these regions that are accumulating sediments [47]. Thus the collision of India with Asia was effective in both reducing a large source of outgassing of CO_2 as well as exposing rock for weathering and drawdown of atmospheric CO_2. The rate of CO_2 drawdown decreases as the CO_2 amount declines because of negative feedbacks, including the effects of temperature and plant growth rate on weathering [30].

10. PROXY CO_2 DATA

There are inconsistencies among the several proxy measures of atmospheric CO_2, including differences between results of investigators using nominally the same reconstruction method. We briefly describe strengths and weaknesses of the four paleo-CO_2 reconstruction methods included in the IPCC report [2], which are shown in Fig. (**S10**) and discussed in detail elsewhere [S18]. The inconsistencies among the different proxies constrain their utility for rigorously evaluating our CO_2 predictions. We also include a comparison of our calculated CO_2 history with results from a version of the Berner [30] geochemical carbon cycle model, as well as a comparison with an emerging CO_2 proxy based on carbon-isotope analyses of nonvascular plant (bryophyte) fossils [S19].

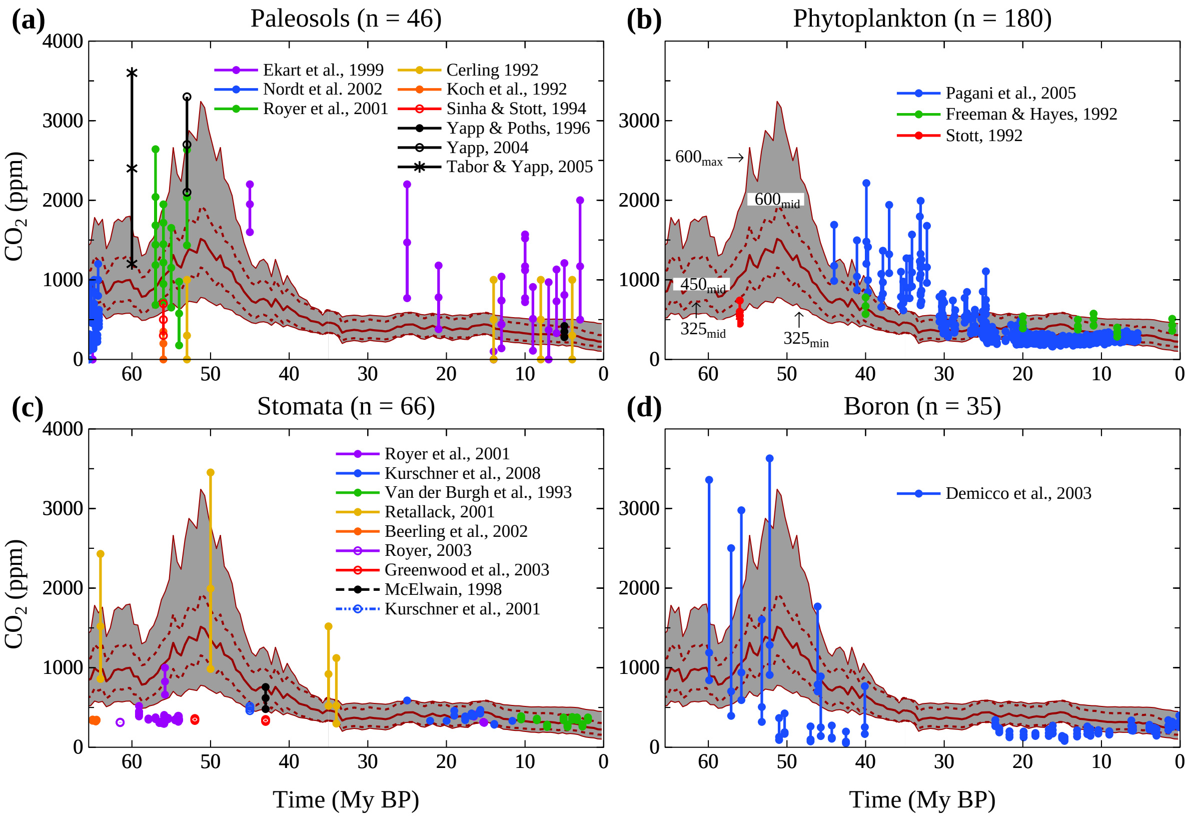


Fig. (S10). Comparison of proxy CO_2 measurements with CO_2 predictions based on deep-ocean temperature, the latter inferred from benthic $\delta^{18}O$. The shaded range of model results is intended mainly to guide the eye in comparing different proxies. The dark central line is for the standard case with CO_2 = 450 ppm at 35 My ago, and the dashed lines are the standard cases for CO_2 = 325 and 600 ppm at 35 My ago. The extremes of the shaded area correspond to the maximum range including a 50% uncertainty in the relation of ΔT_s and ΔT_{do}. Our assumption that CO_2 provides 75% of the GHG throughout the Cenozoic adds additional uncertainty to the predicted CO_2 amount. References for data sources in the legends are provided by Royer [55], except Kurshner *et al.* [S20].

The paleosol method is based on the $\delta^{13}C$ of pedogenic carbonate nodules, whose formation can be represented by a two end-member mixing model between atmospheric CO_2 and soil-derived carbon [S21]. Variables that need to be constrained or assumed include an estimation of nodule depth from the surface of the original soil, the respiration rate of the ecosystem that inhabits the soil, the porosity/diffusivity of the original soil, and the isotopic composition of the vegetation contribution of respired CO_2. The uncertainties in CO_2 estimates with this proxy are substantial at high CO_2 (±500-1000 ppm when CO_2 > 1000 ppm) and somewhat less in the lower CO_2 range (±400-500 ppm when CO_2 < 1000 ppm).

The stomatal method is based on the genetically-controlled relationship [S22] between the proportion of leaf surface cells that are stomata and atmospheric CO_2 concentrations [S23]. The error terms with this method are comparatively small at low CO_2 (< ±50 ppm), but the method rapidly loses sensitivity at high CO_2 (> 500-1000 ppm). Because stomatal-CO_2 relationships are often species-specific, only extant taxa with long fossil records can be used [S24]. Also, because the fundamental response of stomata is to the partial pressure of CO_2 [S25], constraints on paleoelevation are required.

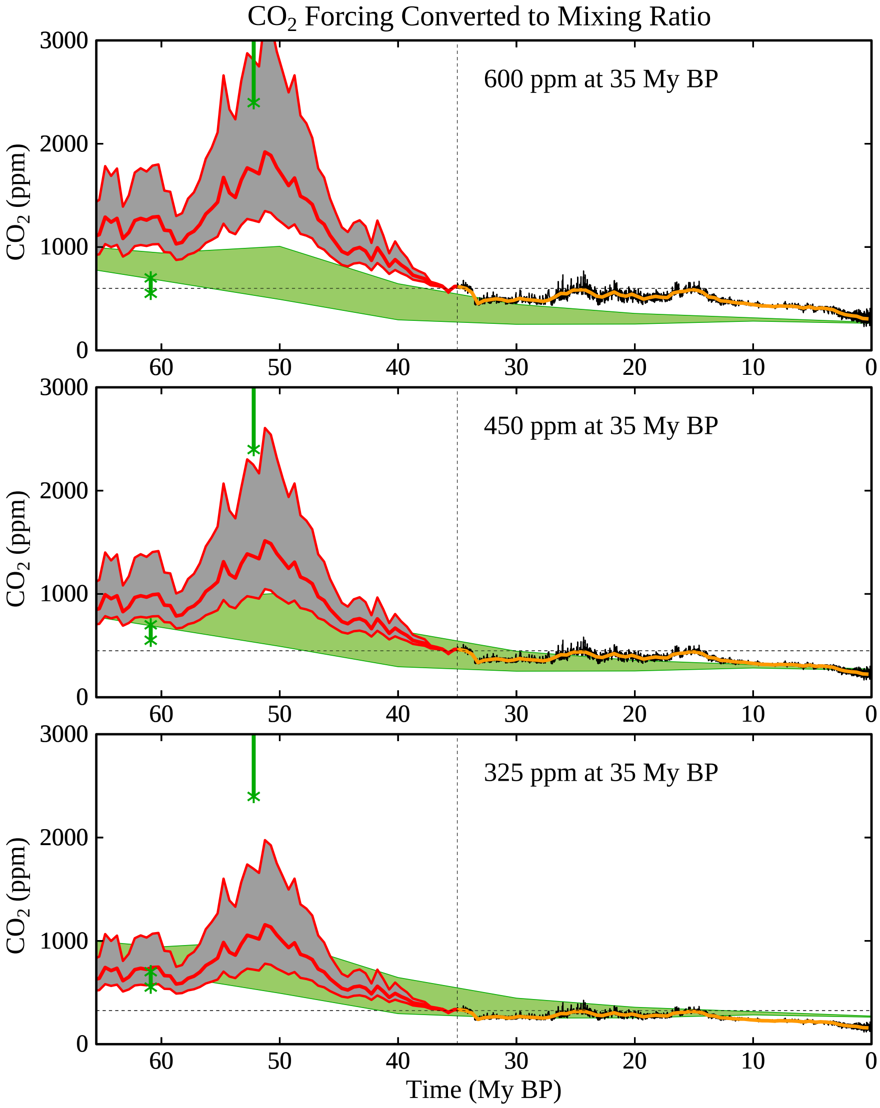


Fig. (S11). Simulated CO_2 in the Cenozoic for three choices of CO_2 amount at 35 My, as in Fig. (**5**), compared with the CO_2 history in a geochemical model [30], specifically the model version described by Fletcher *et al.* [S19]. The green vertical bars are a proxy CO_2 measure [S19] obtained from fossils of non-vascular plants (bryophytes) that is not included among the proxies shown in Fig. (**S10**).

The phytoplankton method is based on the Rayleigh distillation process of fractionating stable carbon isotopes during photosynthesis [S26]. In a high CO_2 environment, for example, there is a higher diffusion rate of CO_2 through phytoplankton cell membranes, leading to a larger available intercellular pool of $CO_{2[aq]}$ and more depleted $\delta^{13}C$ values in photosynthate. Cellular growth rate and cell size also impact the fractionation of carbon isotopes in phytoplankton and thus fossil studies must take these factors into account [S27]. This approach to reconstructing CO_2 assumes that the diffusional transport of CO_2 into the cell dominates, and that any portion of carbon actively transported into the cell remains constant with time. Error terms are typically small at low CO_2 (< ±50 ppm) and increase substantially under higher CO_2 concentrations [S27].

The boron-isotope approach is based on the pH-dependency of the $\delta^{11}B$ of marine carbonate [S28]. This current method assumes that only borate is incorporated in the carbonate lattice and that the fractionation factor for isotope exchange between boric acid and borate in solution is well-constrained. Additional factors that must be taken into account include test dissolution and size, species-specific physiological effects on carbonate $\delta^{11}B$, and ocean alkalinity [S29-S31]. As with the stomatal and phytoplankton methods, error terms are comparatively small at low CO_2 (< ±50 ppm) and the method loses sensitivity at higher CO_2 (> 1000 ppm). Uncertainty is unconstrained for extinct foraminiferal species.

Fig. (**S10**) illustrates the scatter among proxy data sources, which limits inferences about atmospheric CO_2 history. Given the large inconsistency among different data sets in the early Cenozoic, at least some of the data or their interpretations must be flawed. In the range of proxy data shown in Fig. (**5**) we took all data sources as being of equal significance. It seems likely that the low CO_2 values in the early Cenozoic are faulty, but we avoid omission of any data until the matter is clarified, and thus the range of proxy data shown in Fig. (**5**) is based on all data. Reviews of the proxy data [S19, 55] conclude that atmospheric CO_2 amount in the early Cenozoic reached values of at least 500-1000 ppm.

Fig. (**S11**) shows that geochemical carbon cycle modeling [30, S19] is reasonably consistent with our calculated long-term trend of atmospheric CO_2 for the cases with CO_2 at 34 My ago being in the range from about 325 to 450 ppm. The geochemical modeling does not yield a strong maximum of CO_2 at 50 My ago, but the temporal resolution of the modeling (10 My) and the absence of high resolution input data for outgassing due to variations in plate motions tends to mitigate against sharp features in the simulated CO_2.

Fig. (**S11**) also shows (vertical green bars) an emerging CO_2 proxy based on the isotopic composition of fossil liverworts. These non-vascular plants, lacking stomatal pores, have a carbon isotopic fractionation that is strongly CO_2 dependent, reflecting the balance between CO_2 uptake by photosynthesis and inward CO_2 diffusion [S19].

11. CLIMATE SENSITIVITY COMPARISONS

Other empirical or semi-empirical derivations of climate sensitivity from paleoclimate data (Table **S1**) are in reasonable accord with our results, when account is taken of differences in definitions of sensitivity and the periods considered.

Royer *et al.* [56] use a carbon cycle model, including temperature dependence of weathering rates, to find a best-fit doubled CO_2 sensitivity of 2.8°C based on comparison with Phanerozoic CO_2 proxy amounts. Best-fit in their comparison of model and proxy CO_2 data is dominated by the times of large CO_2 in the Phanerozoic, when ice sheets would be absent, not by the times of small CO_2 in the late Cenozoic. Their inferred sensitivity is consistent with our inference of ~3°C for doubled CO_2 at times of little or no ice on the planet.

Higgins and Schrag [57] infer climate sensitivity of ~4°C for doubled CO_2 from the temperature change during the Paleocene-Eocene Thermal Maximum (PETM) ~55 My ago (Fig. **3**), based on the magnitude of the carbon isotope excursion at that time. Their climate sensitivity for an ice-free planet is consistent with ours within uncertainty ranges. Furthermore, recalling that we assume non-CO_2 to provide 25% of the GHG forcing, if one assumes that part of the PETM warming was a direct of effect of methane, then their inferred climate sensitivity is in even closer agreement with ours.

Pagani *et al.* [58] also use the magnitude of the PETM warming and the associated carbon isotopic excursion to discuss implications for climate sensitivity, providing a graphical relationship to help assess alternative assumptions about the origin and magnitude of carbon release. They conclude that the observed PETM warming of about 5°C implies a high climate sensitivity, but with large uncertainty due to imprecise knowledge of the carbon release.

Table S1. Climate Sensitivity Inferred Semi-Empirically from Cenozoic or Phanerozoic Climate Change

Reference	Period	Doubled CO_2 Sensitivity
Royer *et al.* [56]	0-420 My	~ 2.8°C
Higgins and Schrag [57]	PETM	~4°C
Pagani *et al.* [58]	PETM	High

12. GREENHOUSE GAS GROWTH RATES

Fossil fuel CO_2 emissions have been increasing at a rate close to the highest IPCC [S34] scenario (Fig. **S12b**). Increase of CO_2 in the air, however, appears to be in the middle of the IPCC scenarios (Fig. **S12c**, **d**), but as yet the scenarios are too close and interannual variability too large, for assessment. CO_2 growth is well above the "alternative scenario", which was defined with the objective of keeping added GHG forcing in the 21st century at about 1.5 W/m^2 and 21st century global warming less than 1°C [20].

Non-CO_2 greenhouse gases are increasing more slowly than in IPCC scenarios, overall at approximately the rate of the "alternative scenario", based on a review of data through the end of 2007 [69]. There is potential to reduce non-CO_2 forcings below the alternative scenario [69].

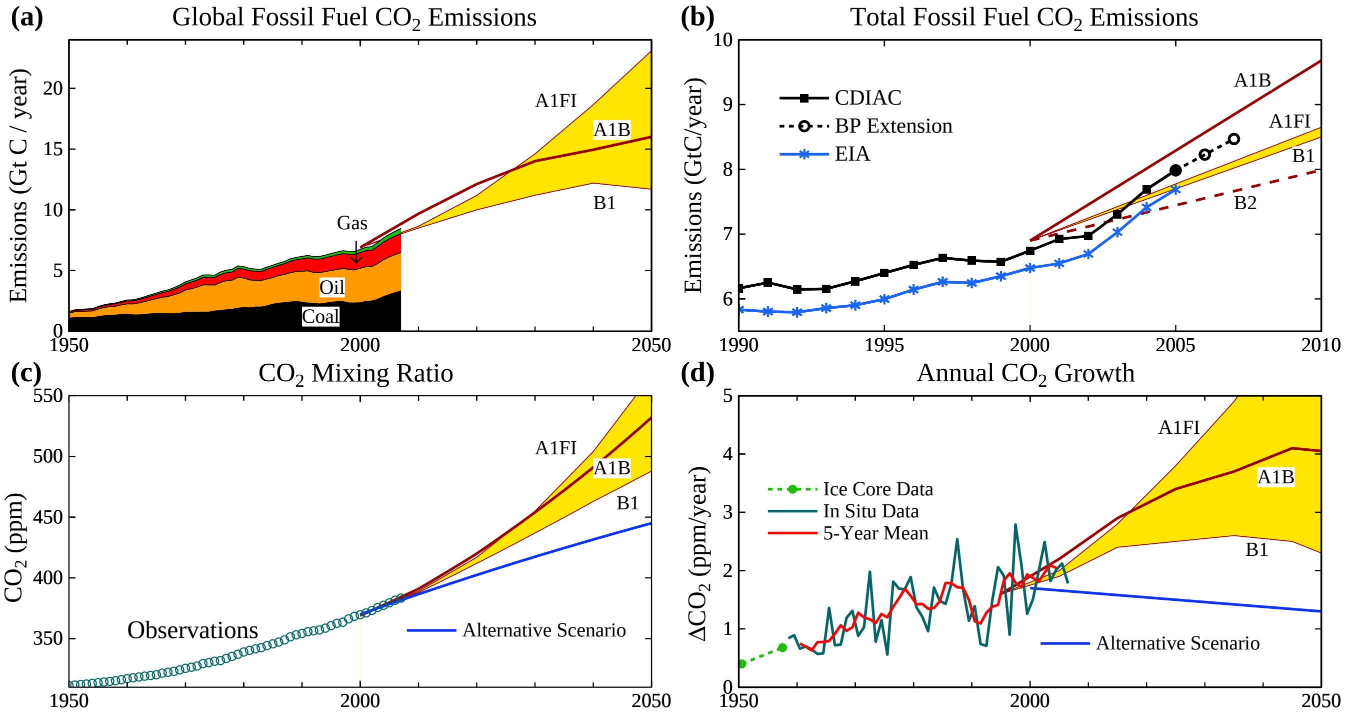


Fig. (S12). (**a**) Fossil fuel CO_2 emissions by fuel type [S32, S33], the thin green sliver being gas flaring plus cement production, and IPCC fossil fuel emissions scenarios, (**b**) expansion global emissions to show recent changes more precisely, the EIA values excluding CO_2 emissions from cement manufacture, (**c**) observed atmospheric CO_2 amount and IPCC and "alternative" scenarios for the future, (**d**) annual atmospheric CO_2 growth rates. Data here is an update of data sources defined in [6]. The yellow area is bounded by scenarios that are most extreme in the second half of the 21st century; other scenarios fall outside this range in the early part of the century.

13. FOSSIL FUEL AND LAND-USE CO_2 EMISSIONS

Fig. (**S13**) shows estimates of anthropogenic CO_2 emissions to the atmosphere. Although fossil emissions through 2006 are known with good accuracy, probably better than 10%, reserves and potential reserve growth are highly uncertain. IPCC [S34] estimates for oil and gas proven reserves are probably a lower limit for future oil and gas emissions, but they are perhaps a feasible goal that could be achieved *via* a substantial growing carbon price that discourages fossil fuel exploration in extreme environments together with national and international policies that accelerate transition to carbon-free energy sources and limit fossil fuel extraction in extreme environments and on government controlled property.

Coal reserves are highly uncertain, but the reserves are surely enough to take atmospheric CO_2 amount far into the region that we assess as being "dangerous". Thus we only consider scenarios in which coal use is phased out as rapidly as possible, except for uses in which the CO_2 is captured and stored so that it cannot escape to the atmosphere. Thus the magnitude of coal reserves does not appreciably affect our simulations of future atmospheric CO_2 amount.

Integrated 1850-2008 net land-use emissions based on the full Houghton [83] historical emissions (Fig. **S14**), extended with constant emissions for the past several years, are 79 ppm CO_2. Although this could be an overestimate by up to a factor of two (see below), substantial pre-1850 deforestation must be added in. Our subjective estimate of uncertainty in the total land-use CO_2 emission is a factor of two.

14. THE MODERN CARBON CYCLE

Atmospheric CO_2 amount is affected significantly not only by fossil fuel emissions, but also by agricultural and forestry practices. Quantification of the role of land-use in the uptake and release of CO_2 is needed to assess strategies to minimize human-made climate effects.

Fig. (**S15**) shows the CO_2 airborne fraction, AF, the annual increase of atmospheric CO_2 divided by annual fossil fuel CO_2 emissions. AF is a critical metric of the modern carbon cycle, because it is based on the two numbers characterizing the global carbon cycle that are well known. AF averages 56% over the period of accurate data, which began with the CO_2 measurements of Keeling in 1957, with no discernable trend. The fact that 44% of fossil fuel emissions seemingly "disappears" immediately provides a hint of optimism with regard to the possibility of stabilizing, or reducing, atmospheric CO_2 amount.

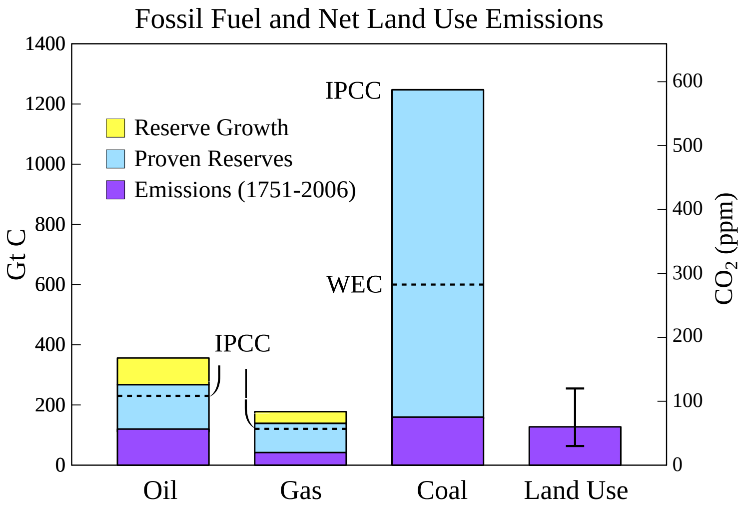


Fig. (S13). Fossil fuel and land-use CO_2 emissions, and potential fossil fuel emissions. Historical fossil fuel emissions are from the Carbon Dioxide Information Analysis Center [CDIAC, S32] and British Petroleum [BP, S33]. Lower limits on oil and gas reserves are from IPCC [S34] and higher limits are from the United States Energy Information Administration [EIA, 80]. Lower limit for coal reserves is from the World Energy Council [WEC, S35] and upper limit from IPCC [S34]. Land use estimate is from integrated emissions of Houghton/2 (Fig. **S14**) supplemented to include pre-1850 and post-2000 emissions; uncertainty bar is subjective.

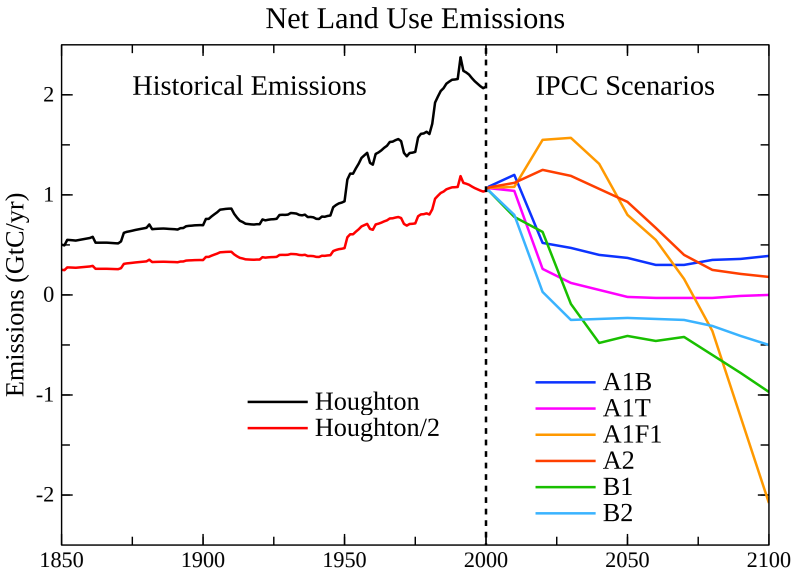


Fig. (S14). Left side: estimate by Houghton [83] of historical net land-use CO_2 emissions, and a 50 percent reduction of that estimate. Right side: IPCC [2] scenarios for land-use CO_2 emissions.

That optimism needs to be tempered, as we will see, by realization of the magnitude of the actions required to halt and reverse CO_2 growth. However, it is equally important to realize that assertions that fossil fuel emissions must be reduced close to 100% on an implausibly fast schedule are not necessarily valid.

