Paleoclimate Implications for Human-Made Climate Change

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ABSTRACT

Milankovic climate oscillations help define climate sensitivity and assess potential human-made climate effects. We conclude that Earth in the warmest interglacial periods was less than 1°C warmer than in the Holocene and that goals of limiting human-made warming to 2°C and CO_2 to 450 ppm are prescriptions for disaster. Polar warmth in prior interglacials and the Pliocene does not imply that a significant cushion remains between today's climate and dangerous warming, rather that Earth today is poised to experience strong amplifying polar feedbacks in response to moderate additional warming. Deglaciation, disintegration of ice sheets, is nonlinear, spurred by amplifying feedbacks. If warming reaches a level that forces deglaciation, the rate of sea level rise will depend on the doubling time for ice sheet mass loss. Gravity satellite data, although too brief to be conclusive, are consistent with a doubling time of 10 years or less, implying the possibility of multi-meter sea level rise this century. The emerging shift to accelerating ice sheet mass loss supports our conclusion that Earth's temperature has returned to at least the Holocene maximum. Rapid reduction of fossil fuel emissions is required for humanity to succeed in preserving a planet resembling the one on which civilization developed.

1. Introduction

Climate change is likely to be the predominant scientific, economic, political and moral issue of the 21st century. The fate of humanity and nature may depend upon early recognition and understanding of human-made effects on Earth's climate (Hansen, 2009).

Tools for assessing the expected climate effects of alternative levels of human-made changes of atmospheric composition include (1) Earth's paleoclimate history, showing how climate responded in the past to changes of boundary conditions including atmospheric composition, (2) modern observations of climate change, especially global satellite observations, coincident with rapidly changing human-made and natural climate forcings, and (3) climate models and theory, which aid interpretation of observations on all time scales and are useful for projecting future climate under alternative climate forcing scenarios.

This paper emphasizes information provided by paleoclimate data. Milankovic climate oscillations, the glacial-interglacial climate swings associated with perturbations of Earth's orbit, provide a precise evaluation of equilibrium climate sensitivity, i.e., the response to changed boundary conditions after the atmosphere and ocean have sufficient time to restore planetary energy balance. Implications become clearer when Pleistocene climate oscillations are viewed in the context of larger climate trends of the Cenozoic Era. Ice cores and ocean cores are complementary tools for understanding, together providing a more quantitative assessment of the dangerous level of human interference with the atmosphere and climate.

Fig. 1 showsestimate global deep ocean temperature over the past 65.5 million years, the Cenozoic Era. The deep ocean temperature is inferred from a global compilation of oxygen isotopic abundances in ocean sediment cores (Zachos et al., 2001), with the temperature estimate extracted from oxygen isotopes via the simple approximation of Hansen et al. (2008).

This deep ocean temperature change is similar to global surface temperature change, we will argue, until the deep ocean temperature approaches the freezing point of ocean water. Thus late Pleistocene glacial-interglacial deep ocean temperature changes (Fig. 1c) are only about two-thirds as large as global mean surface temperature changes.

In this paper we discuss Cenozoic climate change and its relevance to understanding of human-made climate change. We review how Milankovic climate oscillations provide a precise measure of climate sensitivity to any natural or human-made climate forcing. We summarize how temperature is extracted from ocean cores to clarify the physical significance of this data record, because, we will argue, ocean core Milankovic data have profound implications about the dangerous level of human-made interference with global climate. Finally we discuss the temporal response of the climate system to the human-made climate forcing.

2. Cenozoic Climate Change

The Cenozoic era illustrates the huge magnitude of natural climate change. Earth was so warm in the early Cenozoic that polar regions had tropical-like conditions – indeed, there were alligators in Alaska (Markwick, 1998). There were no large ice sheets on the planet, so sea level was about 75 meters higher than today.

Earth has been in a long-term cooling trend for the past 50 million years (Fig. 1a). By approximately 34 Mya (million years ago) the planet had become cool enough for a large ice sheet to form on Antarctica. Ice and snow increased the albedo ('whiteness' or reflectivity) of that continent, an amplifying feedback that contributed to the sharp drop of global temperature at that time. Moderate warming between 30 and 15 Mya was not sufficient to melt all Antarctic ice. The cooling trend resumed about 15 Mya and accelerated as the climate became cold enough for ice sheets to form in the Northern Hemisphere and provide their amplifying feedback.