A second definition of the airborne fraction, AF2, is also useful. AF2 includes the net anthropogenic land-use emission of CO_2 in the denominator. This AF2 definition of airborne fraction has become common in recent carbon cycle literature. However, AF2 is not an observed or accurately known quantity; it involves estimates of net land-use CO_2 emissions, which vary among investigators by a factor of two or more [2].

Fig. (**S15**) shows an estimate of net land-use CO_2 emissions commonly used in carbon cycle studies, labeled “Houghton” [83], as well as “Houghton/2”, a 50% reduction of these land-use emissions. An over-estimate of land-use emissions is one possible solution of the long-standing “missing sink” problem that emerges when the full “Houghton” land-use emissions are employed in carbon cycle models [2, S34, 79].

Principal competing solutions of the “missing sink” paradox are (1) land-use CO_2 emissions are over-estimated by about a factor of two, or (2) the biosphere is being “fertilized” by anthropogenic emissions, *via* some combination of increasing atmospheric CO_2, nitrogen deposition, and global warming, to a greater degree than included in typical carbon cycle models.

Reality may include contributions from both candidate explanations. There is also a possibility that imprecision in the ocean uptake of CO_2, or existence of other sinks such as clay formation, could contribute increased CO_2 uptake, but these uncertainties are believed to be small.

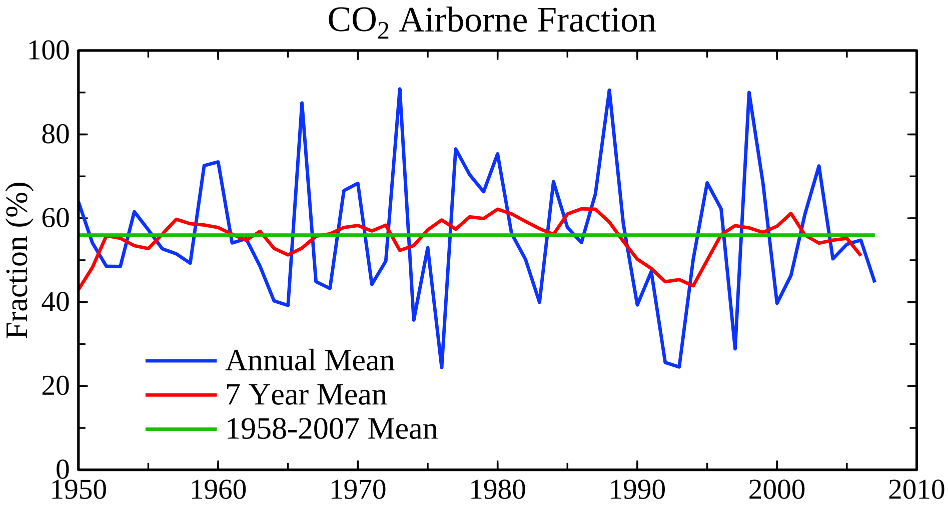


Fig. (S15). CO_2 airborne fraction, AF, the ratio of annual observed atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

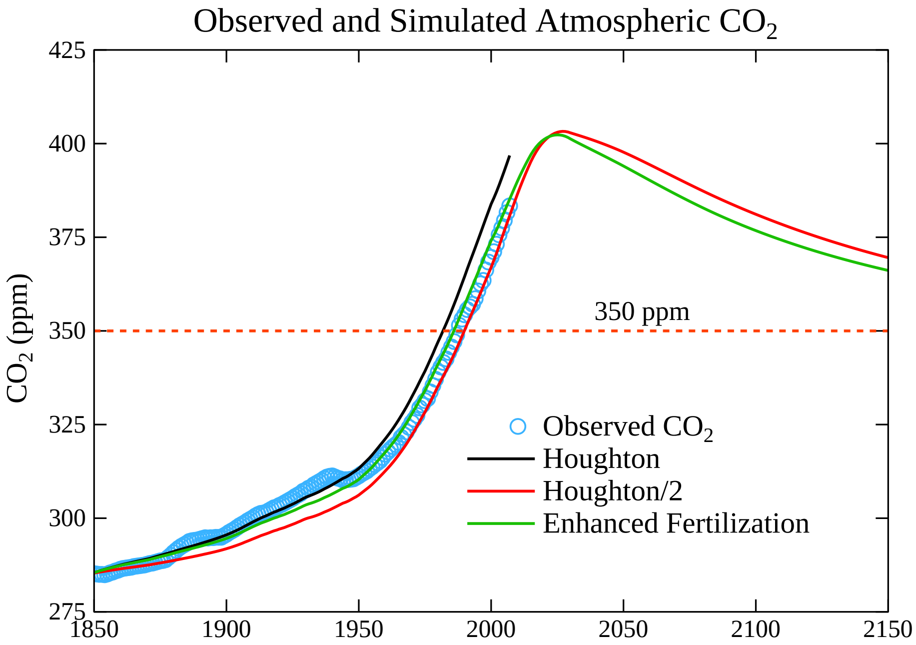


Fig. (S16). Computed and observed time evolution of atmospheric CO_2. "Enhanced Fertilization" uses the full "Houghton" land use emissions for 1850–2000. "Houghton/2" and "Enhanced Fertilization" simulations are extended to 2100 assuming coal phase-out by 2030 and the IPCC [2] A1T land-use scenario. Observations are from Law Dome ice core data and flask and in-situ measurements [6, S36, http://www.esrl.noaa.gov/gmd/ccgg/trends/].

Fig. (**S16**) shows resulting atmospheric CO_2, and Fig. (**S17**) shows AF and AF2, for two extreme assumptions: "Houghton/2" and " Enhanced Fertilization", as computed with a dynamic-sink pulse response function (PRF) representation of the Bern carbon cycle model [78, 79]. Fertilization is implemented *via* a parameterization [78] that can be adjusted to achieve an improved match between observed and simulated CO_2 amount. In the "Houghton/2" simulation the original value [78] of the fertilization parameter is employed while in the "Enhanced Fertilization" simulation the full Houghton emissions are used with a larger fertilization parameter. Both "Houghton/2" and "Enhanced Fertilization" yield good agreement with the observed CO_2 history, but Houghton/2 does a better job of matching the time dependence of observed AF.

It would be possible to match observed CO_2 to an arbitrary precision if we allowed the adjustment to "Houghton" land-use to vary with time, but there is little point or need for that. Fig. (**S16**) shows that projections of future CO_2 do not differ much even for the extremes of Houghton/2 and Enhanced Fertilization. Thus in Fig. (**6**) we show results for only the case Houghton/2, which is in better agreement with the airborne fraction and also is continuous with IPCC scenarios for land use.

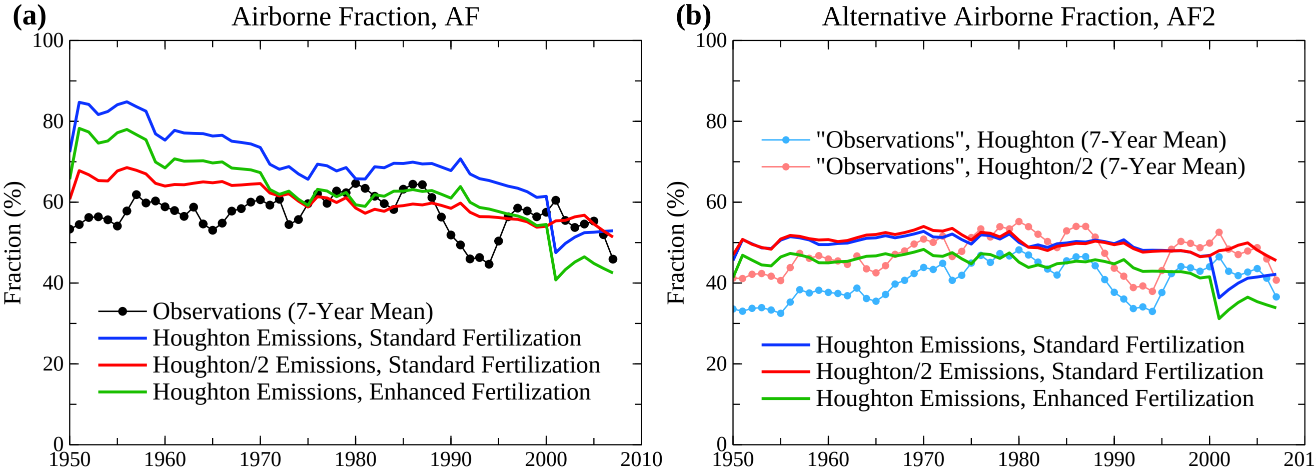


Fig. (S17). (**a**) Observed and simulated airborne fraction (AF), the ratio of annual CO_2 increase in the air over annual fossil fuel CO_2 emissions, (**b**) AF2 includes the sum of land use and fossil fuel emissions in the denominator in defining airborne fraction; thus AF2 is not accurately known because of the large uncertainty in land use emissions.

15. IMPLICATIONS OF FIG. (6): CO_2 EMISSIONS AND ATMOSPHERIC CONCENTRATION WITH COAL PHASE-OUT BY 2030

Fig. (**6**) provides an indication of the magnitude of actions that are needed to return atmospheric CO_2 to a level of 350 ppm or lower. Fig. (**6**) allows for the fact that there is disagreement about the magnitude of fossil fuel reserves, and that the magnitude of useable reserves depends upon policies.

A basic assumption underlying Fig. (**6**) is that, within the next several years, there will be a moratorium on construction of coal-fired power plants that do not capture and store CO_2, and that CO_2 emissions from existing power plants will be phased out by 2030. This coal emissions phase out is the sine qua non for stabilizing and reducing atmospheric CO_2. If the sine qua non of coal emissions phase-out is achieved, atmospheric CO_2 can be kept to a peak amount ~400-425 ppm, depending upon the magnitude of oil and gas reserves.

Fig. (**6**) illustrates two widely different assumptions about the magnitude of oil and gas reserves (illustrated in Fig. **S13**). The smaller oil and gas reserves, those labeled “IPCC”, are realistic if “peak oil” advocates are more-or-less right, i.e., if the world has already exploited about half of readily accessible oil and gas deposits, so that production of oil and gas will begin to decline within the next several years.

There are also “resource optimists” who dispute the “peakists’, arguing that there is much more oil (and gas) to be found. It is possible that both the “peakists” and “resource optimists” are right, it being a matter of how hard we work to extract maximum fossil fuel resources. From the standpoint of controlling human-made climate change, it does not matter much which of these parties is closer to the truth.

Fig. (**6**) shows that, if peak CO_2 is to be kept close to 400 ppm, the oil and gas reserves actually exploited need to be close to the “IPCC” reserve values. In other words, if we phase out coal emissions we can use remaining oil and gas amounts equal to those which have already been used, and still keep peak CO_2 at about 400 ppm. Such a limit is probably necessary if we are to retain the possibility of a drawdown of CO_2 beneath the 350 ppm level by methods that are more-or-less “natural”. If, on the other hand, reserve growth of the magnitude that EIA estimates (Figs. **6** and **S13**) occurs, and if these reserves are burned with the CO_2 emitted to the atmosphere, then the forest and soil sequestration that we discuss would be inadequate to achieve drawdown below the 350 ppm level in less than several centuries.

Even if the greater resources estimated by EIA are potentially available, it does not mean that the world necessarily must follow the course implied by EIA estimates for reserve growth. If a sufficient price is applied to carbon emissions it will discourage extraction of fossil fuels in the most extreme environments. Other actions that would help keep effective reserves close to the IPCC estimates would include prohibition of drilling in environmentally sensitive areas, including the Arctic and Antarctic.

National policies, in most countries, have generally pushed to expand fossil fuel reserves as much as possible. This might partially account for the fact that energy information agencies, such as the EIA in the United States, which are government agencies, tend to forecast strong growth of fossil fuel reserves. On the other hand, state, local, and citizen organizations can influence imposition of limits on fossil fuel extraction, so there is no guarantee that fossil resources will be fully exploited. Once the successors to fossil energy begin to take hold, there may be a shifting away from fossil fuels that leaves some of the resources in the ground. Thus a scenario with oil and gas emissions similar to that for IPCC reserves may be plausible.

Assumptions yielding the Forestry & Soil wedge in Fig. (**6b**) are as follows. It is assumed that current net deforestation will decline linearly to zero between 2010 and 2015. It is assumed that uptake of carbon *via* reforestation will increase linearly until 2030, by which time reforestation will achieve a maximum potential sequestration rate of 1.6 GtC per year [S37]. Waste-derived biochar application will be phased in linearly over the period 2010-2020, by which time it will reach a maximum uptake rate of 0.16 GtC/yr [85]. Thus after 2030 there will be an annual uptake of 1.6 + 0.16 = 1.76 GtC per year, based on the two processes described.

Thus Fig. (**6**) shows that the combination of (1) moratorium and phase-out of coal emissions by 2030, (2) policies that effectively keep fossil fuel reserves from significantly exceeding the IPCC reserve estimates, and (3) major programs to achieve carbon sequestration in forests and soil, can together return atmospheric CO_2 below the 350 ppm level before the end of the century.

The final wedge in Fig. (**6**) is designed to provide an indication of the degree of actions that would be required to bring atmospheric CO_2 back to the level of 350 ppm by a time close to the middle of this century, rather than the end of the century. This case also provides an indication of how difficult it would be to compensate for excessive coal emissions, if the world should fail to achieve a moratorium and phase-out of coal as assumed as our “sine qua non”.

Assumptions yielding the Oil-Gas-Biofuels wedge in Fig. (**6b**) are as follows: energy efficiency, conservation, carbon pricing, renewable energies, nuclear power and other carbon-free energy sources, and government standards and regulations will lead to decline of oil and gas emissions at 4% per year beginning when 50% of the estimated resource (oil or gas) has been exploited, rather than the 2% per year baseline decline rate [79]. Also capture of CO_2 at gas- power plants (with CO_2 capture) will use 50% of remaining gas supplies. Also a linear phase-in of liquid biofuels is assumed between 2015 and 2025 leading to a maximum global bioenergy from “low-input/high-diversity” biofuels of ~23 EJ/yr, inferred from Tilman *et al*. [87], that is used as a substitute for oil; this is equivalent to ~0.5 GtC/yr, based on energy conversion of 50 EJ/GtC for oil. Finally, from 2025 onward, twice this number (i.e., 1 GtC/yr) is subtracted from annual oil emissions, assuming root/soil carbon sequestration *via* this biofuel-for-oil substitution is at least as substantial as in Tilman *et al.* [87]. An additional option that could contribute to this wedge is using biofuels in powerplants with CO_2 capture and sequestration [86].

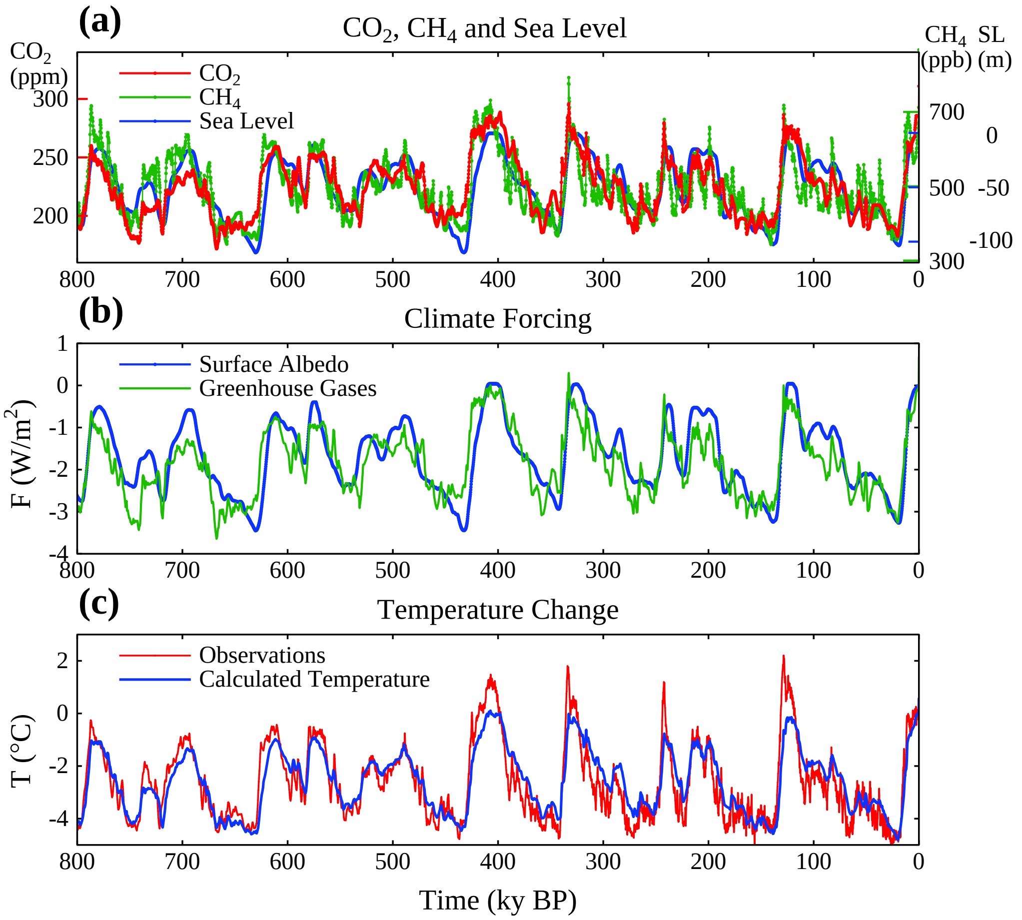


Fig. (S18). (**a**) CO_2 [S38], CH_4 [S39] and sea level [S16] for past 800 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from the sea level history of Bintanja *et al.* [S16]. (**c**) Calculated global temperature change based on the above forcings and climate sensitivity ¾°C per W/m^2. Observations are Antarctic temperature change from the Dome C ice core [S8] divided by two.

16. EPICA 800 KY DATA

Antarctic Dme C ice core data acquired by EPICA (European Project for Ice Coring in Antarctica) provide a record of atmospheric composition and temperature spanning 800 ky [S8], almost double the time covered by the Vostok data [17, 18] of Figs. (**1**) and (**2**). This extended record allows us to examine the relationship of climate forcing mechanisms and temperature change over a period that includes a substantial change in the nature of glacial-interglacial climate swings. During the first half of the EPICA record, the period 800-400 ky BP, the climate swings were smaller, sea level did not rise as high as the present level, and the GHGs did not increase to amounts as high as those of recent interglacial periods.

Fig. (**S18**) shows that the temperature change calculated exactly as described for the Vostok data of Fig. (**1**), i.e., multiplying the fast-feedback climate sensitivity ¾°C per W/m^2 by the sum of the GHG and surface albedo forcings (Fig. **S18b**), yields a remarkably close fit in the first half of the Dome C record to one-half of the temperature inferred from the isotopic composition of the ice. In the more recent half of the record slightly larger than ¾°C per W/m^2 would yield a noticeably better fit to the observed Dome C temperature divided by two (Fig. **S19**). However, there is no good reason to change our approximate estimate of ¾°C per W/m^2, because the assumed polar amplification by a factor of two is only approximate.

The sharper spikes in recent observed interglacial temperature, relative to the calculated temperature, must be in part an artifact of differing temporal resolutions. Temperature is inferred from the isotopic composition of the ice, being a function of the temperature at which the snowflakes formed, and thus inherently has a very high temporal resolution. GHG amounts, in contrast, are smoothed over a few ky by mixing of air in the snow that occurs up until the snow is deep enough for the snow to be compressed into ice. In the central Antarctic, where both Vostok and Dome C are located, bubble closure requires a few thousand years [17].

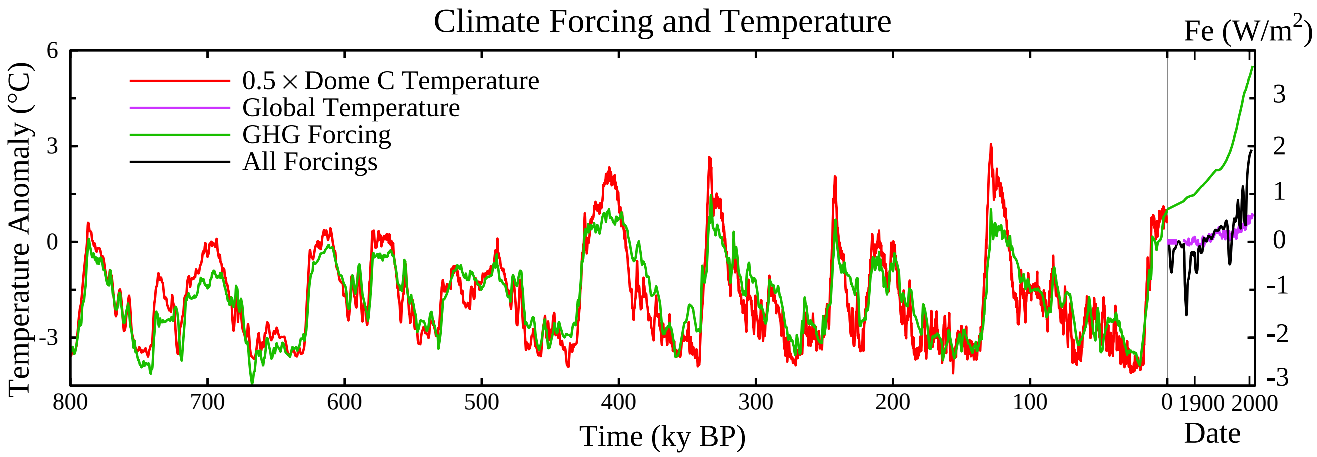


Fig. (S19). Global temperature change (left scale) estimated as half of temperature change from Dome C ice core [S8] and GHG forcing (right scale) due to CO_2, CH_4 and N_2O [S38, S39]. Ratio of temperature and forcing scales is 1.5°C per W/m^2. Time scale is expanded in the extension to recent years. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky before present. Net climate forcing and modern temperature zero points are at 1850. The implicit presumption that the positive GHG forcing at 1850 is largely offset by negative human-made forcings [7] is supported by the lack of rapid global temperature change in the Holocene (Fig. **S6**).

17. COMPARISON OF ANTARCTIC DATA SETS

Fig. (**S20**) compares Antarctic data sets used in this supplementary section and in our parent paper. This comparison is also relevant to interpretations of the ice core data in prior papers using the original Vostok data.

The temperature records of Petit *et al.* [17] and Vimeux *et al.* [18] are from the same Vostok ice core, but Vimeux *et al.* [18] have adjusted the temperatures with a procedure designed to correct for climate variations in the water vapor source regions. The isotopic composition of the ice is affected by the climate conditions in the water vapor source region as well as by the temperature in the air above Vostok where the snowflakes formed; thus the adjustment is intended to yield a record that more accurately reflects the air temperature at Vostok. The green temperature curve in Fig. (**S20c**), which includes the adjustment, reduces the amplitude of glacial-interglacial temperature swings from those in the original (red curve) Petit *et al.* [17] data. Thus it seems likely that there will be some reduction of the amplitude and spikiness of the Dome C temperature record when a similar adjustment is made to the Dome C data set.

The temporal shift of the Dome C temperature data [S8], relative to the Vostok records, is a result of the improved EDC3 [S40, S41] time scale. With this new time scale, which has a 1σ uncertainty of ~3 ky for times earlier than ~130 ky BP, the rapid temperature increases of Termination IV (~335 ky BP) and Termination III (~245 ky BP) are in close agreement with the contention [7] that rapid ice sheet disintegration and global temperature rise should be nearly simultaneous with late spring

(April-May-June) insolation maxima at 60N latitude, as was already the case for Terminations II and I, whose timings are not significantly affected by the improved time scale.

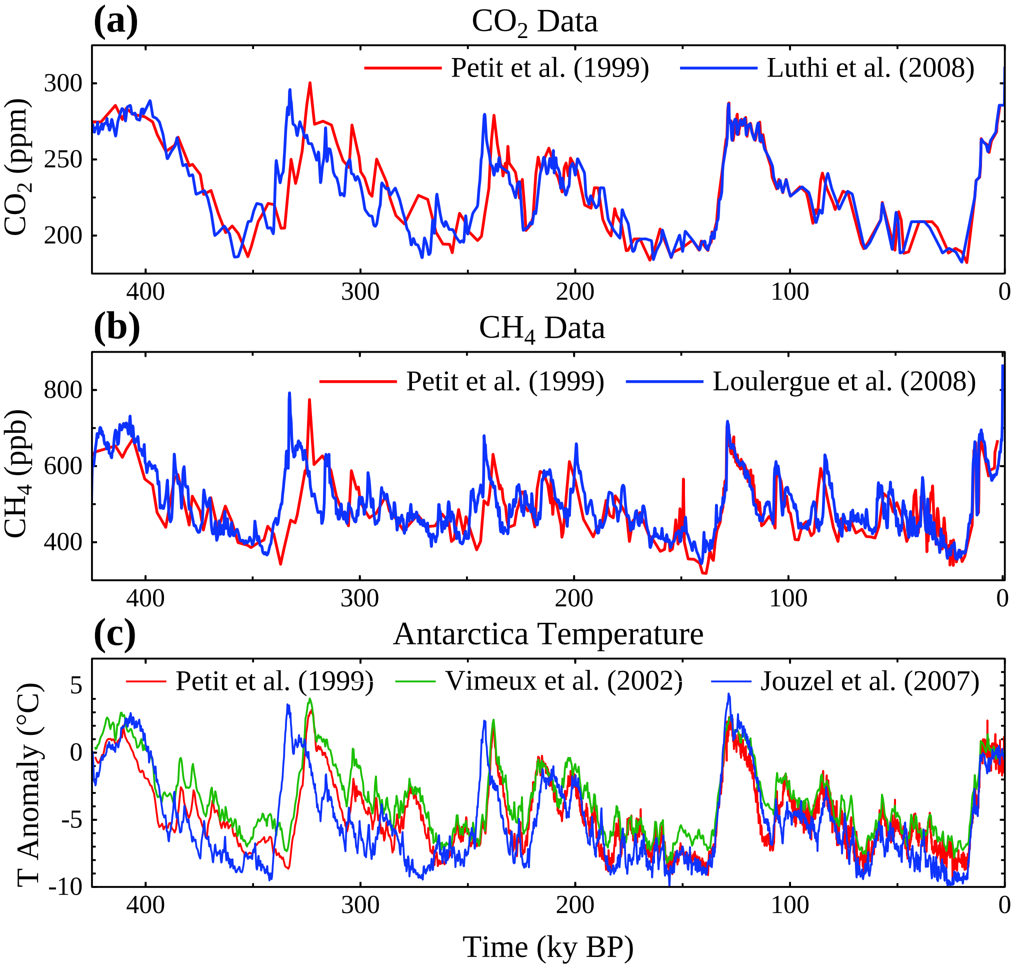


Fig. (S20). Comparison of Antarctic CO$_2$, CH$_4$, and temperature records in several analyses of Antarctic ice core data.

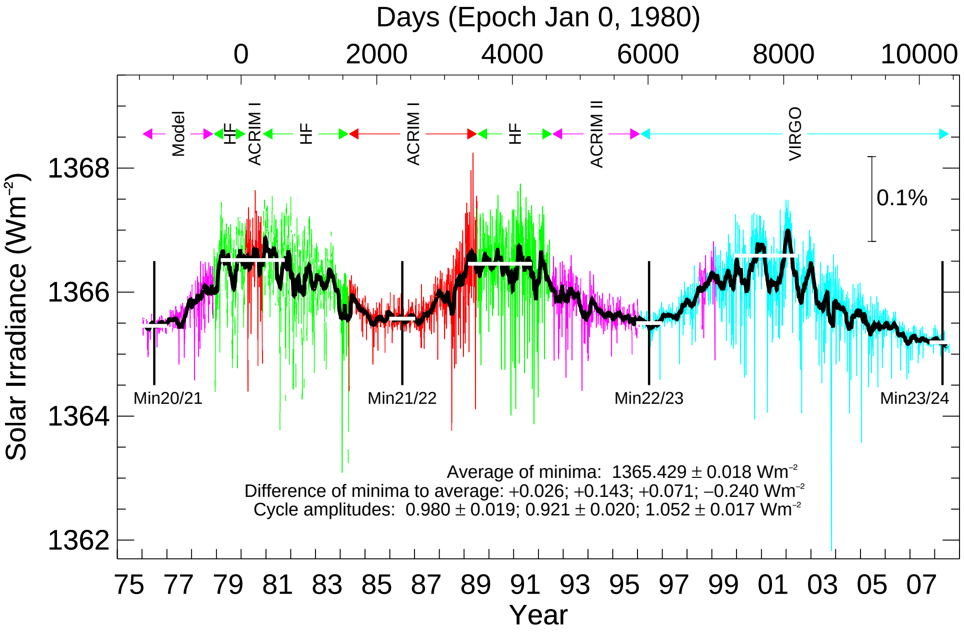


Fig. (S21). Solar irradiance from composite of several satellite-measured time series based on Frohlich and Lean [S44].

18. CLIMATE VARIABILITY, CLIMATE MODELS, AND UNCERTAINTIES

Climate exhibits great variability, forced and unforced, which increases with increasing time scale [2, 90, 91]. Increasing abilities to understand the nature of this natural variability and improving modeling abilities [S42] do not diminish the complications posed by chaotic variability for interpretation of ongoing global change.

Expectation that global temperature will continue to rise on decadal time scales is based on a combination of climate models and observations that support the inference that the planet has a positive energy imbalance [5, 8, 96]. If the planet is out of energy balance by +0.5-1 W/m^2, climate models show that global cooling on decadal time scales is unlikely [96], although one model forecast [95] suggests that the Atlantic overturning circulation could weaken in the next decade, causing a regional cooling that offsets global warming for about a decade.

The critical datum for determining the certainty of continued global warming on decadal time scales is the planet's energy imbalance. Improved evaluations of ocean heat storage in the upper 700 m of the ocean [97] yield ~0.5 x 10^{22} J/yr averaged over the past three decades, which is ~0.3 W/m^2 over the full globe. Our model has comparable heat storage in the ocean beneath 700 m, but limited observational analyses for the deep ocean [S43] report negligible heat storage.

If our modeled current planetary energy imbalance of 0.5-1 W/m^2 is larger than actual heat storage, the likely explanations are either: (1) the climate model sensitivity of 3°C for doubled CO_2 is too high, or (2) the assumed net climate forcing is too large. Our paleoclimate analyses strongly support the modeled climate sensitivity, although a sensitivity as small as 2.5 W/m^2 for doubled CO_2 could probably be reconciled with the paleoclimate data. The net climate forcing is more uncertain. Our model [8] assumes that recent increase of aerosol direct and indirect (cloud) forcings from developing country emissions are offset by decreases in developed countries.

These uncertainties emphasize the need for more complete and accurate measurements of ocean heat storage, as well as precise global observations of aerosols including their effects on clouds. The first satellite observations of aerosols and clouds with the needed accuracy are planned to begin in 2009 [98]. Until accurate observations of the planetary energy imbalance and global climate forcing are available, and found to be consistent with modeled climate sensitivity, uncertainties in decadal climate projections will remain substantial.

The sun is another source of uncertainty about climate forcings. At present the sun is inactive, at a minimum of the normal ~11 year solar cycle, with a measureable effect on the amount of solar energy received by Earth (Fig. **S21**). The amplitude of solar cycle variations is about 1 W/m^2 at the Earth's distance from the sun, a bit less than 0.1% of the ~1365 W/m^2 of energy passing through an area oriented perpendicular to the Earth-sun direction.

Climate forcing due to change from solar minimum to solar maximum is about ¼ W/m^2, because the Earth absorbs ~235 W/m^2 of solar energy, averaged over the Earth's surface. If equilibrium climate sensitivity is 3°C for doubled CO_2 (¾°C per W/m^2), the expected equilibrium response to this solar forcing is ~0.2°C. However, because of the ocean's thermal inertia less than half of the equilibrium response would be expected for a cyclic forcing with ~11 year period. Thus the expected global-mean transient response to the solar cycle is less than or approximately 0.1°C.

It is conceivable that the solar variability is somehow amplified, e.g., the large solar variability at ultraviolet wavelengths can affect ozone. Indeed, empirical data on ozone change with the solar cycle and climate model studies indicate that induced ozone changes amplify the direct solar forcing, but amplification of the solar effect is by one-third or less [S45, S46].

Other mechanisms amplifying the solar forcing have been hypothesized, such as induced changes of atmospheric condensation nuclei and thus changes of cloud cover. However, if such mechanisms were effective, then an 11-year signal should appear in temperature observations (Fig. **7**). In fact a very weak solar signal in global temperature has been found by many investigators, but only of the magnitude (~0.1°C or less) expected due to the direct solar forcing.

The possibility remains of solar variability on longer time scales. If the sun were to remain 'stuck' at the present solar minimum (Fig. **S21**) it would be a decrease from the mean irradiance of recent decades by ~0.1%, thus a climate forcing of about -0.2 W/m^2.

The current rate of atmospheric CO_2 increase is ~2 ppm/year, thus an annual increase of climate forcing of about +0.03 W/m^2 per year. Therefore, if solar irradiance stays at its recent minimum value, the climate forcing would be offset by just seven years of CO_2 increase. Human-made GHG climate forcing is now increasing at a rate that overwhelms variability of natural climate forcings.

Climate models are another source of uncertainty in climate projections. Our present paper and our estimated target CO_2 level do not rely on climate models, but rather are based on empirical evidence from past and ongoing climate change. However, the limited capability of models to simulate climate dynamics and interactions among climate system components makes it difficult to estimate the speed at which climate effects will occur and the degree to which human-induced effects will be masked by natural climate variability.

The recent rapid decline of Arctic ice [S47-S49] is a case in point, as it has been shown that model improvements of multiple physical processes will be needed for reliable simulation. The modeling task is made all the more difficult by likely connections of Arctic change with the stratosphere [S50] and with the global atmosphere and ocean [S51].

REFERENCES

[S1] Hewitt C, Mitchell J. Radiative forcing and response of a GCM to ice age boundary conditions: cloud feedback and climate sensitivity. Clim Dyn 1997; 13: 821-34.

[S2] Chylek P, Lohmann U. Aerosol radiative forcing and climate sensitivity deduced from the Last Glacial Maximum to Holocene transition. Geophys Res Lett 2008; 15: L04804, 1-5.

[S3] Schmidt GA, Ruedy R, Hansen JE, *et al.* Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. J Clim 2006; 19: 153-92.

[S4] Ingersoll AP. The runaway greenhouse: a history of water on Venus. J Atmos Sci 1969; 26, 1191-98.

[S5] Hoffman PF, Schrag DP. The snowball Earth hypothesis: testing the limits of global change. Terra Nova 2002; 14: 129-55.

[S6] Chandler MA, Sohl LE. Climate forcings and the initiation of low-latitude ice sheets during the Neoproterozoic Varanger glacial interval. J Geophys Res 2000; 105: 20737-56.

[S7] Wunsch C. The spectral description of climate change including the 100 ky energy. Clim Dyn 2003; 20: 353-63.

[S8] Jouzel J, Masson-Delmotte V, Cattani O, *et al.* Orbital and millennial Antarctic climate variability over the past 800,000 Years. Science 2007; 317: 793-6.

[S9] Medina-Elizade, M, Lea DW. The mid-Pleistocene transition in the Tropical Pacific. Science 2005; 310: 1009-12.

[S10] Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M. Global temperature change. Proc Natl Acad Sci 2006; 103: 14288-93.

[S11] Lea DW, Pak DK, Spero HJ. Climate impact of late Quaternary equatorial Pacific sea surface temperature variations. Science 2000; 289: 1719-24.

[S12] Lea DW, Pak DK, Belanger CL, Spero HJ, Hall MA, Shackleton NJ. Paleoclimate history of Galapagos surface waters over the last 135,000 yr. Q Sci Rev 2006; 25: 1152-67.

[S13] Saraswat R., Nigam R., Weldeab S., Mackensen A, Naidu PD. A first look at past sea surface temperatures in the equatorial Indian Ocean from Mg/Ca in foraminifera. Geophys Res Lett 2005; 32: L24605.

[S14] Russell GL, Miller JR, Rind D. A coupled atmosphere-ocean model for transient climate change studies. Atmos-Ocean 1995; 33: 683-730.

[S15] Lisiecki LE, Raymo ME. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 2005; 20: PAI 003.

[S16] Bintanja R, van de Wal RSW, Oeriemans J. Modelled atmospheric temperatures and global sea levels over the past million years. Nature 2005; 437: 125-8.

[S17] Blakey R. Global paleogeographic views of Earth history – Late Precambrian to Recent 2008; http://jan.ucc.nau.edu/~rcb7/globaltext2.html

[S18] Royer DL, Berner RA, Beerling DJ. Phanerozoic atmospheric CO_2 change: Evaluating geochemical and paleobiological approaches. Earth-Science Rev 2001; 54: 349-92.

[S19] Fletcher BJ, Brentnall SJ, Anderson CW, Berner RA, Beerling DJ. Atmospheric carbon dioxide linked with Mesozoic and early Cenozoic climate change. Nature Geosci 2008; 1: 43-8.

[S20] Kurschner WM, Zlatko K, Dilcher DL. The impact of Miocene atmospheric carbon dioxide fluctuations on climate and the evolution of terrestrial ecosystems. Proc Natl Acad Sci 2008; 105: 449-53.

[S21] Cerling TE. Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols. Am J Sci 1991; 291: 377-400.

[S22] Gray JE, Holroyd GH, Van der Lee FM, Bahrami AR, Sijmons PC, Woodward FI, Schuch W, Hetherington AM. The HIC signalling pathway links CO_2 perception to stomatal development. Nature 2000; 408: 713-16.

[S23] Woodward FI. Stomatal numbers are sensitive to increases in CO_2 from pre-industrial levels. Nature 1987; 327: 617-8.

[S24] Royer DL. Stomatal density and stomatal index as indicators of paleoatmospheric CO_2 concentration. Rev Palaeobot Palynol 2001; 114: 1-28.

[S25] Woodward FI, Bazzaz FA. The responses of stomatal density to CO_2 partial pressure. J Expert Bot 1988; 39: 1771-81.

[S26] Popp BN, Takigiku R, Hayes JM, Louda JW, Baker EW. The post-Paleozoic chronology and mechanism of 13C depletion in primary marine organic matter. Amer J Sci 1989; 289: 436-54.

[S27] Pagani M. The alkenone-CO_2 proxy and ancient atmospheric CO_2, In Understanding Climate Change: Proxies, Chronology, and Ocean-Atmosphere Interactions. Gröcke DR, Kucera M, Eds. Philos Trans Ro Soc Lond Series A 2002; 360: 609-32.

[S28] Spivack AJ, You C-F, Smith HJ. Foraminiferal boron isotope ratios as a proxy for surface ocean pH over the past 21 Myr. Nature 1993; 363: 149-51.

[S29] Blamart D, Rollion-Bard C, Meibom A, Cuif JP, Juillet-Leclerc A, Dauphin Y. Geochem Geophys Geosyst 2007; 8, 12: Q12001.

[S30] Lemarchand D, Gaillardet J, Lewin É, Allègre CJ. The influence of rivers on marine boron isotopes and implications for reconstructing past pH. Nature 2000; 4008:951-4.

[S31] Pagani M, Lemarchand D. Spivack A, Gaillarde J. A critical evaluation of the boron isotope-pH proxy: The accuracy of ancient ocean pH estimates. Geochimica et Cosmochimica Acta 2005; 69: 953-61.

[S32] Marland G, Boden TA, Andres RJ. Global, regional, and national fossil fuel CO_2 emissions. In trends: A compendium of data on global change. Carbon dioxide information analysis center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA 2007; on-line at http://cdiac.esd.ornl.gov/trends/emis/meth_reg.htm

[S33] British Petroleum. Statistical Review of World Energy 2007 2007; on-line at http://www.bp.com/productlanding.do?categoryId=6848&contentId=7033471

[S34] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2001: Mitigation. Davidson O, Metz B, Eds. Cambridge Univ Press: New York, 2001; pp. 753.

[S35] World Energy Council, Survey of Energy Resources; http://www.worldenergy.org/publications/survey_of_energy_resources_2007/default.asp 2007

[S36] Keeling CD, Whorf TP. Trends: A Compendium on Global Change; Carbon Dioxide Information Analysis Center, Oak Ridge Nat. Lab., US. DOE: Oak Ridge, TN 2005.

[S37] Intergovernmental Panel on Climate Change (IPCC), Land Use, Land-Use Change, and Forestry. Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ, Eds. Cambridge Univ Press: Cambridge, UK 2000; pp. 377.

[S38] Lüthi D, Le Floch M, Stocker TF, Bereiter B, Blunier T, Barnola J-M, Siegenthaler U, Raynaud D, Jouzel J. Unexpected low levels of CO_2 concentration between 650 and 750 kyr BP. Nature 2008; (in press).

[S39] Loulergue L, Schilt A, Spahni R, Masson-Delmotte V, Blunier T, Lemieux B, Barnola J-M, Raynaud D, Stocker TF, Chappellaz J. Orbital and millennial-scale features of atmospheric CH_4 over the last 800,000 years. Nature 2008; (in press).

[S40] Parrenin F, Dreyfus G, Durand G, *et al*. 1-D-ice flow modelling at EPICA Dome C and Dome Fuji, East Antarctica. Clim Past 2007; 3: 243-59.

[S41] Dreyfus G, Parrenin F, Lemieux-Dudon B, *et al.* Anomalous flow below 2700 m in the EPICA Dome C ice core detected using $\delta^{18}O$ of atmospheric oxygen measurements. Clim Past 2007; 3: 341-53.

[S42] Sempf M, Dethloff K, Handorf D, Kurgansky MV. Toward understanding the dynamical origin of atmospheric regime behavior in a baroclinic model. J Atmos Sci 2007; 64: 887-904.

[S43] Levitus S, Anatov JI, Boyer TP. Warming of the world ocean, 1955-2003. Geophys Res Lett 2005; 32: L02604; doi:10.1029/2004GL021592.

[S44] Frohlich C, Lean J. 1998; (http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant)

[S45] Hansen J, Sato M, Ruedy R. Radiative forcing and climate response. J Geophys Res 1997; 102: 6831-64.

[S46] Shindell D, Schmidt GA, Miller RL, Rind D. Northern Hemisphere winter climate response to greenhouse gas, volcanic, ozone, and climate. J Geophys Res 2001; 106: 7193-210.

[S47] Johannessen OM, Bengtsson L, Miles MW, *et al* Arctic climate change: observed and modeled temperature and sea-ice variability. Tellus 2004; 56A: 328-41.

[S48] Dorn W, Dethloff K, Rinke A, Kurgansky M. The recent decline of the Arctic summer sea-ice cover in the context of internal climate variability. Open Atmos Sci 2008; 2: 91-100.

[S49] Dorn W, Dethloff K, Rinke A, Frickenhaus S, Gerdes R, Karcher M, Kauker F. Sensitivities and uncertainties in a coupled regional atmosphere-ocean-ice model with respect to the simulation of Arctic sea ice. J Geophys Res 2007; 112: D10118; doi:10.1029/2006JD007814.

[S50] Brand S, Dethloff K, Handorf D. Tropospheric circulation sensitivity to an interactive stratospheric ozone. Geophys Res Lett 2008; 35: L05809; doi:10.1029/2007GL032312.

[S51] Dethloff K, Rinke A, Benkel A, *et al*. A dynamical link between the Arctic and the global climate system. Geophys Res Lett 2006; 33: L03703; doi:10.1029/2005GL025245.

theguardian

UN chief challenges world to agree tougher target for climate change

Global warming should be limited to 1.5C, not 2C, declares Christiana Figueres

Fiona Harvey in Barcelona
guardian.co.uk, Wednesday 1 June 2011 15.54 EDT

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Christiana Figueres, executive secretary of the UN framework convention on climate change. Photograph: Alex Cruz/EPA

The world should agree to limit global warming to just 1.5C instead of the current target of 2C, the United Nations' climate chief has said, in remarks that shocked the governments of developed nations.

Christiana Figueres, executive secretary of the UN framework convention on climate change, said: "Two degrees is not enough – we should be thinking of 1.5C. If we are not headed to 1.5C we are in big, big trouble."

Scientists estimate that 2C of warming is the limit of safety, beyond which climate change becomes catastrophic and irreversible. Last December at a UN climate conference in Cancun, Mexico, all countries reached a consensus on a 2C target, the first time the world's governments had set a target limit on climate change.

But Figueres said reaching 2C of warming would have a devastating impact, such as sea-level rises that could overwhelm low-lying islands and some coastal nations, and levels of warming in sub-Saharan Africa that could severely damage agriculture.

Figueres was speaking at Carbon Expo, the annual conference of the International Emissions Trading Association.

For Figueres to reopen the debate on the proposed target is regarded as dangerous by some countries, who fear that a push by the UN for a tougher target would derail the already fragile negotiations that officials have been trying to reconstruct after the 2009 summit in Copenhagen ended in only a partial agreement, amid acrimony and scenes of chaos.

Developed nations and some rapidly emerging economies, such as China, want to stick to the weaker target of 2C, arguing that it would be impossible to opt for the tougher target at this stage.

One participant in the talks said: "We need to be ambitious but realistic. Although it's positive to start discussions about more ambitious targets, the UN Environment Programme concluded a while ago that countries will have to make more ambitious emission-reduction pledges [than they have done] if global-temperature rise is to be curbed at 2C."

Another participant said: "This is a big surprise. We had no idea this was on the cards."

A campaign for a 1.5C target by some developing countries was one of the factors that nearly wrecked the Copenhagen summit. A group of governments insisted they would halt negotiations until the arguments for a 1.5C target were heard, delaying the talks and deepening the rift between developing and developed nations' governments.

Figueres said she had the support of the group of about 40 small island states – many of which are in danger of disappearing as sea levels rise – as well as most African countries and other, least developed countries. She pointed out that at Cancun, governments had agreed to review the 2C target in the light of a new scientific study on the effects of climate change.

"I'm not saying this is going to be easy," she said. "The argument I am making is not about feasibility but an argument of social justice. We can't have as our goal something that we already know does not guarantee the survival of low-lying states and sub-Saharan Africa.

"If we already know that, in my book there is no way we can stick to the goal we know is completely unacceptable to the most exposed [countries]."

Warming of 2C above pre-industrial levels would cause sea-level rises, storms, floods, droughts and heatwaves, according to the Intergovernmental Panel on Climate Change, but the effects would be far less severe than if warming were allowed to reach 3C or 4C.

Estimates from the International Energy Agency (IEA), revealed by the Guardian this week, showed a record rise in carbon emissions from energy last year. If that pattern were to continue, the world would be on course for at least 3C to 4C of warming, according to scientific advice.

Figueres said the IEA estimates strengthened the case for urgent action on greenhouse gases. Aiming for a more stringent target would require much more effort from all countries. Current emissions pledges from both developed and developing countries represent only 60% of what is needed to stay below 2C, according to scientific estimates.

But Jörg Haas, programme director for climate diplomacy at the European Climate Foundation, said most of the extra effort would need to be made after 2020, making it easier to push for a tougher target now.

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The Case for Young People and Nature: A Path to a Healthy, Natural, Prosperous Future

James Hansen[1], Pushker Kharecha[1], Makiko Sato[1], Paul Epstein[2], Paul J. Hearty[3], Ove Hoegh-Guldberg[4], Camille Parmesan[5], Stefan Rahmstorf[6], Johan Rockstrom[7], Eelco J.Rohling[8], Jeffrey Sachs[1], Peter Smith[9], Konrad Steffen[10], Karina von Schuckmann[11], James C. Zachos[12],

Abstract. We describe scenarios that define how rapidly fossil fuel emissions must be phased down to restore Earth's energy balance and stabilize global climate. A scenario that stabilizes climate and preserves nature is technically possible and it is essential for the future of humanity. Despite overwhelming evidence, governments and the fossil fuel industry continue to propose that all fossil fuels must be exploited before the world turns predominantly to clean energies. If governments fail to adopt policies that cause rapid phase-down of fossil fuel emissions, today's children, future generations, and nature will bear the consequences through no fault of their own. Governments must act immediately to significantly reduce fossil fuel emissions to protect our children's future and avoid loss of crucial ecosystem services, or else be complicit in this loss and its consequences.

1. Background

Humanity is now the dominant force driving changes of Earth's atmospheric composition and thus future climate on the planet. Carbon dioxide (CO_2) emitted in burning of fossil fuels is, according to best available science, the main cause of global warming in the past century. It is also well-understood that most of the CO_2 produced by burning fossil fuels will remain in the climate system for millennia. The risk of deleterious or even catastrophic effects of climate change driven by increasing CO_2 is now widely recognized by the relevant scientific community.

The climate system has great inertia because it contains a 4-kilometer deep ocean and 2-kilometer thick ice sheets. As a result, global climate responds only slowly, at least initially, to natural and human-made forcings of the system. Consequently, today's changes of atmospheric composition will be felt most by today's young people and the unborn, in other words, by people who have no possibility of protecting their own rights and their future well-being, and who currently depend on others who make decisions today that have consequences over future decades and centuries.

Governments have recognized the need to stabilize atmospheric composition at a level that avoids dangerous anthropogenic climate change, as formalized in the Framework Convention on Climate Change in 1992. Yet the resulting 1997 Kyoto Protocol was so ineffective that global fossil fuel emissions have since accelerated by 2.5% per year, compared to 1.5% per year in the preceding two decades.

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Governments and businesses have learned to make assurances that they are working on clean energies and reduced emissions, but in view of the documented emissions pathway it is not inappropriate to describe their rhetoric as being basically 'greenwash'. The reality is that most governments[13], strongly influenced by the fossil fuel industry, continue to allow and even subsidize development of fossil fuel deposits. This situation was aptly described in a special energy supplement in the New York Times entitled 'There Will Be Fuel' (Krauss, 2010), which described massive efforts to expand fossil fuel extraction. These efforts include expansion of oil drilling to increasing depths of the global ocean, into the Arctic, and onto environmentally fragile public lands; squeezing of oil from tar sands; hydro-fracking to expand extraction of natural gas; and increased mining of coal via mechanized longwall mining and mountain-top removal.