The Cenozoic climate changes summarized in Fig. 1 contain insights and quantitative information relevant to assessment of human-made climate effects. Carbon dioxide (CO_2) plays a central role in both the long-term climate trends and the short-term oscillations that were magnified as the planet became colder and the ice sheets larger. Cenozoic climate change is discussed by Zachos et al. (2001), IPCC (2007), Hansen et al. (2008), and many others. We describe here implications about the role of CO_2 in climate change and climate sensitivity.

CO_2 is the principal forcing that caused the slow Cenozoic climate trends over millions of years, as the solid Earth (volcanic) source altered the amount of CO_2 in surface carbon reservoirs (atmosphere, ocean, soil and biosphere). CO_2 is also a principal factor in the short-term climate oscillations that are so apparent in parts (b) and (c) of Fig. 1. However, in these glacial-interglacial oscillations atmospheric CO_2 operates as a feedback: total CO_2 in the surface reservoirs changes little on these shorter time scales, but the distribution of CO_2 among the surface reservoirs changes as climate changes. As the ocean warms, for example, it releases CO_2 to the atmosphere, providing an amplifying climate feedback that causes further warming.

The fact that CO_2 is the dominant cause of long-term Cenozoic climate trends is obvious from consideration of Earth's energy budget. Such large climate changes cannot result from redistribution of energy within the climate system, as might be caused by changes of atmosphere or ocean dynamics. Instead a substantial global climate forcing is required. The climate forcing must be due to a change of energy coming into the planet or changes within the atmosphere or on the surface that alter the planet's energy budget.

Solar luminosity is increasing on long time scales, as our sun is at an early stage of solar evolution, "burning" hydrogen, forming helium by nuclear fusion, slowly getting brighter. The sun's brightness increased steadily through the Cenozoic, by about 0.4 percent according to solar physics models (Sackmann et al., 1993). Because Earth absorbs about 240 W/m^2 of solar energy, that brightness increase is a forcing of about 1 W/m^2. This small linear increase of forcing, by itself, would have caused a modest global warming through the Cenozoic Era.