The true costs of fossil fuels to human well-being and the biosphere is not imbedded in their price. Fossil fuels are the cheapest energy source today only if they are not made to pay for their damage to human health, to the environment, and to the future well-being of young people who will inherit on-going climate changes that are largely out of their control. Even a moderate but steadily rising price on carbon emissions would be sufficient to move the world toward clean energies, but such an approach has been effectively resisted by the fossil fuel industry.

The so-called 'north-south' injustice of climate disruption has been emphasized in international discussions, and payment of $100B per year to developing countries has been proposed. Focus on this injustice, as developed countries reap the economic benefits of fossil fuels while developing countries are among the most vulnerable to the impacts of climate change, is appropriate. Payments, if used as intended, will support adaptation to climate change and mitigation of emissions from developing countries. We must be concerned, however, about the degree to which such payment, from adults in the North to adults in the South, are a modern form of indulgences, allowing fossil fuel emissions to continue with only marginal reductions or even increase.

The greatest injustice of continued fossil fuel dominance of energy is the heaping of climate and environmental damages onto the heads of young people and those yet to be born in both developing and developed countries. The tragedy of this situation is that a pathway to a clean energy future is not only possible, but even economically sensible.

Fossil fuels today power engines of economic development and thus raise the standards of living throughout most of the world. But air and water pollution due to extraction and burning of fossil fuels kills more than 1,000,000 people per year and affects the health of billions of people **(**Cohen et al., 2005**)**. Burning all fossil fuels would have a climate impact that literally produces a different planet than the one on which civilization developed. The consequences for young people, future generations, and other species would continue to mount over years and centuries. Ice sheet disintegration would cause continual shoreline adjustments with massive civil engineering cost implications as well as widespread heritage loss in the nearly uncountable number of coastal cites. Shifting of climatic zones and repeated climate disruptions would have enormous economic and social costs, especially in the developing world.

These consequences can be avoided via prompt transition to a clean energy future. The benefits would include a healthy environment with clean air and water, preservation of the shorelines and climatic zones that civilization is adapted to, and retention of the many benefits humanity derives from the remarkable diversity of species with which we share this planet.

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[13] Some nations are working hard to reduce their emissions, some with notable success. But there is not global recognition that most of the remaining fossil fuel carbon cannot be emitted to the atmosphere without great damage to the future of young people.

It is appropriate that governments, instituted for the protection of all citizens, should be required to safeguard the future of young people and the unborn. Specific policies cannot be imposed by courts, but courts can require governments to present realistic plans to protect the rights of the young. These plans should be consistent with the scientifically-established rate at which emissions must be reduced to stabilize climate.

Science can also make clear that rapid transition to improved energy efficiency and clean energies is not only feasible but economically sensible, and that rapid transition requires a steadily rising price on undesirable emissions. Other actions by governments are needed, such as enforcement of energy efficiency standards and investment in technology development. However, without the underlying incentive of a price on carbon emissions, such actions, as well as voluntary actions by concerned citizens, are only marginally effective. This is because such actions reduce the demand for fossil fuels, lower their price, and thus encourage fossil fuel use elsewhere. The price on carbon emissions, to be most effective, must be transparent and across-the-board, for the sake of public acceptance, for guidance of consumer decisions, and for guidance of business decisions including technology investments.

Here we summarize the emission reductions required to restore Earth's energy balance, limit CO_2 change to a level that avoids dangerous human-made interference with climate, assure a bright future for young people and future generations, and provide a planet on which both humans and our fellow species can continue to survive and thrive.

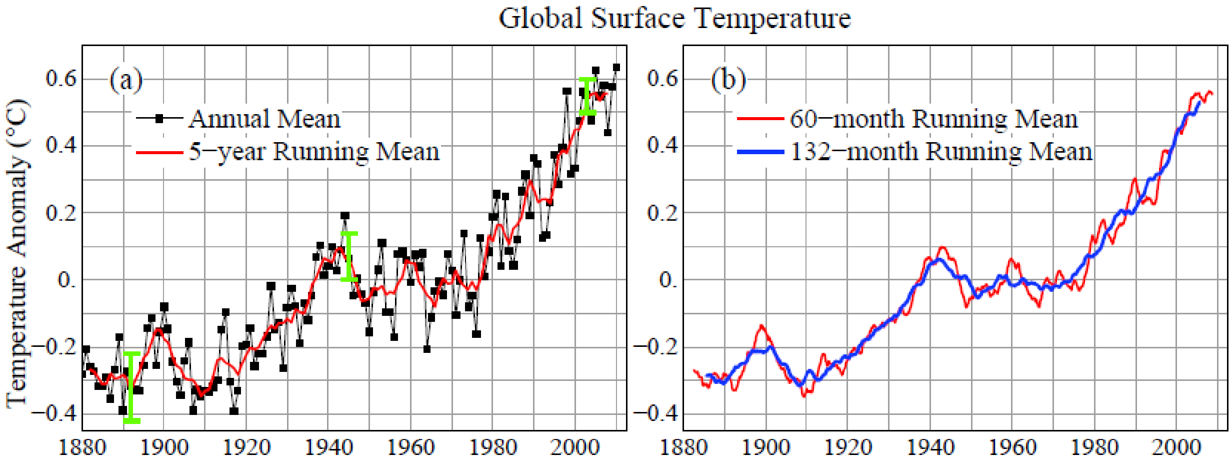

Figure 1. Global surface temperature anomalies relative to 1951-1980 mean for (a) annual and 5-year running means through 2010, and (b) 60-month and 132-month running means through March 2011. Green bars are 2-σ error estimates, i.e., 95% confidence intervals (data from Hansen et al., 2010).

2. Global Temperature

Global surface temperature fluctuates chaotically within a limited range and it also responds to natural and human-made climate forcings. Climate forcings are imposed perturbations of Earth's energy balance. Examples of climate forcings are changes in the luminosity of the sun, volcanic eruptions that inject aerosols (fine particles) into Earth's stratosphere, and human-caused alterations of atmospheric composition, most notably the increase of atmospheric carbon dioxide (CO_2) due to burning of fossil fuels.

2.1. Modern Temperature

Figure 1(a) shows annual-mean global temperature change over the past century. The year-to-year variability is partly unforced chaotic variability and partly forced climate change. For example, the global warmth of 1998 was a consequence of the strongest El Nino of the century, a natural warming of the tropical Pacific Ocean surface associated with a fluctuation of ocean dynamics. The strong cooling in 1992 was caused by stratospheric aerosols from the Mount Pinatubo volcanic eruption, which temporarily reduced sunlight reaching Earth's surface by as much as 2 percent.

Figure 1(b) shows global temperature change averaged over 5 years (60 months) and 11 years (132 months), for the purpose of minimizing year-to-year variability. The rapid warming during the past three decades is a forced climate change that has been shown to be a consequence of the simultaneous rapid growth of human-made atmospheric greenhouse gases, predominately CO_2 from fossil fuel burning (IPCC, 2007).

The basic physics underlying this global warming, the greenhouse effect, is simple. An increase of gases such as CO_2 makes the atmosphere more opaque at infrared wavelengths. This added opacity causes the planet's heat radiation to space to arise from higher, colder levels in the atmosphere, thus reducing emission of heat energy to space. The temporary imbalance between the energy absorbed from the sun and heat emission to space, causes the planet to warm until planetary energy balance is restored.

The great thermal inertia of Earth, primarily a consequence of the 4-kilometer (2½ mile) deep ocean, causes the global temperature response to a climate forcing to be slow. Because atmospheric CO_2 is continuing to increase, Earth is significantly out of energy balance – the solar energy being absorbed by the planet exceeds heat radiation to space. Measurement of Earth's energy imbalance provides the most precise quantitative evaluation of how much CO_2 must be reduced to stabilize climate, as discussed in Section 2.

However, we should first discuss global temperature, because most efforts to assess the level of climate change that would be 'dangerous' for humanity have focused on estimating a permissible level of global warming. Broad-based assessments, represented by the 'burning embers' diagram in IPCC (2001, 2007), suggested that major problems begin with global warming of 2-3°C relative to global temperature in year 2000. Sophisticated probabilistic analyses (Schneider and Mastrandrea, 2005) found a median 'dangerous' threshold of 2.85°C above global temperature in 2000, with the 90 percent confidence range being 1.45-4.65°C.

The conclusion that humanity could readily tolerate global warming up to a few degrees Celsius seemed to mesh with common sense. After all, people readily tolerate much larger regional and seasonal climate variations.

The fallacy of this logic became widely apparent only in recent years. (1) Summer sea ice cover in the Arctic plummeted in 2007 to an area 30 percent less than a few decades earlier. Continued growth of greenhouse gases will likely cause the loss of all summer sea ice within the next few decades, with large effects on wildlife and indigenous people, increased heat absorption at high latitudes, and potentially the release of massive amounts of methane, a powerful greenhouse gas, presently frozen in Arctic sediments on both land and sea floor. (2) The great continental ice sheets of Greenland and Antarctic have begun to shed ice at a rate, now several hundred cubic kilometers per year, which is continuing to accelerate. With the loss of protective sea ice and buttressing ice shelves, there is a danger that ice sheet mass loss will reach a level that causes catastrophic, and for all practical purposes irreversible, sea level rise. (3) Mountain glaciers are receding rapidly all around the world. Summer glacier melt provides fresh water to major world rivers during the dry season, so loss of the glaciers would be highly detrimental to billions of people. (4) The hot dry subtropical climate belts have expanded, affecting climate most notably in the southern United States, the Mediterranean and Middle East regions, and Australia, contributing to more intense droughts, summer heat waves, and devastating wildfires. (5) Coral reef ecosystems are already being impacted by a combination of ocean warming and acidification (a direct consequence of rising atmospheric CO_2), resulting in a 1-2% per year decline in geographic extent. Coral reef ecosystems will be eliminated with continued increase of atmospheric CO_2, with huge consequences for an estimated 500 million people that depend on the ecosystem services of coral reefs (Bruno and Selig, 2007; Hoegh-guldberg et al., 2007; Veron et al., 2009). (6) So-called mega-heatwaves have become noticeably more frequent, for example the 2003 and 2010 heatwaves over Europe and large parts of Russia, each with heat-death tolls in the range of 55,000 to 70,000 (Barriopedro et al., 2011).

Reassessment of the dangerous level of global warming has been spurred by realization that large climate effects are already beginning while global warming is less than 1°C above preindustrial levels. The best tool for assessment is provided by paleoclimate, the history of ancient climates on Earth.

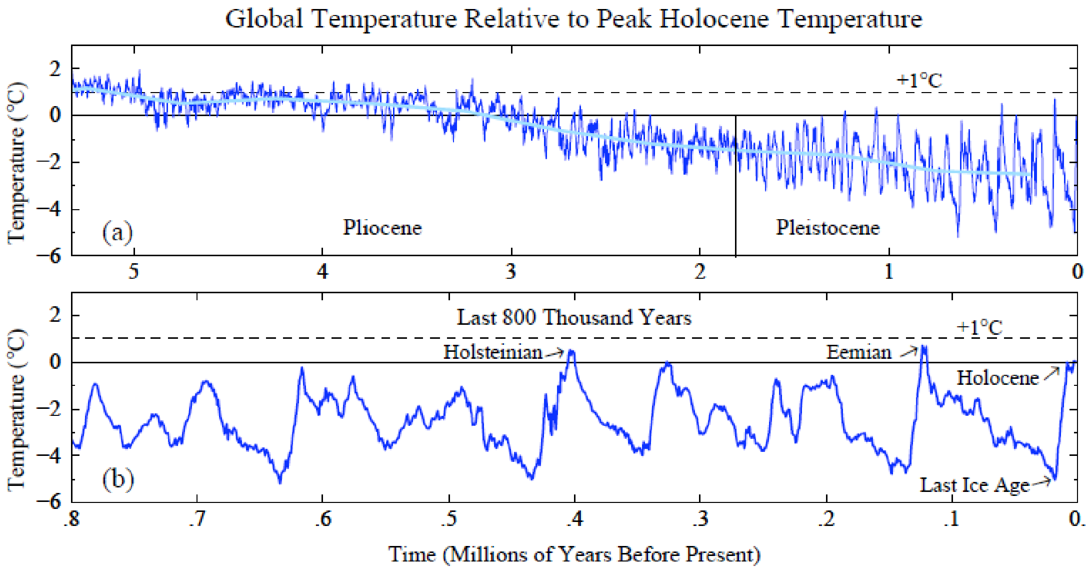

Figure 2. Global temperature relative to peak Holocene temperature (Hansen and Sato, 2011).

2.2. Paleoclimate Temperature

Hansen and Sato (2011) illustrate Earth's temperature on a broad range of time scales. Figure 2(a) shows estimated global mean temperature[14] during the Pliocene and Pleistocene, approximately the past five million years. Figure 2(b) shows higher temporal resolution, so that the more recent glacial to interglacial climate oscillations are more apparent.

Climate variations summarized in Figure 2 are huge. During the last ice age, 20,000 years ago, global mean temperature was about 5°C lower than today. But regional changes on land were larger. Most of Canada was under an ice sheet. New York City was buried under that ice sheet, as were Minneapolis and Seattle. On average the ice sheet was more than a mile (1.6 km) thick. Although thinner near its southern boundary, its thickness at the location of the above cities dwarfs the tallest buildings in today's world. Another ice sheet covered northwest Europe.

These huge climate changes were instigated by minor perturbations of Earth's orbit about the sun and the tilt of Earth's spin axis relative to the orbital plane. By altering the seasonal and geographical distribution of sunlight, the orbital perturbations cause small temperature change. Temperature change then drives two powerful amplifying feedbacks: higher temperature melts ice globally, thus exposing darker surfaces that absorb more sunlight; higher temperature also causes the ocean and soil to release CO_2 and other greenhouse gases. These amplifying feedbacks are responsible for practically the entire glacial-to-interglacial temperature change.

In these slow natural climate changes the amplifying feedbacks (ice area and CO_2 amount) acted as slaves to weak orbital forcings. But today CO_2, global temperature, and ice area are under the command of humanity: CO_2 has increased to levels not seen for at least 3 million years, global temperature is rising, and ice is melting rapidly all over the planet. Another ice age will never occur, unless humans go extinct. A single chlorofluorocarbon factory can produce gases with a climate forcing that exceeds the forcing due to Earth orbital perturbations.

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[14] This estimate of global mean temperature is obtained from ocean sediments at many locations around the world (Zachos et al., 2001; Hansen et al., 2008). The composition of the shells of deep-sea-dwelling microscopic animals (foraminifera), preserved in ocean sediments, carry a record of ocean temperature. Deep ocean temperature change is about two-thirds as large as global mean surface temperature change for the range of climates from the last ice age to the present interglacial period; that proportionality factor is included in Figure 2.

During the climate oscillations summarized in Figure 2, Earth's climate remained in near equilibrium with its changing boundary conditions, i.e., with changing ice sheet area and changing atmospheric CO_2. These natural boundary conditions changed slowly, over millennia, because the principal Earth orbital perturbations occur on time scales predominately in the range of 20,000 to 100,000 years.

Human-made changes of atmospheric composition are occurring much faster, on time scales of decades and centuries. The paleoclimate record does not tell us how rapidly the climate system will respond to the high-speed human-made change of climate forcings – our best guide will be observations of what is beginning to happen now. But the paleoclimate record does provide an indication of the eventual consequences of a given level of global warming.

The Eemian and Hosteinian interglacial periods, also known as marine isotope stages 5e and 11, respectively about 130,000 and 400,000 years ago, were warmer than the Holocene, but global mean temperature in those periods was probably less than 1°C warmer than peak Holocene temperature (Figure 2b). Yet it was warm enough for sea level to reach mean levels 4-6 meters higher than today.

Global mean temperature 2°C higher than peak Holocene temperature has not existed since at least the Pliocene, a few million years ago. Sea level at that time was estimated to have been 15-25 meters higher than today (Dowsett et al., 1999). Changes of regional climate during these warm periods were much greater than the global mean changes.

How does today's global temperature, given the warming of the past century, compare with prior peak Holocene temperature? Holocene climate has been highly variable on a regional basis (Mayewski et al., 2004). However, Hansen and Sato (2011) show from records at several places around the globe that mean temperature has been remarkably constant during the Holocene. They estimate that the warming between the 1800s and the period 1951-1980 (a warming of ~0.25°C in the Goddard Institute for Space Studies analysis, Hansen et al., 2010) brought global temperatures back to approximately the peak Holocene level.

If the 1951-1980 global mean temperature approximates peak Holocene temperature, this implies that global temperature in 2000 (5-year running mean) was already 0.45°C above the peak Holocene temperature. The uncertainty in the peak Holocene temperature is a least several tenths of a degree Celsius. However, strong empirical evidence that global temperature has already risen above the prior peak Holocene temperature is provided by the ongoing mass loss of the Greenland and West Antarctic ice sheets, which began within the last fewdecades. Sea level was relatively stable for the past five to six thousand years, indicating that these ice sheets were in near mass balance. Now, however, both Greenland and West Antarctica are shedding ice at accelerating rates. This is strong evidence that today's global temperature has reached a level higher than prior Holocene temperatures.

The conclusion is that global warming of 1°C relative to 1880-1920 mean temperature (i.e., 0.75°C above the 1951-1980 temperature or 0.3°C above the 5-year running mean temperature in 2000), if maintained for long, is already close to or into the 'dangerous' zone. The suggestion that 2°C global warming may be a 'safe' target is extremely unwise based on critical evidence accumulated over the past three decades. Global warming of this amount would be putting Earth on a path toward Pliocene-like conditions, i.e., a very different world marked by massive and continual disruptions to both society and ecosystems. It would be a world in which the world's species and ecosystems will have had no recent evolutionary experience, surely with consequences and disruptions to the ecosystem services that maintain human communities today. There are no credible arguments that such rapid change would not have catastrophic circumstances for human well-being.

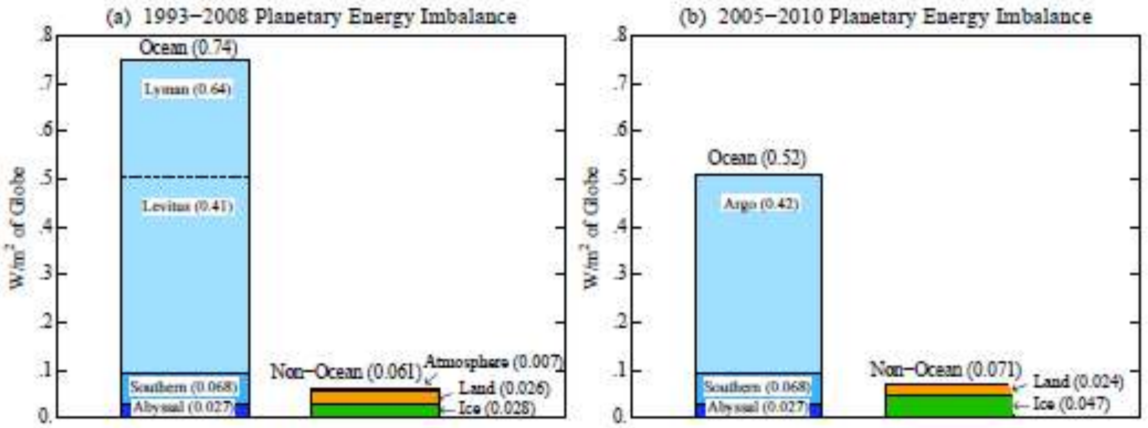

Figure 3. (a) Estimated planetary energy imbalance in 1993-2008, and (b) in 2005-2010. Data sources are given by Hansen et al. (2011).

3. Earth's Energy Imbalance

Earth's energy balance is the ultimate measure of the status of Earth's climate. In a period of climate stability, Earth radiates the same amount of energy to space that it absorbs from incident sunlight. Today it is anticipated that Earth is out of balance because of increasing atmospheric CO_2. Greenhouse gases such as CO_2 reduce Earth's heat radiation to space, thus causing a temporary energy imbalance, more energy coming in than going out. This imbalance causes Earth to warm until energy balance is restored.

The immediate planetary energy imbalance due to an increase of CO_2 can be calculated precisely. It does not require a climate model. The radiation physics is rigorously understood. However, the current planetary energy imbalance is complicated by the fact that increasing CO_2 is only one of the factors affecting Earth's energy balance, and Earth has already partly responded to the net climate forcing by warming 0.8°C in the past century.

Thus authoritative determination of the state of the climate system requires measuring the planet's current energy imbalance. This is a technical challenge, because the magnitude of the imbalance is expected to be only about 1 W/m^2 or less, so measurements must have an accuracy that approaches 0.1 W/m^2. The most promising approach to achieve this accuracy is to measure ongoing changes of the heat content of the ocean, atmosphere, land, and ice on the planet.

The vast global ocean is the primary reservoir for changes of Earth's heat content. Because of the importance of this measurement, nations of the world launched a cooperative Argo float program, which has distributed more than 3000 floats around the world ocean (Roemmich and Gilson, 2009). Each float repeatedly yoyos an instrument package to a depth of two kilometers and satellite-communicates the data to shore.

The Argo program did not attain planned distribution of floats until late 2007, but coverage reached 90% by 2005, allowing good accuracy provided that systematic measurement errors are kept sufficiently small. Prior experience showed how difficult it is to eliminate all measurement biases, but the exposure of the difficulties over the past decade leads to expectationthat the data for the 6-year period 2005-2010 are the most precise achieved so far. The estimated standard error for that period, necessarily partly subjective, is 0.15 W/m^2.[15]

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[15] Barker et al. (2011) describe a remaining bias due to sensor drift in pressure measurements. That bias is reduced in the analysis of von Schuckmann and Le Traon by excluding data from floats on a pressure-bias black list and data from profiles that fail climatology checks, but errors remain and require further analysis.

Smaller contributions to the planetary energy imbalance, from changes in the heat content of the land, ice and atmosphere, are also know more accurately in recent years. A key improvement during the past decade has been provided by the GRACE satellite that measures Earth's gravitational field with a precision that allows the rate of ice loss by Greenland and Antarctica to be monitored accurately.

Figure 3 summarizes the results of analyses of Earth's energy imbalance averaged over the periods 1993-2008 and 2005-2010. In the period 1993-2008 the planetary energy imbalance ranges from 0.57 W/m^2 to 0.80 W/m^2 among different analyses, with the lower value based on upper ocean heat content analysis of Levitus et al. (2009) and the higher value based on Lyman et al. (2010). For the period 2005-2010 the upper ocean heat content change is based on analysis of the Argo data by von Schuckmann and Le Traon (2011), which yields a planetary energy imbalance of 0.59 ± 0.15 W/m^2 (Hansen et al., 2011).

The energy imbalance in 2005-2010 is particularly important, because that period coincides with the lowest level of solar irradiance in the period since satellites began measuring the brightness of the sun in the late 1970s. Changes of solar irradiance are often hypothesized as being the one natural climate forcing with the potential to compete with human-made climate forcings, so measurements during the strongest solar minimum on record provide a conclusive evaluation of the sun's potential to reduce the planet's energy imbalance.

The conclusion is that Earth is out of energy balance by at least ~0.5 W/m^2. Our measured 0.59 W/m^2 for 2005-2010 suggests that the average imbalance over the 11-year solar cycle may be closer to 0.75 W/m^2.

This planetary energy imbalance is substantial, with implications for future climate change. It means that global warming will continue on decadal time scales, as the 0.8°C global warming so far is the response to only about half of the net human-made climate forcing.

Knowledge of Earth's energy imbalance allows us to specify accurately how much CO_2 must be reduced to restore energy balance and stabilize climate. CO_2 must be reduced from the current level of 390 ppm to 360 ppm to increase Earth's heat radiation to space by 0.5 W/m^2, or to 345 ppm to increase heat radiation to space by 0.75 W/m^2, thus restoring Earth's energy balance and stabilizing climate.

Earth's energy imbalance thus provides accurate affirmation of a conclusion reached earlier (Hansen et al., 2008), that the appropriate initial target level of atmospheric CO_2 to stabilize climate is "<350 ppm". This target level may need to be adjusted as it is approached, but, considering the time required to achieve a reversal of atmospheric CO_2 growth, more precise knowledge of the ultimate target for CO_2 will be available by the time CO_2 has been restored to a level approaching 350 ppm.

One reason that more precise specification than "<350 ppm" is inadvisable now is the uncertainty about the net effect of changes of other human-made climate forcings such as methane, other trace gases, reflecting aerosols, black soot, and the surface reflectivity. These forcings are smaller than that by CO_2, but not negligible.

Indeed, there is a concern that expected future reductions of particulate air pollution will exacerbate global warming via reduction of reflective aerosols. It has been suggested (Hansen et al., 2000) that a concerted effort to reduce methane, tropospheric ozone, other trace gases and black soot could substantially reduce the human-made climate forcing, possibly enough to counteract the warming effect of a decline in reflective aerosols. Our calculations of future global temperature in section 5 assume that a major effort will be made to reduce the non-CO_2 forcings sufficient to obviate warming due to a decline of reflective aerosols. To the degree that this goal is not achieved, future warming could exceed that which we calculate.

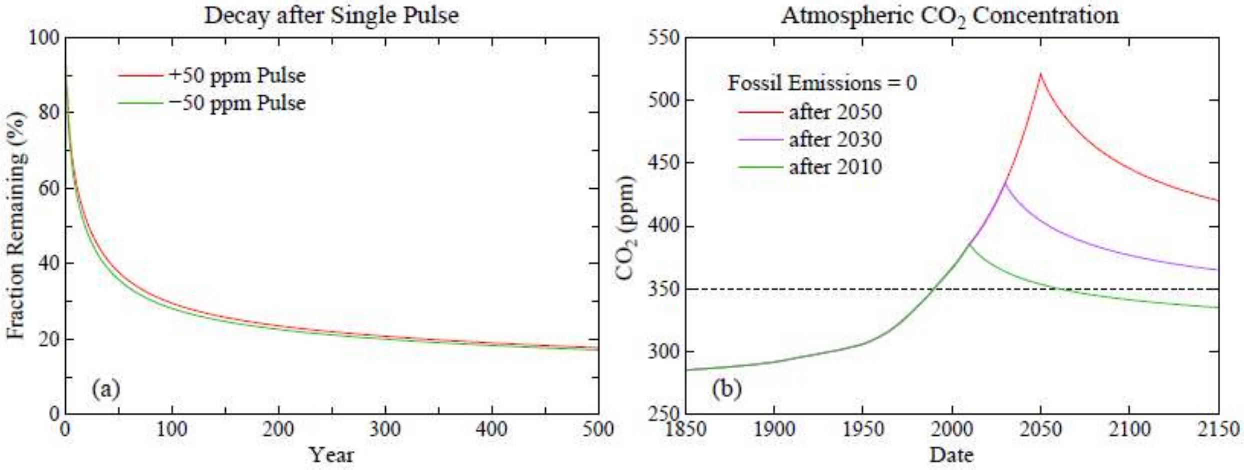

Figure 4. (a) Decay of instantaneous (pulse) injection and extraction of atmospheric CO_2, (b) atmospheric CO_2 if fossil fuel emissions terminated at end of 2011, 2030, 2050.

The important point is that CO_2 is the dominant climate forcing agent and it will be all the more so in the future. The CO_2 injected into the climate system by burning fossil fuels will continue to affect our climate for millennia. We cannot burn all of the fossil fuels without producing a different planet, with changes occurring with a rapidity that will make Earth far less hospitable for young people, future generations, and most other species.

4. Carbon Cycle and Atmospheric CO_2

The 'carbon cycle' that defines the fate of fossil fuel carbon injected into the climate system is well understood. This knowledge allows accurate estimation of the amount of fossil fuels that can be burned consistent with stabilization of climate this century.

Atmospheric CO_2 is already about 390 ppm. Is it possible to return to 350 ppm or less within this century? Yes. Atmospheric CO_2 would decrease if we phased out fossil fuels. The CO_2 injected into the air by burning fossil fuels becomes distributed, over years, decades, and centuries, among the surface carbon reservoirs: the atmosphere, ocean, soil, and biosphere.

Carbon cycle models simulate how the CO_2 injected into the atmosphere becomes distributed among the carbon reservoirs. We use the well-tested Bern carbon cycle model (Joos et al., 1996)[16] to illustrate how rapidly atmospheric CO_2 can decrease.

Figure 4 (a) shows the decay of a pulse of CO_2 injected into the air. The atmospheric amount is reduced by half in about 25 years. However, after 500 years about one-fifth of the CO_2 is still in the atmosphere. Eventually, via weathering of rocks, this excess CO_2 will be deposited on the ocean floor as carbonate sediments. However, that process requires millennia.

It is informative, for later policy considerations, to note that a negative CO_2 pulse decays at about the same rate as positive pulse. Thus if we decide to suck CO_2 from the air, taking CO_2 out of the carbon cycle, for example by storing it in carbonate bricks, the magnitude of the CO_2 change will decline as the negative increment becomes spread among the carbon reservoirs.

It is also informative to examine how fast atmospheric CO_2 would decline if fossil fuel use were halted today, or in 20 years, or in 40 years. Results are shown in Figure 4 (b). If emissions were halted in 2011, CO_2 would decline to 350 ppm at mid-century. With a 20 year

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[16] Specifically, we use the dynamic-sink pulse-response function representation of the Bern carbon cycle model (Joos et al., 1996), as described by Kharecha and Hansen (2008) and Hansen et al. (2008).

delay in halting emissions, CO_2 returns to 350 ppm at about 2250. With a 40 year delay, CO_2 does not return to 350 ppm until after year 3000.

The scenarios in Figure 4 (b) assume that emissions continue to increase at the 'business-as-usual' (BAU) rate of the past decade (increasing by just over 2% per year) until they are suddenly halted. The results are indicative of how difficult it will be to get back to 350 ppm, if fossil fuel emissions continue to accelerate.

Do these results imply that it is implausible to get back to 350 ppm in a way that is essentially 'natural', i.e., in a way other than a 'geo-engineering' approach that sucks CO_2 from the air? Not necessarily. There is one other major factor, in addition to fossil fuel use, that affects atmospheric CO_2 amount: deforestation/reforestation.

Fossil fuel emissions account for about 80 percent of the increase of atmospheric CO_2 from 275 ppm in the preindustrial atmosphere to 390 ppm today. The other 20 percent is from net deforestation (here net deforestation accounts for any forest regrowth in that period). We take net deforestation over the industrial era to be about 100 GtC (gigatons of carbon), with an uncertainty of at least 50 percent (Stocker et al., 2011)[17].

There is considerable potential for extracting CO_2 from the atmosphere via reforestation and improved forestry and agricultural practices. The largest practical extraction is probably about 100 GtC (IPCC, 2001), i.e., equivalent to restoration of deforested land. Complete restoration of deforested areas is unrealistic, yet a 100 GtC drawdown seems feasible for the following reasons: (1) the current human-enhanced atmospheric CO_2 level leads to an increase of carbon uptake by vegetation and soils, (2) improved agricultural practices can convert agriculture from being a large CO_2 source into a carbon sink, as discussed in the following paragraph, (3) part of this CO_2 drawdown can be achieved by burning biomass at powerplants and capturing the CO_2, with the provision that the feedstock for this bioenergy is residues and wastes, unlike most current-generation bioenergy sources, thus avoiding loss of natural ecosystems and cropland (Tilman et al., 2006; Fargione et al., 2008; Searchinger et al., 2008). Competing uses for land – primarily expansion of agriculture to supply a growing world population – could complicate reforestation efforts. A decrease in the use of animal products would substantially decrease the demand for agricultural land, as more than half of all crops are currently fed to livestock (Stehfest et al., 2009; UNEP, 2010).

The 100 GtC 'reforestation' thus is a major task, but it is needed to get CO_2 back to 350 ppm and it is an opportunity to achieve other major benefits. Present agricultural practices, based on plowing and chemical fertilizers, are dependent on fossil fuels and contribute to loss of carbon from soil via land degradation. World agriculture could sequester 0.4-1.2 GtC per year by adopting minimum tillage and biological nutrient recycling (Lal, 2004). Such a strategy can also increase water conservation in soils, build agricultural resilience to climate change, and increase productivity especially in smallholder rain-fed agriculture, thereby reducing expansion of agriculture into forested ecosystems (Rockstrom et al., 2009).

We thus assume a 100 GtC drawdown (biospheric C uptake) in our reforestation scenarios, with this obtained via a sinusoidal drawdown over the period 2031-2080. Alternative timings for this reforestation drawdown of CO_2 would have no qualitative effect on our conclusions about the potential for achieving a given CO_2 level such as 350 ppm.

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[17] Net historical deforestation of 100 GtC and historical fossil fuel use yield good agreement with historical growth of atmospheric CO_2 (Figure S16 of Hansen et al., 2008), based on simulations with the Bern carbon cycle model.

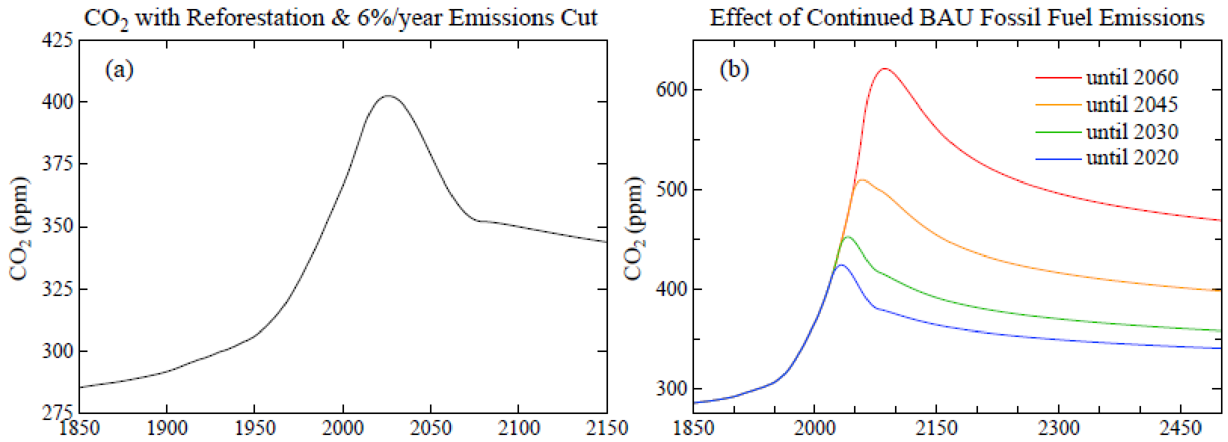

Figure 5. (a) Atmospheric CO_2 if fossil fuel emissions are cut 6% per year beginning in 2012 and 100 GtC reforestation drawdown occurs in the 2031-2080 period, (b) Atmospheric CO_2 with BAU emission increases until 2020, 2030, 2045, and 2060, followed by 5% per year emission reductions.

Figure 5 (a) shows that 100 GtC reforestation results in atmospheric CO_2 declining to 350 ppm by the end of this century, provided that fossil fuel emissions decline by 6% per year beginning in 2013. Figure 5 (b) shows the effect of continued BAU fossil fuel emission (just over 2% per year) until 2020, 2030, 2045 and 2060 with 100 GtC reforestation in 2031-2080.

The scenario with emission cuts beginning in 2020 has atmospheric CO_2 return to 350 ppm at about 2300. If the initiation of emissions reduction is delayed to 2030 or later, then atmospheric CO_2 does not return to the 350 ppm level even by 2500.

The conclusion is that a major reforestation program does permit the possibility of returning CO_2 to the 350 ppm level within this century, but only if fossil fuel emission reductions begin promptly.

What about artificially drawing down atmospheric CO_2? Some people may argue that, given the practical difficulty of overcoming fossil fuel lobbyists and persuading governments to move rapidly toward post-fossil-fuel clean energy economies, 'geo-engineering' is the only hope. At present there are no large-scale technologies for air capture of CO_2. It has been suggested that with strong research and development support and industrial scale pilot projects sustained over decades, it may be possible to achieve costs of about ~$200/tC (Keith et al., 2006).

At this rate, the cost of removing 50 ppm[18] of CO_2 is ~$20 trillion. However, as shown by Figure 4 (a), the resulting atmospheric CO_2 reduction is only ~15 ppm after 100 years, because most of the extraction will have leaked into other surface carbon reservoirs. The cost of CO_2 extraction needed to maintain a 50 ppm reduction on the century time scale is thus better estimated as ~$60 trillion.

In section 7 we note the economic and social benefits of rapidly phasing over to clean energies and increased energy efficiency, as opposed to continued and expanded extraction of fossil fuels. For the moment, we simply note that the present generation will be passing the CO_2 clean-up costs on to today's young people and future generations.

5. Future Global Temperature Change

Future global temperature change will depend primarily upon atmospheric CO_2 amount. Although other greenhouse gases, such as methane and chlorofluorocarbons, contributed almost

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[18] The conversion factor to convert atmospheric CO_2 in ppm to GtC is 1 ppm ~ 2.12 GtC.

as much as CO_2 to the total human-caused climate forcings over the past century, CO_2 now accounts for more than 80 percent of the growth of greenhouse gas climate forcing (over the past 15 years). Natural climate forcings, such as changes of solar irradiance and volcanic aerosols, can cause global temperature variations, but their effect on the long-term global temperature trend is small compared with the effect of CO_2.

A simple climate response function can provide a realistic estimate of expected global temperature change for a given scenario of future atmospheric CO_2. Indeed, Hansen et al. (2011) show that such a function accurately replicates the results from sophisticated global climate models. In the simulations here we use the 'intermediate' response function of Hansen et al. (2011), which accurately replicates observed ocean heat uptake and observed temperature change over the past century, and we assume that the net change of other human-made climate forcings is small in comparison with the effect of CO_2.

One important caveat must be stressed. These calculations, as with most global climate models, incorporate only the effect of the so-called 'fast feedbacks' in the climate system, such as water vapor, clouds, aerosols, and sea ice. Slow feedbacks, such as ice sheet disintegration and climate-induced changes of greenhouse gases, as may occur with the melting of tundra and warming of continental shelves, are not included.

Exclusion of slow feedbacks is appropriate for the past century, because we know the ice sheets were stable and our climate simulations employ observed greenhouse gas amounts. The observed greenhouse gas amount includes any contribution from slow feedbacks. Exclusion of slow feedbacks in the 21st century is a dubious assumption, used in our illustrative computations only because the rate at which slow feedbacks come into play is poorly understood. However, we must bear in mind the potential for slow feedbacks to fundamentally alter the nature of future climate change, specifically the possibility of creating a situation in which continued climate change is largely out of humanity's control.

Slow feedbacks are thus one important consideration that helps to crystallize the need to keep maximum warming from significantly exceeding 1°C. With the current global warming of ~0.8°C evidence of slow feedbacks is beginning to appear, e.g., melting of tundra with release of methane (Walter et al., 2006), submarine methane release from dissociation of sea-bed gas hydrates in association with sea water temperature increase (Westbrook et al., 2009), and increasing ice mass loss from Greenland and Antarctica (Velicogna, 2009). The fact that observed effects so far are small suggests that these feedbacks may not be a major factor if maximum global warming is only ~1°C and then recedes.

On the other hand, if BAU CO_2 emissions continue for many decades there is little doubt that these slow feedbacks will come into play in major ways. Because the CO_2 injected into the air stays in the surface carbon reservoirs for millennia, the slow feedbacks surely will occur. It is only a question of how fast they will come into play, and thus which generations will suffer the greatest consequences.

There is thus strong indication that we face a dichotomy. Either we achieve a scenario with declining global CO_2 emissions, thus preserving a planetary climate resembling that of the Holocene or we set in motion a dynamic transition to a very different planet.

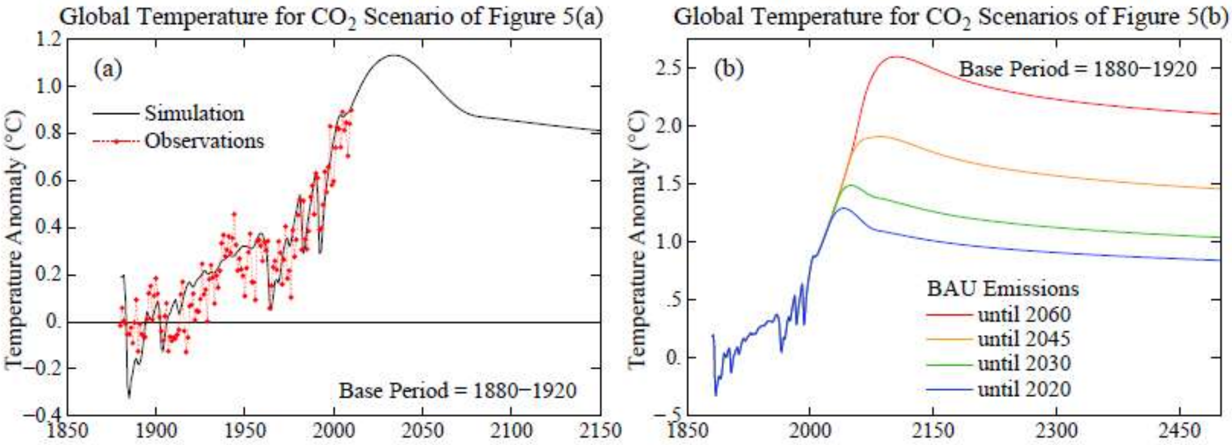

Figure 6. Simulated future global temperature for the CO_2 scenarios of Figure 5. Observed temperature record is from Hansen et al. (2010). Temperature is relative to the 1880-1920 mean. Subtract 0.26°C to use 1951-1980 as zero-point. Subtract 0.70°C to use 5-year running mean in 2000 as zero point.

Can we define the level of global warming that would necessarily push us into such a dynamic transition? Given present understanding of slow feedbacks, we cannot be precise. However, consider the case in Figure 6 in which BAU emissions continue to 2030. In that case, even though CO_2 emissions are phased out rapidly (5% per year emission reductions) after 2030 and 100 GtC reforestation occurs in 2031-2080, the (fast-feedback) human-caused global temperature rise reaches 1.5°C and stays above 1°C until after 2500. It is highly unlikely that the major ice sheets could remain stable at their present size with such long-lasting warmth. Even if BAU is continued only until 2020, the temperature rise exceeds 1°C for about 100 years.

In contrast to scenarios with continued BAU emissions, Figure 6 (a) shows the scenario with 6% per year decrease of fossil fuel CO_2 emissions and 100 GtC reforestation in the period 2031-2080. This scenario yields additional global warming of ~0.3°C. Global temperature relative to the 1880-1920 mean would barely exceed 1°C and would remain above 1°C for only about 3 decades. Thus this scenario provides the prospect that young people, future generations, and other life on the planet would have a chance of residing in a world similar to the one in which civilization developed.

The precise consequences if BAU emissions continue several decades are difficult to define, because such rapid growth of climate forcing would take the world into uncharted territory. Earth has experienced a huge range of climate states during its history, but there has never been such a large rapid increase of climate forcings as would occur with burning of most fossil fuels this century. The closest analogy in Earth's history is probably the PETM (Paleocene-Eocene Thermal Maximum) in which rapid global warming of at least 5°C occurred (Zachos et al., 2001), probably as a consequence of melting methane hydrates (Zeebe et al., 2009). The PETM is instructive because it occurred during a 10-million year period of global warming, and thus the methane release was probably a feedback effect magnifying the warming.

Global warming that occurred over the period from 60 Mya (million years ago) to 50 Mya can be confidently ascribed to increasing atmospheric CO_2. That was the period in which the Indian subcontinent was moving rapidly through the Indian Ocean, just prior to its collision with Asia, when it began to push up the Himalayan Mountains and Tibetan Plateau. Continental drift over carbonate-rich ocean crust is the principal source of CO_2 from the solid Earth to the surface reservoirs of carbon.[19]

The global warming between 60 Mya and 50 Mya was about 5°C, thus at a rate less than 1°C per million years. Approximately 55 Mya there was, by paleoclimae standards, a very rapid release of 3000-5000 GtC into the surface climate system, presumably from melting of methane hydrates based on the absence of any other known source of that magnitude. This injection of carbon and rapid additional warming of about 5°C occurred over a period of about 10,000 years, with most of the carbon injection during two 1-2 thousand year intervals. The PETM witnessed the extinction of almost half of the deep ocean foraminifera (microscopic shelled animals, which serve as a biological indicator for ocean life in general), but, unlike several other large warming events in Earth's history, there was little extinction of land plants and animals.

The important point is that the rapid PETM carbon injection was comparable to what will occur if humanity burns most of the fossil fuels, but the PETM occurred over a period that was 10-100 times longer. The ability of life on Earth today to sustain a climate shock comparable to the PETM but occurring 10-100 times faster is highly problematic, at best. Climate zones would be shifting at a speed far faster than species have ever faced. Thus if humanity continues to burn most of the fossil fuels, Earth, and all of the species residing on it, will be pushed into uncharted climate change territory, with consequences that are practically impossible to foresee.

6. Consequences of Continued Global Warming

The unparalleled rapidity of the human-made increase of global climate forcing implies that there are no close paleoclimate analogies to the current situation. However, the combination of paleoclimate data and observations of ongoing climate change provide useful insight.

Paleoclimate data serve mainly as an indication of likely long-term responses to changed boundary conditions. Observations of ongoing climate change provide information relevant to the rate at which changes may occur.

Yet we must bear in mind that some important processes, such as ice sheet disintegration and species extermination, have the potential to be highly non-linear. That means changes can be slow until a tipping point is reached (Lenton et al., 2008) and more rapid change occurs.

Sea level. If most fossil fuels are burned global temperatures will rise at least several degrees Celsius. The eventual sea level change in response to the global warming will be many meters and global coast lines will be transfigured. We do not know how rapidly ice sheets can disintegrate, because Earth has never experienced such rapid global warming. However, even moderate sea level rise will create millions of global warming refugees from highly-populated low-lying areas, who must migrate from the coastline, throwing existing global demographics into chaos.

During the most recent prior interglacial period, the Eemian, global temperature was at most of the order of 1°C warmer than the Holocene (Figure 2). Sea level reached heights several meters above today's level and there were instances of sea level change by 1-2 meters per century (Rohling et al., 2008; Muhs et al., 2011). Hearty and Neumann (2001) and Hearty et al. (2007) interpret geologic shoreline evidence as indicating a rapid sea level rise to a peak 6-9 meters above present late in the Eemian followed by a precipitous sea level fall, but there is not unanimity in the research community about this specific history. The important point is that the

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[19] The principal sink of CO_2, i.e., the mechanism that returns carbon to the solid Earth on long time scales, is the weathering process. Chemical reactions associated with weathering of rocks results in rivers carrying carbonate sediments that are deposited on the ocean floor.

high sea level excursions in the Eemian imply rapid partial melting of Antarctic and/or Greenland ice when the world was little warmer than today. During the Pliocene, when global mean temperature may have been 2°C warmer than the Holocene (Figure 2), sea level was probably 15-25 meters higher than today (Dowsett et al., 1999, 2009; Naish et al., 2009).

Expected sea level rise due to human-caused climate change has been controversial partly because the discussion and the predictions of IPCC (2001, 2007) have focused on sea level rise at a specific date, 2100. Recent estimates of likely sea level rise by 2100 are of the order of 1 m (Vermeer and Rahmstorf, 2009; Grinsted et al., 2010). Ice-dynamics studies estimate that rates of sea-level rise of 0.8 to 2 m per century are feasible (Pfeffer et al., 2008) and Antarctica alone may contribute up to 1.5 m per century (Turner et al., 2009). Hansen (2005, 2007) has argued that BAU CO_2 emissions produce a climate forcing so much larger than any experienced in prior interglacial periods that a non-linear ice sheet response with multi-meter sea level rise may occur this century.

The best warning of an imminent period of sustained nonlinear ice sheet loss will be provided by accurate measurements of ice sheet mass. The GRACE satellite, which has been measuring Earth's gravitational field since 2003 reveals that the Greenland ice sheet is losing mass at an accelerating rate, now more than 200 cubic kilometers per year, and Antarctica is losing more than 100 cubic kilometers per year (Sorensen and Forsberg, 2010; Rignot et al., 2011). However, the present rate of sea level rise, 3 cm per decade, is moderate, and the ice sheet mass balance record is too short to determine whether we have entered a period of continually accelerating ice loss.

Satellite observations of Greenland show that the surface area with summer melting has increased over the period of record, which extends back to the late 1970s (Steffen et al., 2004; Tedesco et al., 2011). Yet the destabilizing mechanism of greatest concern is melting of ice shelves, tongues of ice that extend from the ice sheets into the oceans and buttress the ice sheets, limiting the rate of discharge of ice to the ocean. Ocean warming is causing shrinkage of ice shelves around Greenland and Antarctica (Rignot and Jacobs, 2002).

Loss of ice shelves can open a pathway to the ocean for portions of the ice sheets that rest on bedrock below sea level. Most of the West Antarctic ice sheet, which alone could raise sea level by 6 meters, is on bedrock below sea level, so it is the ice sheet most vulnerable to rapid change. However, parts of the larger East Antarctic ice sheet are also vulnerable. Indeed, satellite gravity and radar altimetry reveal that the Totten Glacier of East Antarctica, fronting a large ice mass grounded below sea level, is already beginning to lose mass (Rignot et al., 2008)

The important point is that uncertainties about sea level rise mainly concern the timing of large sea level rise if BAU emissions continue, not whether it will occur. If all or most fossil fuels are burned, the carbon will be in the climate system for many centuries, in which case multi-meter sea level rise should be expected (e.g., Rohling et al., 2009).

Children born today can expect to live most of this century. If BAU emissions continue, will they suffer large sea level rise, or will it be their children, or their grandchildren?

Shifting climate zones. Theory and climate models indicate that subtropical regions will expand poleward with global warming (Held and Soden, 2006; IPCC, 2007). Observations reveal that a 4-degree poleward expansion of the subtropics has occurred already on average (Seidel and Randel, 2006), yielding increased aridity in southern United States (Barnett et al., 2008; Levi, 2008), the Mediterranean region, and Australia. Increased aridity and temperatures have contributed to increased forest fires that burn hotter and are more destructive in all of these regions (Westerling et al., 2006).

Although there is large year-to-year variability of seasonal temperature, decadal averages reveal that isotherms (lines of a given average temperature) having been moving poleward at a rate of about 100 km per decade during the past three decades (Hansen et al., 2006). This rate of shifting of climatic zones exceeds natural rates of change. The direction of movement has been monotonic (poleward) since about 1975. Wild species have responded to this climatic shift, with at least 52 percent of species having shifted their ranges poleward (and upward) by as much as 600 km in terrestrial systems and 1000 km in marine systems (Parmesan and Yohe, 2003). As long as the planet is as far out of energy balance as at present, that trend necessarily will continue, a conclusion based on comparison of the observed trend with interdecadal variability in climate simulations (Hansen et al., 2007).

Humans may be better able to adapt to shifting of climate zones, compared with many other species. However, political borders can interfere with migration, and indigenous ways of life have already been adversely affected. Impacts are apparent in the Arctic, with melting tundra, reduced sea ice, and increased shoreline erosion. Effects of shifting climate zones may also be important for native Americans who possess specific designated land areas, as well as other cultures with long-standing traditions in South America, Africa, Asia and Australia.

Loss of Species. Explosion of the human population and its presence on the landscape in the past few centuries is having a profound influence on the well being of all the other species. As recently as two decades ago biologists were more concerned with effects on biodiversity other than climate change, such as land use changes, nitrogen fertilization, and direct effects of increased atmospheric CO_2 on plant ecophysiology (Parmesan, 2006). However, easily discernible impacts on animals, plants, and insects of the nearly monotonic global warming during the past three decades (Figure 1) has sharply altered perceptions of the greatest threats.

A dramatic awakening was provided by sudden widespread decline of frogs, with extinction of entire mountain-restricted species attributed to global warming (Pounds et al., 1999, 2006). Although there are somewhat different interpretations of detailed processes involved in global amphibian declines and extinctions (Alford et al., 2007; Fagotti and Pascolini, 2007), there is agreement that global warming is a main contributor to a global amphibian crisis: "The losses portend a planetary-scale mass extinction in the making. Unless humanity takes immediate action to stabilize the climate, while also fighting biodiversity's other threats, a multitude of species is likely to vanish" (Pounds et al., 2007).

Mountain-restricted species in general are particularly vulnerable to global warming. As warming causes isotherms to move up the mountainside so does the specific climate zone in which a given specific species can survive. If global warming continues unabated, i.e., if all fossil fuels are burned, many mountain-dwelling species will be driven to extinction.

The same is true for species living in polar regions. There is documented evidence of reductions in the population and health of Arctic species living in the southern parts of the Arctic and Antarctic species in the more northern parts of the Antarctic.

A critical factor for survival of some Arctic species will be retention of all-year sea ice. Continued BAU fossil fuel use will result in loss of all Arctic summer sea ice within the next several decades. In contrast, the scenario in Figure 5a, with global warming peaking just over 1°C and then declining slowly, should allow some summer sea ice to survive and then gradually increase to levels representative of recent decades.

The threat to species survival is not limited to mountain and polar species. Plant and animal distributions are a reflection of the regional climates to which they are adapted. Although species attempt to migrate in response to climate change, their paths may be blocked by human-constructed obstacles or natural barriers such as coast lines. As the shift of climate zones

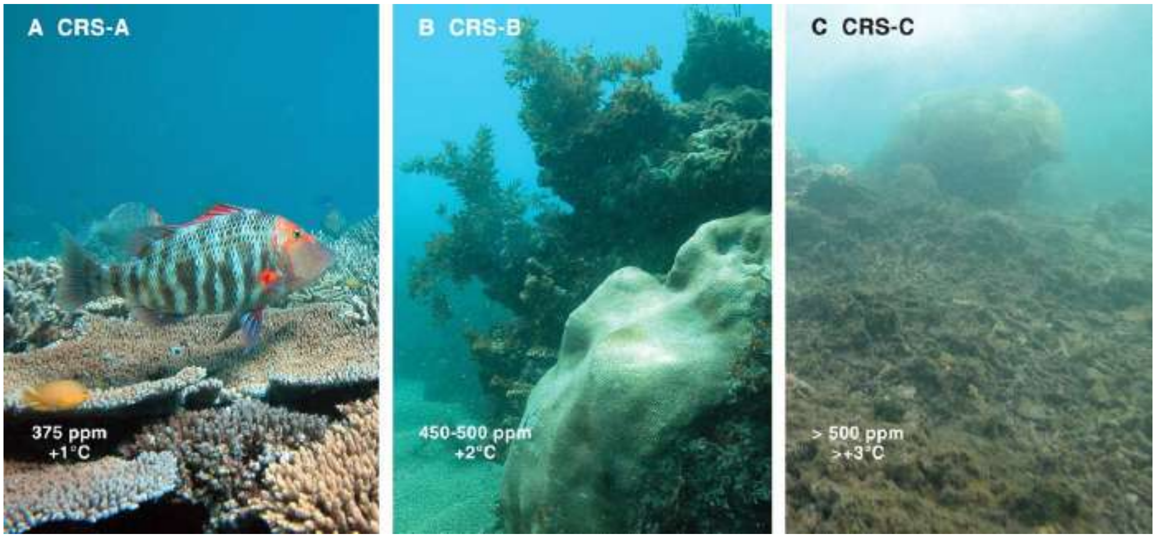

Figure 7. Extant reefs used as analogs (Hoegh-Guldberg et al., 2007) for ecological structures anticipated for scenarios A (375 ppm CO_2, +1°C), B (450-500 ppm CO_2, +2°C), C (>500 ppm CO_2, >+3°C)

becomes comparable to the range of some species, the less mobile species will be driven to extinction. Because of extensive species interdependencies, this can lead to mass extinctions.

The IPCC Working Group II assessment (IPCC WG-II, 2007) reviews studies relevant to estimating the eventual extinction rate for different magnitudes of global warming. If global warming relative to the pre-industrial level exceeds 1.5°C, they estimate that 9-31 percent of species will be committed to extinction. With global warming of 2.7°C, an estimated 21-52 percent of species will be committed to extinction.

Mass extinctions have occurred in conjunction with rapid climate change during Earth's long history, and new species evolved over hundreds of thousands and millions of years. But such time scales are almost beyond human comprehension. If we drive many species to extinction we will leave a more desolate planet for our children, grandchildren, and as many generations as we can imagine.

Coral reef ecosystems. Coral reef ecosystems are the most biologically diverse marine ecosystem, often described as the rainforests of the ocean. An estimated 1-9 million species (most of which have not yet been described; Reaka-Kudla 1997) populate coral reef ecosystems generating ecosystem services that are crucial to the well-being of at least 500 million people that populate tropical coastal areas. These coral reef ecosystems are vulnerable to current and future warming and acidification of tropical oceans. Acidification arises due to the production of carbonic acid as increasing amounts of CO_2 enter the world's oceans. Comparison of current changes with those seen in the palaeontological record indicate that ocean pH is already outside where it has been for several million years (Raven et al. 2005; Pelejero et al. 2010).

Mass coral bleaching and a slowing of coral calcification are already disrupting coral reef ecosystem health (Hoegh-Guldberg et al 2007; De'Ath et al. 2009). The decreased viability of reef-building corals have led to mass mortalities, increasing coral disease, and slowing of reef carbonate accretion. Together with more local stressors, the impacts of global climate change and ocean acidification are driving a rapid contraction (1-2% per year, Bruno and Selig 2007) in the extent of coral reef ecosystems.

Figure 7 shows extant reefs that are analogs for ecological structures anticipated by Hoegh-Guldberg et al. (2007) to be representative of ocean warming and acidification expected to accompany CO_2 levels of 375 ppm with +1°C, 450-500 ppm with +2°C, and >500 ppm with >

+3°C. Loss of the three-dimensional framework that typifies coral reefs today has consequences for the millions of species that depend on this coral reef framework for their existence. The loss of these three-dimensional frameworks also has consequences for other important roles coral reefs play in supporting fisheries and protecting coastlines from wave stress. The consequences of losing coral reefs are likely to be substantial and economically devastating for multiple nations across the planet when combined with other impacts such as sea level rise.

The situation with coral reefs is summarized by Schuttenberg and Hoegh-Guldberg (2007) thus: "Although the current greenhouse trajectory is disastrous for coral reefs and the millions of people who depend on them for survival, we should not be lulled into accepting a world without corals. Only by imagining a world with corals will we build the resolve to solve the challenges ahead. We must avoid the "game over" syndrome and marshal the financial, political, and technical resources to stabilize the climate and implement effective reef management with unprecedented urgency."

Hydrologic extremes and storms. The extremes of the hydrologic cycle are intensified as Earth becomes warmer. A warmer atmosphere holds more moisture, so heavy rains become more intense and increase flooding. Higher temperatures, on the other hand, cause an intensification of droughts, as does expansion of the subtropics with global warming. The most recent IPCC (2007) report confirms existence of expected trends, e.g., precipitation has generally increased over land north of 30°N and decreased in more tropical latitudes. Heavy precipitation events have increased substantially. Droughts are more common, especially in the tropics and subtropics. Tropospheric water vapor has increased.

Mountain glaciers. Mountain glaciers are in near-global retreat (IPCC, 2007). After a one-time added flush of fresh water, glacier demise will yield summers and autumns of frequently dry rivers originating in the Himalayas, Andes, and Rocky Mountains (Barnett et al., 2008) that now supply water to hundreds of millions of people. Present glacier retreat, and warming in the pipeline, indicate that 390 ppm of CO_2 is already a threat for future fresh water security.

Human health. Children are especially vulnerable to the health impacts of climate change. Principal effects are categorized in Table 1 under the headings: (1) heat waves, (2) asthma and allergies, (3) infectious disease spread, (4) pests and disease spread across taxa: forests, crops and marine life, (5) winter weather anomalies, (6) drought, (7) food insecurity. Climate change poses a threat to child health through many pathways, especially by placing additional stress on the availability of food, clean air, clean water, and potentially expanding the burden of disease from vector-borne diseases (Bernstein and Myers, 2011).

World health experts have concluded with "very high confidence" that climate change already contributes to the global burden of disease and premature death (IPCC WG-II, 2007). At this point the effects are small but are projected to progressively increase in all countries and regions. IPCC (WG-II, 2007) describes evidence that climate change has already altered the distribution of some infectious disease vectors, altered the seasonal distribution of some allergenic pollen species, and increased heat-related deaths.

Table 1. Climate Change Impacts on Human Health

Heatwaves.	Heatwaves are not only increasing in frequency, intensity and duration, but their nature is changing. Warmer nighttime temps [double the increase of average temperature since 1970 (Karl et al.)] and higher humidity (7% more for each 1ºC warming) that raises heat indices and makes heat-waves all the more lethal.
Asthma and allergies.	Asthma prevalence has more than doubled in the U.S. since 1980 and several exacerbating factors stem from burning fossil fuels. Increased CO_2 and warming boost pollen production from fast growing trees in the spring and ragweed in the fall (the allergenic proteins also increase). Particulates help deliver pollen and mold spores deep into the lung sacs. Ground-level ozone primes the allergic response (and O_3 increases in heat-waves). Climate change has extended the allergy and asthma season two-four weeks in the Northern Hemisphere (depending on latitude) since 1970. Increased CO_2 stimulates growth of poison ivy and a chemical in it (uruschiol) that causes contact dermatitis.
Infectious disease spread.	The spread of infectious diseases is influenced by climate change in two ways: warming expands the geographic and temporal conditions conducive to transmission of vector-borne diseases (VBDs), while floods can leave "clusters" of mosquito-, water – and rodent-borne diseases (and spread toxins). With the ocean the repository for global warming and the atmosphere holding more water vapor, rain is increasing in intensity -- 7% overall in the U.S. since 1970, 2"/day rains 14%, 4"/day rains 20%, and 6"/day rains 27% since 1970 (Groisman et al., 2005), with multiple implications for health, crops and nutrition. Tick-borne Lyme disease (LD) is the most important VBD in the U.S. LD case reports rose 8-fold in New Hampshire in the past decade and 10-fold (and now include all of its 16 counties). Warmer winters and disproportionate warming toward the poles mean that the changes in range are occurring faster than models based on changes in average temperatures project. Biological responses of vectors (and plants) to warming are, in general, underestimated and may be seen as leading indicators of warming due to the disproportionate winter (Tminimum or Tmin) and high latitude warming.
Pests and disease spread across taxa: forests, crops and marine life.	Pests and diseases of forests, crops and marine life are favored in a warming world. Bark beetles are overwintering (absent sustained killing frosts) and expanding their range, and getting in more generations, while droughts in the West dry the resin that drowns the beetles as they try to drive through the bark. (Warming emboldens the pests while extremes weaken the hosts.) Forest health is also threatened in the Northeast U.S. (Asian Long-horned beetle and wooly adelgid of hemlock trees), setting the stage for increased wildfires with injury, death and air pollution, loss of carbon stores, and damage to oxygen and water supplies. In sum, forest pests threaten basic life support systems that underlie human health. Crop pests and diseases are also encouraged by warming and extremes. Warming increases their potential range, while floods foster fungal growth and droughts favor whiteflies, aphid and locust. Higher CO_2 also stimulates growth of agricultural weeds. More pesticides, herbicides and fungicides (where available) pose other threats to human health. Crop pests take up to 40% of yield annually, totaling ~$300 billion in losses (Pimentel) Marine diseases (e.g., coral, sea urchin die-offs, and others), harmful algal blooms (from excess nutrients, loss of filtering wetlands, warmer seas and extreme weather events that trigger HABs by flushing nutrients into estuaries and coastal waters), plus the over 350 "dead zones" globally affect fisheries, thus nutrition and health.
Winter weather anomalies.	Increasing winter weather anomalies is a trend to be monitored. More winter precipitation is falling as rain rather than snow in the Northern Hemisphere, increasing the chances for ice storms, while greater atmospheric moisture increases the chances of heavy snowfalls. Both affect ambulatory health (orthopedics), motor vehicle accidents, cardiac disease and power outages with accompanying health effects.
Drought.	Droughts are increasing in frequency, intensity, duration, and geographic extent. Drought and water stress are major killers in developing nations, are associated with disease outbreaks (water-borne cholera, mosquito-borne dengue fever (mosquitoes breed in stored water containers)), and drought and higher CO_2 increase the cyanide content of cassava, a staple food in Africa, leading to neurological disabilities and death.
Food insecurity.	Food insecurity is a major problem worldwide. Demand for meat, fuel prices, displacement of food crops with those grown for biofuels all contribute. But extreme weather events today are the acute driver. Russia's extensive 2010 summer heat-wave (over six standard deviations from the norm, killing over 50,000) reduced wheat production ~40%; Pakistan and Australian floods in 2010 also affected wheat and other grains; and drought in China and the U.S. Southwest are boosting grain prices and causing shortages in many nations. Food riots are occurring in Uganda and Burkino Faso, and the food and fuel hikes may be contributing to the uprisings in North Africa and the Middle East. Food shortages and price hikes contribute to malnutrition that underlies much of poor health and vulnerability to infectious diseases. Food insecurity also leads to political instability, conflict and war.

If global warming increases IPCC (WG-II, 2007) projects the following trends, where we include only those that are assigned either high confidence or very high confidence: (1) increased malnutrition and consequent disorders, including those related to child growth and development, (2) increased death, disease and injuries from heat waves, floods, storms, fires and droughts, (3) increased cardio-respiratory morbidity and mortality associated with ground-level ozone, (4) some benefits to health, including fewer deaths from cold, although it is expected that these would be outweighed by the negative effects.

7. Societal Implications

The science is clear. Human-made climate forcing agents, principally CO_2 from burning of fossil fuels, have driven planet Earth out of energy balance – more energy coming in than going out. The human-made climate forcing agents are the principal cause of the global warming of 0.8°C in the past century, most of which occurred in the past few decades.

Earth's energy imbalance today is the fundamental quantity defining the state of the planet. With the completion of the near-global distribution of Argo floats and reduction of calibration problems, it is confirmed that the planet's energy imbalance averaged over several years, is at least 0.5 W/m^2. The imbalance averaged over the past solar cycle is probably closer to 0.75 W/m^2. An imbalance of this magnitude assures that continued global warming is in the pipeline, and thus so are increasing climate impacts.

Global climate effects are already apparent. Arctic warm season sea ice has decreased more than 30 percent over the past few decades. Mountain glaciers are receding rapidly all over the world. The Greenland and Antarctic ice sheets are shedding mass at an accelerating rate, already several hundred cubic kilometers per year. Climate zones are shifting poleward. The subtropics are expanding. Climate extremes are increasing. Summer heat of a degree that occurred only 2-3 percent of the time in the period 1950-1980, or, equivalently, in a typical summer covered 2-3 percent of the globe, now occurs over 20-40 percent of Earth's surface each summer (http://www.columbia.edu/~jeh1/mailings/2011/20110327_Perceptions.pdf). Within these expanded areas smaller regions of more extreme anomalies, such as the European heat wave of 2003 and the Moscow and Pakistan heat waves of 2010.

Global climate anomalies and climate impacts will continue to increase if fossil fuel use continues at current levels or increases. Earth's history provides our best measure of the ultimate climate response to a given level of climate forcing and global temperature change. Continuation of business-as-usual fossil fuel emissions for even a few decades would guarantee that global warming would pass well beyond the warmest interglacial periods in the past million years, implying transition to literally a different planet than the one that humanity has experienced. Today's young people and following generations would be faced with continuing climate change and climate impacts that would be out of their control.

Yet governments are taking no actions[13] to substantially alter business-as-usual fossil fuel emissions. Rhetoric about a 'planet in peril' abounds. But actions speak louder than words. Continued investments in infrastructure to expand the scope and nature of fossil fuel extraction expose reality.

The matter is urgent. CO_2 injected into the atmosphere by burning fossil fuels remains in the surface climate system for millennia. The practicality of any scheme to extract CO_2 from the air is dubious. Potentially huge costs would be left to young people and future generations.

The apparent solution is to phase out fossil fuel emissions in favor of clean energies and energy efficiency. Governments have taken steps to promote renewable energies and encourage energy efficiency. But renewable energies total only a few percent of all energy sources, and improved efficiency only slows the growth of energy use. The transition to a post-fossil fuel world of clean energies is blocked by a fundamental fact, as certain as the law of gravity: as long as fossil fuels are the cheapest energy, they will be burned.

However, fossil fuels are cheapest only because they are subsidized directly and indirectly, and because they are not made to pay their costs to society – the costs of air and water pollution on human health and costs of present and future climate disruption and change.

Those people who prefer to continue business-as-usual assert that transition to fossil fuel alternatives would be economically harmful, and they implicitly assume that fossil fuel use can continue indefinitely. In reality, it will be necessary to move to clean energies eventually, and most economists believe that it would be economically beneficial to move in an orderly way to the post fossil fuel era via a steadily increasing price on carbon emissions.

A comprehensive assessment of the economics, the arguments for and against a rising carbon price, is provided in the book The Case for a Carbon Tax (Hsu, 2011). An across-the-board price on all fossil fuel CO_2 emissions emerges as the simplest, easiest, fastest and most effective way to phase down carbon emissions, and this approach presents fewer obstacles to international agreement.

The chief obstacles to a carbon price are often said to be the political difficulty, given the enormous resources that interest groups opposing it can bring to bear, and the difficulty of getting the public to understand arcane economic issues. On the other hand, a simple, transparent, gradually rising fee on carbon emissions collected, with the proceeds distributed to the public, can be described succinctly, as it has by Jim DiPeso, Policy Director of Republicans for Environmental Protection http://www.rep.org/opinions/weblog/weblog10-10-11.html

A gradually rising carbon price is the sine qua non, but it must be combined with a portfolio of other actions: energy research and development with demonstration programs; public investment in complementary infrastructure such as improved electric grids; global monitoring systems; energy efficiency regulations; public education and awareness; support for climate change mitigation and adaptation in undeveloped countries. In economic theory, within a nation or a common block of nations, a carbon trading system may be useful, but given the need for rapid global emissions reduction, a simple across-the-board carbon tax is the preferred approach from the standpoint of conservative economics (Mankiw, 2007).

The basic matter, however, is not one of economics. It is a matter of morality – a matter of intergenerational justice. The blame, if we fail to stand up and demand a change of course, will fall on us, the current generation of adults. Our parents honestly did not know that their actions could harm future generations. We, the current generation, can only pretend that we did not know.

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References

Ackerman, F., E.A. Stanton, S.J. DeCaanio, E. Goodstein, R.B. Howarth, R.B. Norgaard, C.S. Norman, K.A. Sheeran, 2009: The economics of 350: the benefits and costs of climate stabilization, October 2009 report for ecotrust (www.ecotrust.org) and Stockholm environment Institute (www.sei-us.org), 50 pp.

Alford, R.A., K.S. Bradfield, S.J. Richards, 2007: Global warming and amphibian losses, *Nature*, **447**, E3-E4.

Barker, P.M., J.R. Dunn, C.M. Domingues, S.E. Wijffels, 2011: Pressure sensor drifts in Argo and their impacts, *J. Atmos. Ocean. Technology*, Early Online Release. doi: 10.1175/2011JTECHO831.1.

Barnett, T.P., D.W. Pierce, H.D. Hidalgo, et al., 2008: Human-induced changes in the hydrology of the Western United States, *Science*, **319**, 1080-1083.

Barriopedro, D., E. M. Fischer, J. Luterbacher, R.M. Trigo, R. Garcia-Herrera, 2011: The hot summer of 2010: redrawing the temperature record map of Europe, *Science Express*, 10.1126/science.1201224.

Bernstein, A., S. Myers, 2011: Climate change and children's health, *Current Opin. Pediatrics*, **23**, 221-226.

Bruno, J.F., E.R. Selig, 2007, Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons: PLoS ONE, v. 2, p. e711.

Cohen, A.J., H.R. Andrson, B. Ostro, K.D. Pandey, M. Krzyzanowski, N. Kunzli, K. Gutschmidt, A. Pope, I. Romieu, J.M. Samet, K. Smith, 2005: The global burden of disease due to outdoor air pollution, *J. Toxicol. Environ. Health*, **68**, 1301-1307, doi:10.1080/152873905909361666

De'ath, G., J.M. Lough, K.E. Fabricius, 2009: Declining Coral Calcification on the Great Barrier Reef, *Science*, **323**, 116-119.

Dowsett, H. J., J. A. Barron, R. Z. Poore, R. S. Thompson, T. M. Cronin, S. E. Ishman, and D. A. Willard, 1999: Middle Pliocene paleoenvironmental reconstruction: PRISM2, *U.S. Geol. Surv. Open File Rep.*, 99-535. (Available at http://pubs.usgs.gov/openfile/of99-535)

Dowsett, H.J., M.M. Robinson, K.M. Foley, 2009: Pliocene three-dimensional global ocean temperature reconstruction, *Clim. Past*, **5**, 769-783.

Epstein, P.R., J.J. Buonocore, K. Eckerle, M. Hendryx, B.M. Stout, R. Heinberg, R.W. Clapp, B. May, N.L. Reinhart, M.M. Ahern, S.K. Doshi, L. Glustrom, 2011: Full cost accounting for the life cycle of coal, *Ann. New York Acad. Sci.*, **1219**, 73-98.

Fargione, J., J. Hill, D. Tilman, S. Polansky, P. Hawthorne, 2009: Land clearing and the biofuel carbon debt, *Science*, **319**, 1235-1238.

Fagotti, A., R. Pascolini, 2007: The proximate cause of frog declines? *Nature*, **447**, E4-E5.

Grinsted, A., J.C. Moore, S. Jevrejeva, 2010: Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD, *Clim. Dyn.*, **34**, 461-472.

Groisman, P.Y., R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, V.N. Razuvaev, 2005: Trends in intense precipitation in the climate record, *J. Clim.*, **18**, 1326-1350.

Hansen, J.E., 2005: A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? An editorial essay. *Climatic Change*, **68**, 269-279, doi:10.1007/s10584-005-4135-0.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, M. Medina-Elizade, 2006: Global temperature change, *Proc. Nat. Acad. Sci.*, **103**, 14288-14293.

Hansen, J.E., 2007: Scientific reticence and sea level rise, *Environ. Res. Lett.*, **2**, 1-6.

Hansen, J., M. Sato, R. Ruedy, *et al.*, 2007: Dangerous human-made interference with climate: a GISS modelE study, *Atmos. Chem. & Phys.*, **7**, 2287-2312.

Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO_2: where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231.

Hansen, J., R. Ruedy, M. Sato, K. Lo, 2010: Global surface temperature change, *Rev. Geophys.*, **48**, RG4004, 29 pp.

Hansen, J.E., and Mki. Sato, 2011: Paleoclimate implications for human-made climate change. http://arxiv.org/abs/1105.0968 pdf also available at http://www.columbia.edu/~jeh1/

Hansen, J., Mki. Sato, P. Kharecha, and K. von Schuckmann, 2011:Earth's energy imbalance and implications. http://arxiv.org/abs/1105.1140 pdf also available at http://www.columbia.edu/~jeh1/

Hearty, P.J., A.C. Neumann, 2001: Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): evidence from the Bahama Islands, 2001: *Quatern. Sci. Rev.*, **20**, 1881-1895.

Hearty, P.J., J.T. Hollin, A.C. Neumann, M.J. O'Leary, M. McCulloch, 2007: Global sea-level fluctuations during the last interglaciation (Mis 5e), *Quarter. Sci. Rev.*, **26**, 2090-2112.

Held, I.M., B.J. Soden, 2006: Robust rsponses of the hydrological cycle to global warming, *J. Clim*, **19**, 5686-5699.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Stenek, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, M.E. Hatziolos, 2007: Coral reefs under rapid climate change and ocean acidification, *Science*, **318**, 1737-1742.

Hsu, S.-L., 2011: *The Case for a Carbon Tax*, Island Press, Washington (in pressf).

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Scientific Basis*, Houghton, J.T., Y. Ding, D.J. Griggs, *et al.* (eds., Cambridge University Press, 881 pp.

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Science Basis*, S. Solomon, Q. Dahe, M. Manning, et al. (eds., Cambridge Univ. Press, 996 pp.

Intergovernmental Panel on Climate Change (WGII), *Climate Change 2007: Impacts, Adaptation and Vulnerability,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (eds., Cambridge Univ. Press, 996 pp.

Joos, F., M. Bruno, R. Fink, U. Siegenthaler, T. F. Stocker, C. Le Quéré, J. Sarmiento, 1996: An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake, *Tellus B, 48/3*, 397-417.

Karl, T.R., P.D. Jones, R.W. Knight, G. Kukla, N. Plummer, V. Razuvayev, K.P. Gallo, J. Linday, R.J. Charlson, T.C. Peterson, 1993: A new perspective on recent global warming: asymmetric trends of daily maximum and minimum temperature, *Bull. Amer. Meteorol. Soc*., **74**, 1007-1023.

Keith, D.W., M. Ha-Duong, J.K. Stolaroff, 2006: *Clim. Change*, **74**, 17-45.

Kharecha, P.A., and J.E. Hansen, 2008: Implications of "peak oil" for atmospheric CO_2 and climate. *Global Biogeochem. Cycles*, **22**, GB3012.

Lal, R., 2004: Soil carbon sequestration impacts on global climate change and food security, *Science*, **304**, 1623 – 1627.

Lenton, T.M., H. Held, E. Kriegler, J.W. Hall, W. Lucht, S. Rahmstorf, H.J. Schellnhuber, 2008: Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci.*, **105**, 1786-1793.

Levi, B.G., 2008: Trends in the hydrology of the western U.S. bear the imprint of manmade climate change, *Phys. Today*, April 16-18.

Levitus, S., J. Antonov, T. Boyer, R.A. Locarnini, H.E. Garcia, A.V. Mishonov, 2009: Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems, *Geophys. Res. Lett.*, **36**, L07608, doi:10.1029/2008GL037155 http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/basin_data.html (1955-2010)

Lyman, J.M., S.A. Good, V.V. Gouretski, M. Ishii, G.C. Johnson, M.D. Palmer, D.A. Smith, J.K. Willis, 2010: Robust warming of the global upper ocean, *Nature*, **465**, 334-337, doi:10.1038/nature09043

Mankiw, N.G., 2007: One answer to global warming: a new tax, *New York Times*, 16 September, http://www.nytimes.com/2007/09/16/business/16view.html).

Mayewski, P.A., E.E. Rohling, J.C. Stager, W. Karlen, K.A. Maasch, L.D. Meeker, E.A. Meyerson, F. Gasse, S. van Kreveld, K. Holmgren, J. Lee-Thorp, G. Rosqvist, F. Rack, M. Staubwasser, R.R. Schneider, E. J. Steig, 2004: Holocene climate variability, *Quat. Res.*, **62**, 243-255.

Muhs, D.R., K.R. Simmons, R.R. Schumann, R.B. Halley, 2011: Sea-level history of the past two interglacial periods: new evidence from U-series cating of reef corals from south Florida, *Quarter. Sci. Rev.*, **30**, 570-590.

Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, M. Oppenheimer, 2009: Probabilistic assessment of sea level during the last interglacial stage. *Nature* **462**, 863-867

Krauss, C., 2010: There will be fuel, *New York Times*, Page F1 of the New York edition, November 17, 2010.

Naish, T. *et al.*, 2009: Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**, 322–328).

Olson, S.I., P.J. Hearrty, 2009: A sustained +21 m highstand during MIS 11 (400 ka): direct fossil and sedimentary evidence from Bermuda, *Quat. Sci. Rev*., **28**, 271-285.

Pelejero, C., E. Calvo, O. Hoegh-Guldberg, 2010: Paleo-perspectives on ocean acidification, *Trends in Ecology & Evolution*. doi: 10.1016/j.tree.2010.02.002.

Parmesan, C., G. Yohe, 2003: A globally coherent fingerprint of climate change impacts in natural systems, *Nature*, **421**, 37-42.

Parmesan, C., 2006: Ecological and evolutionary responses to recent climate change, *Ann. Rev. Ecol. Evol. Syst.*, **37**, 637-669.

Pfeffer, W.T., J.T. Harper, S. O'Neel, 2008: Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* **321**, 1340–1343.

Pounds, J.A., M.P.L. Fogden, J.H. Campbell, 1999: Biological response to climate change on a tropical mountain, *Nature*, **398**, 611-615.

Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marcall, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, B.E. Young, 2006: Widespread amphibian extinctions from epidemic disease driven by global warming, *Nature*, **439**, 161-167.

Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marcall, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still, B.E. Young, 2007: Reply, *Nature*, **447**, E5-E6.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley, A. Watson, 2005: Ocean acidification due to increasing atmospheric carbon dioxide, Policy document 12/05, Volume **ISBN 0 85403 617 2**: London Royal Society.

Reaka-Kudla, M.L., 1997, Global biodiversity of coral reefs: a comparison with rainforests., *in* Reaka-Kudla, M.L., and Wilson, D.E., eds., Biodiversity II: Understanding and Protecting Our Biological Resources, Volume II, Joseph Henry Press, p. 551.

Rignot, E., S.S. Jacobs, 2002: Rapid bottom melting widespread near Antarctic ice sheet grounding lines, *Science*, 296, 2020-2023.

Rignot' E., J.L. Bamber, M.R. van den Broeke, C. Davis, Y. Li, W.J. van de Berg, E. van Meijgaard, 2008: Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, *Nature Geoscience*, **1**, 106 – 110.

Rignot, E., I. Velicogna, M.R. van den Brooke, A. Monaghan, J.T.M. Lenarts, 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res.. Lett.*, **38**, L05503, doi:10.1029/2011GL046583

Rockström, J., M. Falkenmark, L. Karlberg, H. Hoff, S. Rost, D. Gerten, 2009: Future water availability for global food production: The potential of green water for increasing resilience to global change, *Water Resour. Res.*, **45**, W00A12, doi: 10.1029/2007WR006767.

Roemmich, D., J. Gilson, 2009: The 2004-2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program, *Prog. Oceanogr.*, **82**, 81-100.

Rohling, E.J., K. Grant, M. Bolshaw, A.P. Roberts, M. Siddall, Ch. Hemleben, M. Kucera,, 2009: Antarctic temperature and global sea level closely coupled over the past five glacial cycles. *Nat. Geosci.* **2**, 500-504.

Rohling, E.J., K. Grant, C. Hemleben, M. Siddall, B.A. Hoogakker, M. Bolshaw, M. Kucera, 2008: High rates of sea-level rise during the last interglacial period, *Nat. Geosci.*, **1**, 38-42.

Schneider, S.H., and M.D. Mastrandrea, 2005: Probabilistic assessment of "dangerous" climate change and emissions pathways, *Proc. Nat. Acad. Sci.*, **102**, 15728-15735.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, T. Yu, 2008: Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, *Science*, **319**, 1238-1240.

Seidel, D.J., W.J. Randel, 2006: Variability and trends in the global tropopause estimated from radiosonde data, *J. Geophys. Res.*, **111**, D21101

Sherwood, S.C., M. Huber, 2010: An adaptability limit to climate change due to heat stress, *Proc. Natl. Acad. Sci.*, Early Edition, www.pnas.org/cgi/doi/10.1073/pnas.0913352107

Socolow, R., et al., 2011: Direct air capture of CO_2 with chemicals, American Physical Society report, 28 April, http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=244407

Sorensen, L.S., R. Forsberg, 2010: Greenland ice sheet mass loss from GRACE monthly models, in *Gravity, Geoid and Earth Observations*, S.P. Mertikas (ed.), International Association of Geodesy Symposia 135, doi 10.1007/978-3-10634-7_70

Steffen, K., S.V. Nghiem, R. Huff, G. Neumann, 2004: The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophys. Res. Lett.*, **34**, L204210/2004GL020444

Stocker, B.D., K. Strassmann1, F. Joos, 2011: Sensitivity of Holocene atmospheric CO_2 and the modern carbon budget to early human land use: analyses with a process-based model. *Biogeosciences*, **8**, 69–88.

Stehfest, E., L. Bouwman, D.P. van Vuuren, M.G.J. den Elzen, B. Eikhout, P. Kabat, 2009: Climate benefits of changing diet, *Clim. Change*, **95**, 83-102.

Tedesco, M., X. Fettweis, M.R. van den Broeke, R.S.W. van de Wal, C.J.P.P. Smeets, W.J. van de berg, M.C. Serreze, J.E. Box, 2011: The role of albedo and accumulation in the 2010 melting record in Greenland, *Environ. Res. Lett.*, **6**, 014005.

Tilman, D., J. Hill, C. Lehman, 2006: Carbon-negative biofuels from low-input high-diversity grassland biomass, *Science*, **314**, 1598-1600.

Turner J. et al. (eds.), 2009: *Antarctic Climate change and the environment: a contribution to the International Polar year 2007-2008*, Scientific Committee on Antarctic Research, Scott Polar Research Institute, Lensfield Road, Cambridge UK.

United Nations Environment Programme (UNEP), 2010: Assessing the Enviromental Impacts of Consumption and Production: Priority Products and Materials, A Report of the Working Group on the Environmental Impacts of Products and Materials to the International Panel for Sustainable Resource Management, Hertwich, E. E. van der Voet, S. Suh, A. Tukker, M. Huijbregts, P. Kazmierczyk, M. Lenzen, J. McNeely, Y. Moriguchi.

Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophys. Res. Lett.*, **36**, L19503, doi:10.1029/2009GL040222.

Vermeer, M., and S. Rahmstorf, 2009: Global sea level linked to global temperature, *Proc. Natl. Acad. Sci.*, **106**, 21527-21532.

Veron, J.E.N., O.Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R.C. Sheppard, M. Spalding, M.G. Stafford-Smith, A.D. Rogers, 2009: The coral reef crisis: the critical importance of <350 ppm CO_2, *Marine Poll. Bull.*, **58**, 1428-1436.

von Schuckmann, K., P.-Y. Le Traon, 2011: How well can we derive global ocean indicators from Argo data?

Walter, K.M., S.A. Zimov, J.P. Chanton, D. Verbyla, F.S. Chapin, III, 2006: Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming, *Nature*, **443**, 71-75.

Westbrook, G.K., Thatcher, K.E., Rohling, E.J., Piotrowski, A.M., Pälike, H., Osborne, A.H., Nisbet, E.G., Minshull, T.A., Lanoisellé, M., James, R.H., Hühnerbach, V., Green, D., Fisher, R.E., Crocker, A.J., Chabert, A., Bolton, C., Beszczynska-Möller, A., Berndt, C., and Aquilina, A., 2009: Escape of methane gas from the seabed along the West Spitsbergen continental margin. *Geophys. Res. Lett.*, **36**, L15608, doi:10.1029/2009GL 039191.

Westerling, A., H. Hidalgo, D. Cayan, T. Swetnam, 2006: Warming and earlier spring increases western U.S. forest wildfire activity, *Science*, **313**, 940-943.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups, 2001: Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, **292**, 686-693.

Zeebe, R.E., J.C. Zachos, G.R. Dickens, 2009: Carbon dioxide forcing alone insufficient to explain Paleocene-Ereocene Thermal Maximum warming, *Nature Geoscience*, **2**, 576-580.

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Latest Information

Prospect of limiting the global increase in temperature to 2ºC is getting bleaker

30 May 2011

CO2 emissions reach a record high in 2010; 80% of projected 2020 emissions from the power sector are already locked in

Energy-related carbon-dioxide (CO2) emissions in 2010 were the highest in history, according to the latest estimates by the International Energy Agency (IEA).

After a dip in 2009 caused by the global financial crisis, emissions are estimated to have climbed to a record 30.6 Gigatonnes (Gt), a 5% jump from the previous record year in 2008, when levels reached 29.3 Gt.

In addition, the IEA has estimated that 80% of projected emissions from the power sector in 2020 are already locked in, as they will come from power plants that are currently in place or under construction today.

"This significant increase in CO2 emissions and the locking in of future emissions due to infrastructure investments represent a serious setback to our hopes of limiting the global rise in temperature to no more than 2ºC," said Dr Fatih Birol, Chief Economist at the IEA who oversees the annual *World Energy Outlook*, the Agency's flagship publication.

Global leaders agreed a target of limiting temperature increase to 2°C at the UN climate change talks in Cancun in 2010. For this goal to be achieved, the long-term concentration of greenhouse gases in the atmosphere must be limited to around 450 parts per million of CO2-equivalent, only a 5% increase compared to an estimated 430 parts per million in 2000.

The IEA's 2010 *World Energy Outlook* set out the 450 Scenario, an energy pathway consistent with achieving this goal, based on the emissions targets countries have agreed to reach by 2020. For this pathway to be achieved, global energy-related emissions in 2020 must not be greater than 32 Gt.This means that over the next ten years, emissions must rise less in total than they did between 2009 and 2010.

"Our latest estimates are another wake-up call," said Dr Birol. "The world has edged incredibly close to the level of emissions that should not be reached until 2020 if the 2ºC target is to be attained. Given the shrinking room for manœuvre in 2020, unless bold and decisive decisions are made very soon, it will be extremely challenging to succeed in achieving this global goal agreed in Cancun."

In terms of fuels, 44% of the estimated CO2 emissions in 2010 came from coal, 36% from oil, and 20% from natural gas.

The challenge of improving and maintaining quality of life for people in all countries while limiting CO2 emissions has never been greater. While the IEA estimates that 40% of global emissions came from OECD countries in 2010, these countries only accounted for 25% of emissions growth compared to 2009. Non-OECD countries – led by China and India – saw much stronger increases in emissions as their economic growth accelerated.

However, on a per capita basis, OECD countries collectively emitted 10 tonnes, compared with 5.8 tonnes for China, and 1.5 tonnes in India.

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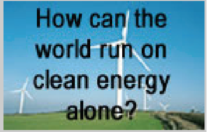

GLOSSARY and ACRONYMS

theguardian

Worst ever carbon emissions leave climate on the brink

Exclusive: Record rise, despite recession, means 2C target almost out of reach

Fiona Harvey, Environment correspondent
guardian.co.uk, Sunday 29 May 2011 17.00 EDT

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Economic recession has failed to curb rising emissions, undermining hope of keeping global warming to safe levels Photograph: Dave Reede/All Canada Photos/Corbis

Greenhouse gas emissions increased by a record amount last year, to the highest carbon output in history, putting hopes of holding global warming to safe levels all but out of reach, according to unpublished estimates from the International Energy Agency.

The shock rise means the goal of preventing a temperature rise of more than 2 degrees Celsius – which scientists say is the threshold for potentially "dangerous climate change" – is likely to be just "a nice Utopia", according to Fatih Birol, chief economist of the IEA. It also shows the most serious global recession for 80 years has had only a minimal effect on emissions, contrary to some predictions.

Last year, a record 30.6 gigatonnes of carbon dioxide poured into the atmosphere, mainly from burning fossil fuel – a rise of 1.6Gt on 2009, according to estimates from the IEA regarded as the gold standard for emissions data.

"I am very worried. This is the worst news on emissions," Birol told the Guardian. "It is becoming extremely challenging to remain below 2 degrees. The prospect is getting bleaker. That is what the numbers say."

Professor Lord Stern of the London School of Economics, the author of the influential Stern Report into the economics of climate change for the Treasury in 2006, warned that if the pattern continued, the results would be dire. "These figures indicate that [emissions] are now close to being back on a 'business as usual' path. According to the [Intergovernmental Panel on Climate Change's] projections, such a path ... would mean around a 50% chance of a rise in global average temperature of more than 4C by 2100," he said.

"Such warming would disrupt the lives and livelihoods of hundreds of millions of people across the planet, leading to widespread mass migration and conflict. That is a risk any sane person would seek to drastically reduce."

Birol said disaster could yet be averted, if governments heed the warning. "If we have bold, decisive and urgent action, very soon, we still have a chance of succeeding," he said.

The IEA has calculated that if the world is to escape the most damaging effects of global warming, annual energy-related emissions should be no more than 32Gt by 2020. If this year's emissions rise by as much as they did in 2010, that limit will be exceeded nine years ahead of schedule, making it all but impossible to hold warming to a manageable degree.

Emissions from energy fell slightly between 2008 and 2009, from 29.3Gt to 29Gt, due to the financial crisis. A small rise was predicted for 2010 as economies recovered, but the scale of the increase has shocked the IEA. "I was expecting a rebound, but not such a strong one," said Birol, who is widely regarded as one of the world's foremost experts on energy.

John Sauven, the executive director of Greenpeace UK, said time was running out. "This news should shock the world. Yet even now politicians in each of the great powers are eyeing up extraordinary and risky ways to extract the world's last remaining reserves of fossil fuels – even from under the melting ice of the Arctic. You don't put out a fire with gasoline. It will now be up to us to stop them."

Most of the rise – about three-quarters – has come from developing countries, as rapidly emerging economies have weathered the financial crisis and the recession that has gripped most of the developed world.

But he added that, while the emissions data was bad enough news, there were other factors that made it even less likely that the world would meet its greenhouse gas targets.

• About 80% of the power stations likely to be in use in 2020 are either already built or under construction, the IEA found. Most of these are fossil fuel power stations unlikely to be taken out of service early, so they will continue to pour out carbon – possibly into the mid-century. The emissions from these stations amount to about 11.2Gt, out of a total of 13.7Gt from the electricity sector. These "locked-in" emissions mean savings must be found elsewhere.

"It means the room for manoeuvre is shrinking," warned Birol.

• Another factor that suggests emissions will continue their climb is the crisis in the nuclear power industry. Following the tsunami damage at Fukushima, Japan and Germany have called a halt to their reactor programmes, and other countries are reconsidering nuclear power.

"People may not like nuclear, but it is one of the major technologies for generating electricity without carbon dioxide," said Birol. The gap left by scaling back the world's nuclear ambitions is unlikely to be filled entirely by renewable energy, meaning an increased reliance on fossil fuels.

• Added to that, the United Nations-led negotiations on a new global treaty on climate change have stalled. "The significance of climate change in international policy debates is much less pronounced than it was a few years ago," said Birol.

He urged governments to take action urgently. "This should be a wake-up call. A chance [of staying below 2 degrees] would be if we had a legally binding international agreement or major moves on clean energy technologies, energy efficiency and other technologies."

Governments are to meet next week in Bonn for the next round of the UN talks, but little progress is expected.

Sir David King, former chief scientific adviser to the UK government, said the global emissions figures showed that the link between rising GDP and rising emissions had not been broken. "The only people who will be surprised by this are people who have not been reading the situation properly," he said.

Forthcoming research led by Sir David will show the west has only managed to reduce emissions by relying on imports from countries such as China.

Another telling message from the IEA's estimates is the relatively small effect that the recession – the worst since the 1930s – had on emissions. Initially, the agency had hoped the resulting reduction in emissions could be maintained, helping to give the world a "breathing space" and set countries on a low-carbon path. The new estimates suggest that opportunity may have been missed.

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LETTERS

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Emission pathways consistent with a 2 °C global temperature limit

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In recent years, international climate policy has increasingly focused on limiting temperature rise, as opposed to achieving greenhouse-gas-concentration-related objectives. The agreements reached at the United Nations Framework Convention on Climate Change conference in Cancun in 2010 recognize that countries should take urgent action to limit the increase in global average temperature to less than 2 °C relative to pre-industrial levels[1]. If this is to be achieved, policymakers need robust information about the amounts of future greenhouse-gas emissions that are consistent with such temperature limits. This, in turn, requires an understanding of both the technical and economic implications of reducing emissions and the processes that link emissions to temperature. Here we consider both of these aspects by reanalysing a large set of published emission scenarios from integrated assessment models in a risk-based climate modelling framework. We find that in the set of scenarios with a 'likely' (greater than 66%) chance of staying below 2 °C, emissions peak between 2010 and 2020 and fall to a median level of 44 Gt of CO_2 equivalent in 2020 (compared with estimated median emissions across the scenario set of 48 Gt of CO_2 equivalent in 2010). Our analysis confirms that if the mechanisms needed to enable an early peak in global emissions followed by steep reductions are not put in place, there is a significant risk that the 2 °C target will not be achieved.

Cumulative emissions of long-lived greenhouse gases (GHGs) approximately define the temperature response of the climate system at timescales of centuries to millennia[2–4] because a significant fraction of CO_2 emissions, the dominant anthropogenic GHG, is removed very slowly from the atmosphere[5,6]. The temperature response will therefore continue, even when global emissions return to zero, or when concentrations are stabilized[6,7]. Cumulative emissions provide very little information on the technical feasibility and cost implications of following a particular 'emissions pathway', information that is needed for policymakers who are deciding now on emissions goals for the coming decades. Path-dependent assessments, such as the United Nations Environment Programme's *The Emissions Gap Report*[8], are therefore highly policy-relevant. This work extends the pathway analysis of that report (see Supplementary Information).

The Cancun Agreements refer to holding global mean temperature increase below 2 °C. Therefore, we do not allow a temperature overshoot in this study, although concentrations may temporarily overshoot a level that in equilibrium would lead to an exceedance of the temperature limit. There is increasing evidence from recent studies[7,9,10] that a decline of temperature might be unlikely on timescales relevant to human societies in the absence of strongly negative emissions. The slow ocean mixing that delays warming due to anthropogenic radiative forcing at present would also limit the amount of cooling for many decades to centuries[9–11].

Scenarios developed by integrated assessment models (IAMs) represent analyses of how society could evolve given assumed constraints of feasibility. In general, 'feasibility' encompasses technological, economic, political and social factors. IAMs account for some of these factors by assuming a set of mitigation technologies, constraining their potential and the rate at which these technologies can be introduced, amongst other things. Examples of such constraints include assumptions about the maximum feasible technology penetration rates, maximum cost, constraints on the use of renewables based on their intermittency and a maximum speed of specific system changes. Societal and political factors have typically received only limited attention: for instance, nearly all mitigation scenarios assume full participation of all regions in global mitigation efforts.

Scenarios from different IAMs consistent with different policy targets have been compared in previous studies[12,13]. Most of these focus on optimal (least-cost) pathways to achieve GHG concentration stabilization. Only recently, modelling comparison studies[12] have started focusing on second-best scenarios, which assume limited/delayed international participation of countries and/or reduced technology availability implying delayed emission reductions. The range in IAM outcomes for similar targets is broad, and reflects prevailing uncertainties captured by different methods and underlying assumptions[12,14,15]. Considering the combined impact on mitigation targets of both climate and technical and economic constraints and uncertainties has thus far received little attention.

Here we present a scenario reanalysis focusing on temperature targets. We use the carbon-cycle and climate model MAGICC6 (ref. 16), constrained by historical observations, to obtain estimates

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Table 1 | Overview of pathway characteristics of emission pathways that limit global average temperature increase to below 2 °C relative to pre-industrial levels during the twenty-first century.

	Number of pathways	Peaking decade* (2000 + year)	Total GHG emissions in 2020 (Gt CO$_2$e)	Average industrial CO$_2$ post-peak reduction rates† (percentage of 2000 emissions per year)
'Very likely' chance (>90%) of staying below 2 °C during twenty-first century‡				
Without global net negative industrial CO$_2$ emissions	0	—	—	—
With global net negative industrial CO$_2$ emissions	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
All pathways	3	10(—[10]—)15	41(—[43]—)44	3.2(—[3.3]—)3.3
'Likely' chance (>66%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO$_2$ emissions	14	10(10[10]10)20	21(26[42]45)48	0(1.0[2.3]3.3)3.6
With global net negative industrial CO$_2$ emissions	12	10(10[10]15)15	41(41[44]46)48	1.5(1.7[3.0]3.5)3.8
All pathways	26	10(10[10]15)20	21(31[44]46)48	0(1.5[2.7]3.4)3.8
'At least fifty-fifty' chance (>50%) of staying below 2 °C during twenty-first century				
Without global net negative industrial CO$_2$ emissions	20	10(10[10]15)20	21(28[44]47)48	0(1.3[2.4]3.1)3.6
With global net negative industrial CO$_2$ emissions	19	10(10[10]20)30	41(42[45]48)50	1.2(1.7[3.0]3.6)5.9
All pathways	39	10(10[10]15)30	21(38[44]47)50	0(1.5[2.7]3.5)5.9

Data are provided for three probability options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) or 'at least fifty-fifty' (greater than 50%) chance.
Format: minimum(15%quantile[median]85%quantile)maximum. *The year given is an indication of the middle of the decade in which the peaking occurs in the scenarios. †Being relative to constant 2000 emissions, these reduction rates differ from exponential reduction rates (see Methods). ‡Owing to the low number of pathways, only minimum, median and maximum values are given for the 'very likely' option.

of future atmospheric GHG concentrations and transient temperatures (see Methods). This approach eliminates the uncertainty due to differing climate representations within the individual IAM studies[17]. We compiled a set of 193 emissions pathways from the literature (see Methods and Supplementary Information). Of this set, roughly one third represents baseline scenarios (that is, possible developments in the absence of climate policy intervention) and the remainder represents emission mitigation scenarios.

Owing to the uncertainty in our quantitative understanding of the climate system and carbon-cycle response to emissions, the projected results can be defined in terms of a probability of staying below a given temperature target. The choice of which target and with which probability it is to be reached can be informed by science but is fundamentally a political question depending on risk and value judgements. Policymakers in Cancun did not specify such a probability, neither quantitatively nor qualitatively. To cover a range of possible choices, we evaluate pathways for three options: a 'very likely' (greater than 90%), a 'likely' (greater than 66%) and an 'at least fifty-fifty' (greater than 50%) probability throughout the twenty-first century (see Methods). Pathways with a 'very likely' 2 °C probability are a subset of pathways with a 'likely' probability, which are in turn a subset of the pathways with an 'at least fifty-fifty' probability of limiting temperature increase to below 2 °C.

In our set, none of the baseline scenarios is able to limit the global temperature increase to below 2 °C. On the other hand, 3, 26 and 39 pathways have a 'very likely', 'likely' and 'at least fifty-fifty' chance to limit global temperature change to below 2 °C during the twenty-first century, respectively (Table 1, Fig. 1). In all pathways, emissions peak in the short term and decline later to stay below 2 °C. We start from estimated median 2010 emissions across our harmonized set (see Methods) of about 48 Gt of CO$_2$ equivalent (CO$_2$e). For pathways with a 'likely' chance of staying below 2 °C we find the following characteristics: median 2020 emissions are 44 Gt CO$_2$e, with a 15–85% quantile range of 31–46 Gt CO$_2$e. Most of these pathways (at least 85% of all cases) peak global emissions before 2020. After the peak, emissions decline. Still for the same pathways, median annual post-peak CO$_2$ reduction rates (see Methods) are around 2.7% (range 1.5–3.4%), and global total GHG emissions in 2050 show a median reduction of 45% (range 35–55%) below 1990 levels of 36.6 Gt CO$_2$e.

Besides a 2 °C limit, the Cancun Agreements furthermore include a commitment to review and consider strengthening the long-term goal, particularly in relation to a 1.5 °C limit. No ensemble member (including even the most stringent mitigation scenarios) limits warming to less than 1.5 °C throughout the entire century for any of the probability options. However, some scenarios in our set bring warming back below 1.5 °C by 2100: a first scenario (from 'POLES' in ref. 13) does so with a probability of about 50%, and a second scenario (from 'MERGE' in ref. 13) with a 'likely' chance (>66%).

An important difference[14] is noted between pathways that do not show global CO$_2$ emissions from energy and industry to become negative compared with those that do. Net negative emissions from the energy and industry sector may be possible through the application of a combination of capture and geological storage[18] of CO$_2$ (CCS) and bio-energy[19] (BECCS). In the pathways with no negative emissions, the median 2020 values for the 'likely' option are 2 Gt CO$_2$e lower at 42 Gt CO$_2$e (Table 1). Pathways that have net negative emissions (28 in total) feature higher rates of post-peak emission reductions while not exhibiting significant differences for the peak period. An in-depth analysis of the influence of BECCS on the

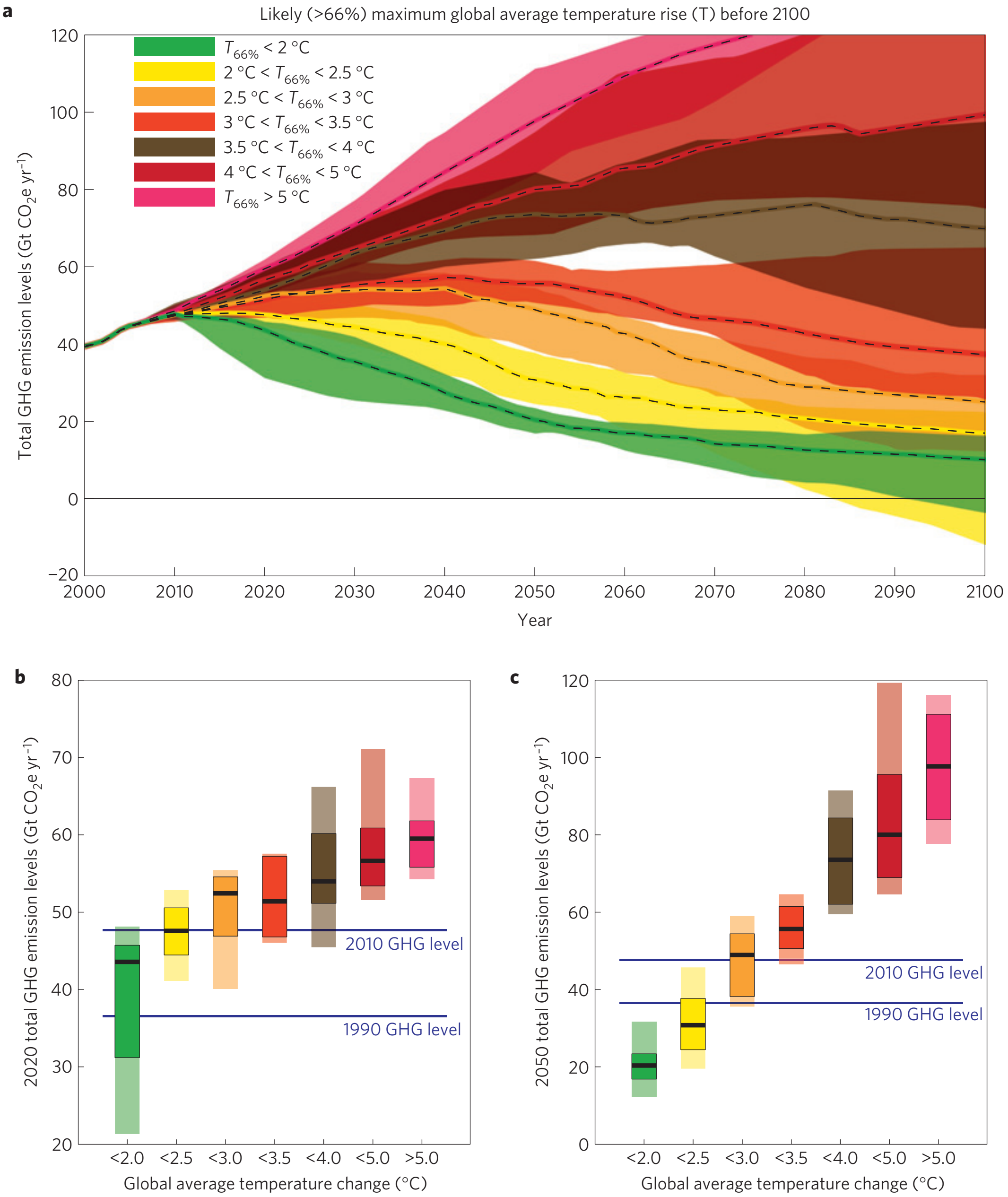

Figure 1 | Emission ranges of published IAM scenarios, colour coded as a function of the likely (greater than 66% probability) avoided global average temperature increase. a, 15–85% quantile ranges over time of global total GHG emissions of pathway sets consistent with a given temperature limit during the twenty-first century. Colour coding defines the respective temperature limit per pathway set. Black dashed lines show the median for each respective pathway set. **b**,**c**, 2020 (**b**) and 2050 (**c**) time slices of global total emissions consistent with a temperature limit during the twenty-first century. Shaded areas represent the minimum–maximum ranges; the coloured bounded rectangles the 15–85% quantile ranges and the thick black horizontal lines the median values for each temperature level, respectively. Horizontal blue lines represent median 1990 and 2010 emissions. Ranges for the other probability options (>90% and >50%) and time slices are given in Supplementary Figs S1–S5.

global peak of emissions is not possible with the available scenarios and would require specifically designed experiments that address this question.

Weakening the stringency of the 2 °C limit and accepting a lower chance of success (at least 50% instead of 66% probability), slightly shifts the 15–85% quantile range of scenarios in 2020 to 38–47 Gt CO_2e (the median remains at 44 Gt CO_2e). The peaking period remains during the present decade (precision-limited by the decadal-resolution data from the IAMs) and the median post-peak emission reduction rates are virtually the same as for the 'likely' case in more than 85% of the cases. Finally, the three pathways with a 'very likely' (greater than 90%) chance of success show a peak during this decade, 2020 emissions not exceeding 44 Gt CO_2e and post-peak reduction rates that are higher than the medians from the other cases. These three pathways have negative emissions.

Atmospheric CO_2 and CO_2e concentrations in 2100 of the pathways 'likely' consistent with 2 °C (Table 2) are around 425 ppm CO_2 (range 415–460) and 465 ppm CO_2e (range 435–475), respectively. Pathways consistent with 2 °C with a 'likely' or 'fifty-fifty' chance have peaked CO_2 concentrations during the twenty-first century (see Methods) in about 30 and 40% of the cases, respectively. CO_2-equivalent concentrations peaked in about 40% of the cases for both probability options. If scenarios do not peak concentrations, they stabilize during the twenty-first century. A

Table 2 | Overview of 2020 emissions, 2100 atmospheric CO_2 and total GHG concentrations of pathways that hold global average temperature increase below a specific temperature limit.

	Number of pathways	Total GHG emissions in 2020 (Gt CO_2e)	Atmospheric concentrations in 2100	
			CO_2 (ppm CO_2)	Total GHG (ppm CO_2e)
Emission pathways with a 'likely' (>66%) probability to limit temperature increase to below:				
1.5 °C	Insufficient data	Insufficient data	Insufficient data	Insufficient data
2 °C	26	21(31[44]46)48	375(412[423]457)468	400(436[463]476)486
2.5 °C	46	41(44[48]51)53	376(416[490]506)542	422(472[526]554)557
3 °C	45	40(47[52]55)55	477(501[542]574)616	554(561[609]636)645
3.5 °C	22	46(47[51]57)58	540(562[602]659)709	647(649[669]751)775
4 °C	18	45(51[54]60)66	649(661[726]811)890	759(782[833]869)939
5 °C	19	52(53[57]61)71	678(746[817]958)1104	851(922[993]1101)1134
Above 5 °C	10	54(56[59]62)67	888(905[975]1046)1049	1116(1153[1207]1318)1482

Data are provided for pathways that hold temperature increase to below a given temperature limit during the twenty-first century with a 'likely' (greater than 66%) chance. Results are given for temperature bins defined by the temperature limit and its preceding limit. For example, the '3 °C' row shows characteristics for emission pathways that limit warming below 3 °C with a 'likely' chance, but above 2.5 °C. See also Fig. 1 and Supplementary Fig. S6. Data for the other probability options are presented in Supplementary Figs S3, S5, S7 and S8, and in Supplementary Tables S1 and S2. Format: minimum(15%quantile[median]85%quantile)maximum.

decline afterward is not excluded. All 'very likely' chance pathways show a peak and decline in CO_2e concentrations of GHGs. More than 70% of the 'likely' chance scenarios assume global net negative CO_2 emissions from industry and energy to achieve such peaking. Furthermore, all scenarios that would comply with a 'fifty-fifty' chance and are outside the 'likely' subset include such negative emissions.

There are a number of caveats in interpreting our results. First, by describing the 15–85% quantiles over time, the intertemporal relationship between different emission paths is masked. Although the median path can be considered as a representative evolution of emissions for 'likely' pathways, the 15 and 85% quantile paths cannot. Emissions near the 85% quantile path in the first half of the century are followed by emissions near the 15% quantile path in the second half and vice versa (see Supplementary Fig. S9).

Second, besides results from the 15–85% quantiles, results outside this range also give insights. They provide information about potential future worlds in the tails of the distributions. A few pathways[20,21] (three in total) suggest that emissions could decline globally to about 30%–40% below 1990 levels by 2020. On the other side of the spectrum, one pathway[22] peaks at 48 Gt CO_2e in 2020 owing to delayed participation and still stays below 2 °C with a 'likely' chance. Another scenario[23] shows steep emission reduction rates of 5.9% after peaking at 50 Gt CO_2e around 2030, while still having an 'at least fifty-fifty' probability to stay below 2 °C. CCS contributes massively to the mitigation portfolio in this scenario, capturing up to almost double the present global CO_2 emissions per year by 2065. For most scenarios in our set, a peak in world emissions in 2030 would be more consistent with a 'likely' chance to stay below 3 °C instead of 2 °C.

A third issue is that for many scenarios the potential for net negative global CO_2 emissions from energy and industry is a crucial factor[14]. The potential of BECCS (refs 18,19) is already included in many IAMs. However, as for other advanced technologies, BECCS has not been demonstrated on a significant scale in the real world. Concerns exist with respect to CO_2 storage potential[18] as well as with respect to competition of large-scale bio-energy systems[24] with food production, biodiversity and ecosystem services. Other negative emission technologies, such as direct air capture of CO_2, are not explicitly included in most models at present.

Fourth, our set of pathways represents scenarios that are considered feasible by IAMs. The extent to which the realization of such scenarios is plausible in the real world goes beyond techno-economic and physical constraints represented by the IAMs, and also depends highly on factors such as political circumstances and public acceptance. Our analysis of the scenario space relies on the soundness and quality of the underlying IAM studies, and does not imply any independent assessment of the feasibility of the above-mentioned factors. We also acknowledge that only a limited set of scenarios were run for the low-temperature targets discussed here, and that scenario details are often not reported when IAMs find these targets infeasible[12]. Our findings, in particular with respect to low-emissions scenarios, therefore should be interpreted as an indication of the stringency of mitigation that would need to occur to keep specific targets within reach. They should, however, not be interpreted as a comprehensive assessment of the feasibility of the required mitigation action.

Related to this, it should be noted that most of the IAM scenarios used in this study tried to find cost-effective pathways for long-term climate targets. Scenarios that would look at economically less attractive[12,25] options could feature higher and/or later peaks with steeper declines afterwards. The ensemble we used was not designed to systematically sample all possible options, but represents an 'ensemble of opportunity'[26]. Clearly, IAMs do not set 'hard laws' on the consideration of whether achieving a particular scenario is possible. They are based on modellers' assumptions about technological and economic constraints, which are subject to change. Finally, a better understanding of socio-economic impacts of regional climate change and their inclusion in IAMs might have a large influence on the medium- and long-term cost efficiency of emission pathways. As understanding evolves, it will be necessary to update assessments such as the one presented here and develop studies that address this question directly. Furthermore, the treatment of political feasibility, including the will of national governments to implement transitions to low-carbon economies, remains a big unknown.

This analysis implies that the range of published IAM scenarios in line with the goal of staying below 2 °C with a 'likely' chance would peak during this decade and have annual 2020 emissions of around 44 Gt CO_2e (range of 31–46 Gt CO_2e). Our scenario set includes hardly any scenarios that take delayed participation of regions in international carbon markets into account. However, not assuming this at present seems optimistic given the reluctance of some major emitters to join such a system. Following higher 2020 emissions and later peaking as a result of weaker early mitigation action would significantly reduce the chances of staying below 2 °C. Without a firm commitment to put in place the mechanisms to enable an early global emissions peak followed by steep reductions thereafter, there are significant risks that the 2 °C target, endorsed by so many nations, is already slipping out of reach.

Methods

We reanalysed an ensemble of 193 emission pathways from IAMs. This ensemble includes reference and mitigation pathways from model intercomparison studies (refs 12,13,27, among others, see Supplementary Table S3 for an overview of all references), as well as from other stabilization and non-intervention scenarios. All members are treated equally likely in the set.

Historical emission estimates come with a typical uncertainty range of 20–30% (ref. 28). Therefore, for each member of the ensemble, the historical emissions up to 2005 are harmonized to the historical multi-gas emission inventory developed in the framework of the representative concentration pathways[29,30] (RCPs). Emissions of each ensemble member are adjusted with a tapered scaling factor that returns to unity in 2050. This approach prevents possible amplification of negative emissions in the second half of the century[28]. When future emissions of a particular gas are missing, the multi-gas characteristics of the RCP3-PD scenario[31] are assumed, including sulphate aerosols, organic carbon, black carbon and atmospheric ozone precursors. The RCP3-PD scenario models strong environmental and climate policies. This choice is therefore consistent with our set-up to primarily analyse mitigation pathways that reduce emissions to be consistent with international temperature limits. Ozone-depleting substances controlled by the Montreal Protocol are assumed to follow a gradual phase-out during the twenty-first century.

After harmonization, six IAM pathways that show a decline or stabilization in historical emissions from 2005 to 2010 are excluded from the final ensemble. We also excluded one scenario for which insufficient detailed information about the underlying assumptions was available (as in ref. 12).

Each member of the harmonized multi-gas emission pathway ensemble is analysed probabilistically with the reduced-complexity climate system and carbon-cycle model MAGICC (ref. 16), version 6. MAGICC has been calibrated and shown to be able to reliably determine the atmospheric burden of CO_2 concentrations following high-complexity carbon-cycle models[16,32]. It is also able to project global average near-surface warming in line with estimates made by complex atmosphere–ocean general circulation models for a range of forcing scenarios, as assessed in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change[33] (IPCC). Here it has been set up with historical constraints for observed hemispheric land/ocean temperatures and ocean heat-uptake (see Supplementary Information), emulating the C^4MIP carbon-cycle models[34] and with the same climate-sensitivity probability distribution as the 'illustrative default case' in ref. 2 that closely reflects IPCC estimates[33]. Herewith, the uncertainties in climate sensitivity, ocean heat-uptake and the response of the carbon-cycle to a given emissions pathway are taken into account. For each pathway, a 600-member ensemble is calculated to determine its resulting time-evolving temperature probability distribution.

We carried out a sensitivity analysis on the climate-sensitivity choice and on the assumptions regarding anthropogenic aerosols, soot and organic carbon, and found that our results are robust under those sensitivity cases (see Supplementary Information and Supplementary Table S4).

The range of results from this reanalysis of IAM pathways always refers to the median, and the 15–85% quantile range (as an approximation of the one-standard-deviation range around the mean). This provides a point of comparison with the approach in the IPCC AR4 (ref. 15). For completeness, also the minimum–maximum range is given. Total GHG emissions refer to emissions included in the Kyoto basket of GHGs, which contains carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (SF_6) (see Supplementary Information). 'Negative CO_2 emissions' refer to net global emissions from energy and industry, excluding land-use emissions. The 'post-peak' reduction rates are calculated over the period between 10 and 30 years after the peak. To allow comparison and ensure consistency with the IPCC AR4, reduction rates are computed for global CO_2 emissions from energy and industry, and relative to 2000 levels. If fewer than 10 pathways were available in a particular subset, only median, minimum and maximum values are provided. If a pathway yields atmospheric CO_2 concentrations in 2100 that are at least 5% lower than the maximum concentration during the twenty-first century, this pathway is defined to have peaked concentrations during this century. The same approach applies to the total GHG (CO_2e) concentrations.

Temperatures projections 'relative to pre-industrial' are calculated relative to the 1850–1875 base period.

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References

1. United Nations Framework Convention on Climate Change *Report of the Conference of the Parties on its Sixteenth Session, held in Cancun from 29 November to 10 December* 2010 (FCCC/CP/2010/7/Add.1, United Nations, 2011); available at http://unfcc.int/resource/docs/2010/cop16/eng/07a01.pdf.
2. Meinshausen, M. *et al*. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
3. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459,** 829–832 (2009).
4. Allen, M. R. *et al*. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
5. Archer, D. *et al*. Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* **37,** 117–134 (2009).
6. Plattner, G. K. *et al*. Long-term climate commitments projected with climate & carbon cycle models. *J. Clim.* **21,** 2721–2751 (2008).
7. Lowe, J. A. *et al*. How difficult is it to recover from dangerous levels of global warming? *Environ. Res. Lett.* **4,** 014012 (2009).
8. United Nations Environment Programme *The Emissions Gap Report — Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2 °C or 1.5 °C?* (UNEP, 2010).
9. Held, I. M. *et al*. Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. *J. Clim.* **23,** 2418–2427 (2010).
10. Solomon, S. *et al*. Persistence of climate changes due to a range of greenhouse gases. *Proc. Natl Acad. Sci. USA* **107,** 18354–18359 (2010).
11. Schewe, J., Levermann, A. & Meinshausen, M. Climate change under a scenario near 1.5 °C of global warming: Monsoon intensification, ocean warming and steric sea level rise. *Earth Syst. Dynam.* **2,** 25–35 (2011).
12. Clarke, L. *et al*. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.* **31,** S64–S81 (2009).
13. Edenhofer, O. *et al*. The economics of low stabilization: Model comparison of mitigation strategies and costs. *Energy J.* **31,** 11–48 (2010).
14. van Vuuren, D. & Riahi, K. The relationship between short-term emissions and long-term concentration targets. *Climatic Change* **104,** 793–801 (2011).
15. IPCC *Climate Change 2007: Mitigation of Climate Change* (eds Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., & Meyer, L. A.) (Cambridge Univ. Press, 2007).
16. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 — Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
17. van Vuuren, D. *et al*. How well do integrated assessment models simulate climate change? *Climatic Change* **104,** 255–285 (2011).
18. IPCC *Special Report on Carbon Dioxide Capture and Storage* (eds Metz, B., Davidson, O., de Coninck, H., Loos, M. & Meyer, L.) (Cambridge Univ. Press, 2005).
19. Azar, C. *et al*. The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* **100,** 195–202 (2010).
20. Barker, T. & Scrieciu, S. Modeling low climate stabilization with E3MG: Towards a 'new economics' approach to simulating energy–environment–economy system dynamics. *Energy J.* **31,** 137–164 (2010).
21. Loulou, R., Labriet, M. & Kanudia, A. Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. *Energy Econ.* **31,** S131–S143 (2009).
22. Krey, V. & Riahi, K. Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—Greenhouse gas mitigation scenarios for the 21st century. *Energy Econ.* **31,** S94–S106 (2009).
23. Calvin, K. *et al*. 2.6: Limiting climate change to 450 ppm CO_2 equivalent in the 21st century. *Energy Econ.* **31,** S107–S120 (2009).
24. Wise, M. A. *et al*. Implications of limiting CO_2 concentrations for land use and energy. *Science* **324,** 1183–1186 (2009).
25. O'Neill, B. C., Riahi, K. & Keppo, I. Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proc. Natl Acad. Sci. USA* **107,** 1011–1016 (2009).
26. Tebaldi, C. & Knutti, R. The use of the multi-model ensemble in probabilistic climate projections. *Phil. Trans. R. Soc. A* **365,** 2053–2075 (2007).
27. Luderer, G. *et al*. The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Climatic Change* http://dx.doi.org/10.1007/s10584-011-0105-x (2011).
28. Rogelj, J., Hare, W., Chen, C. & Meinshausen, M. Discrepancies in historical emissions point to a wider 2020 gap between 2 °C benchmarks and aggregated national mitigation pledges. *Environ. Res. Lett.* **6,** 1–9 (2011).
29. Meinshausen, M. *et al*. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* http://dx.doi.org/10.1007/s10584-011-0156-z (2011).
30. Granier, C. *et al*. Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period. *Climatic Change* http://dx.doi.org/10.1007/s10584-011-0154-1 (2011).
31. van Vuuren, D. *et al*. RCP2.6: Exploring the possibility to keep global mean temperature increase below 2 °C. *Climatic Change* http://dx.doi.org/10.1007/s10584-011-0152-3 (2011).

32. Meinshausen, M., Wigley, T. M. L. & Raper, S. C. B. Emulating atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 — Part 2: Applications. *Atmos. Chem. Phys.* **11,** 1457–1471 (2011).
33. IPCC *Climate Change 2007: The Physical Science Basis (eds Solomon, S. et al.)* (Cambridge Univ. Press, 2007).
34. Friedlingstein, P. *et al.* Climate–carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *J. Clim.* **19,** 3337–3353 (2006).

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Author contributions

J.R., W.H., J.L., K.R., B.M., M.M. and D.P.v.V. designed the research. M.M. developed the climate model set-up. J.R. carried out the research. All authors discussed the results and contributed to writing the paper.

Additional information

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