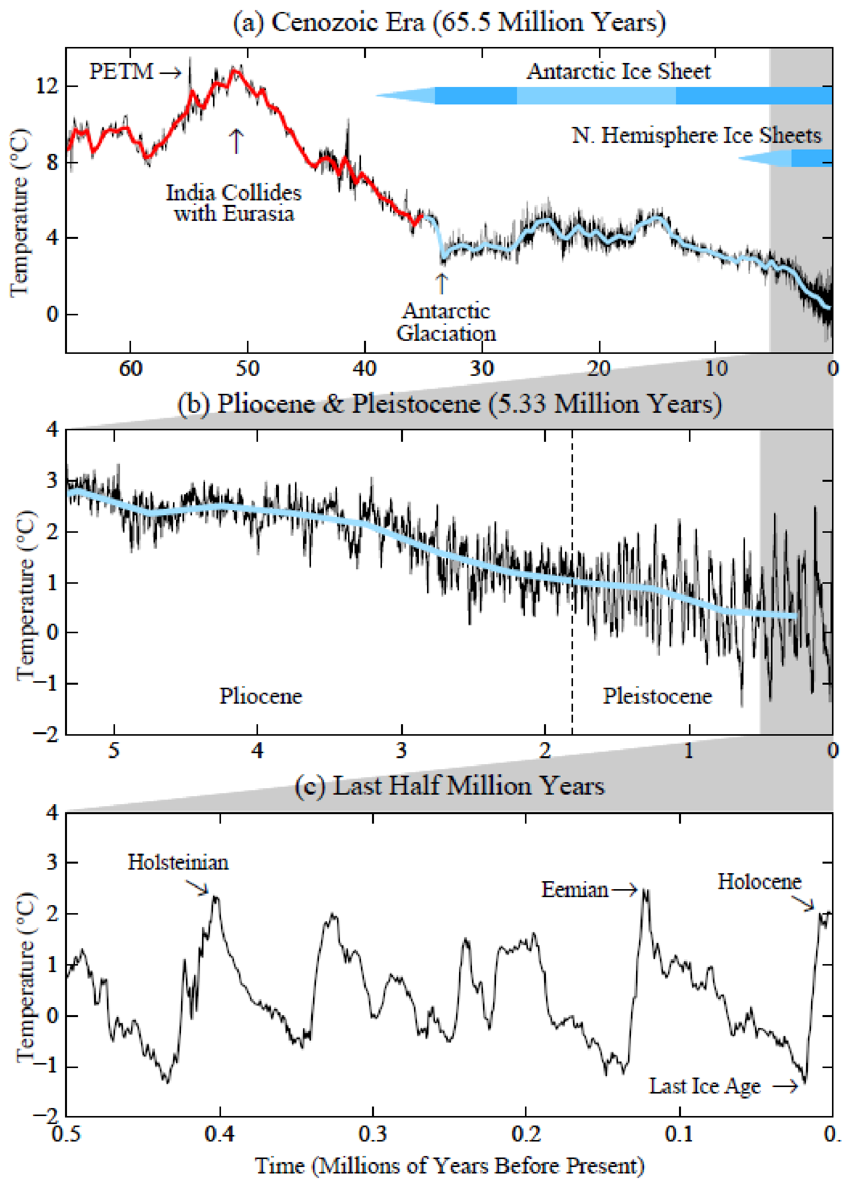

Fig. 1. Global deep ocean temperature in the Cenozoic Era, with the Pliocene and Pleistocene expanded in (b) and the last half million years further expanded in (c). High frequency variations (black) are 5-point running means of original data (Zachos et al., 2001), while the red and blue curves have 500 ky resolution. Blue bars indicating ice sheet presence are darker when ice sheets were close to their full size.

Continental locations also affect the planet's energy balance, because ocean and continent albedos differ. However, most continents were near their present latitudes at the beginning of the Cenozoic (Blakey, 2008), so this surface climate forcing did not exceed about 1 W/m^2.

In contrast, atmospheric CO_2 during the Cenozoic changed from at least 1000 ppm in the early Cenozoic to as small as 170 ppm during recent ice ages. The resulting climate forcing, as can be computed accurately for this CO_2 range using formulae in Table 1 of Hansen et al. (2000), exceeds 10 W/m^2. It is clear that CO_2 was the dominant climate forcing in the Cenozoic.

Global temperature change during the first half of the Cenozoic is consistent with expectations based on knowledge of plate tectonics (continental drift). India was the only land area located far from its current location at the beginning of the Cenozoic. The Indian plate was still south of the Equator, but moving northward at a rate of about 20 cm per year (Kumar et al., 2007), a rapid continental drift rate. The Indian plate moved toward and through the Tethys Ocean, now the Indian Ocean, which had long been the depocenter for carbonate and organic sediments from major world rivers.

The total amount of carbon in the surface carbon reservoirs on long time scales is determined by the balance between outgassing (via volcanoes and seltzer springs) from the solid Earth and burial back into Earth's crust (Berner, 2004). CO_2 outgassing occurs via metamorphism of ocean crust as it is subducted beneath moving continental plates. Burial is primarily via the chemical weathering of rocks with deposition of carbonates on the ocean floor, but to a less extent via burial of organic matter, some of which eventually may form fossil fuels.

Rates of outgassing and burial of CO_2 are each typically 10^{12}-10^{13} mol C/year (Staudigel et al., 1989; Edmond and Huh, 2003; Berner, 2004). The imbalance between outgassing and burial is limited by negative feedbacks in the geochemical carbon cycle (Berner and Caldeira, 1997), but a net natural imbalance of the order of 10^{12} mol C/year can be maintained on long time scales, as continental drift changes the rate of outgassing. Such an imbalance, after distribution among surface reservoirs, is only ~0.0001 ppm/year of atmospheric CO_2. That rate is negligible compared to the present human-made atmospheric CO_2 increase of ~2 ppm/year, yet in a million years such a crustal imbalance alters atmospheric CO_2 by ~100 ppm.

The strong global warming trend between 60 and 50 My ago was surely a consequence of increasing atmospheric CO_2, as the Indian plate subducted carbonate-rich ocean crust while traversing the Tethys Ocean. The magnitude of the CO_2 source continued to increase until India crashed into Asia and began pushing up the Himalaya Mountains and Tibetan Plateau. Emissions from this tectonic source continue even today, but the magnitude of emissions began decreasing after the Indo-Asian collision and as a consequence the planet cooled. The climate variations between 30 and 15 million years ago, when the size of the Antarctic ice sheet fluctuated, may have been due to temporal variations of plate tectonics and outgassing rates (Patriat et al., 2008). Although many mechanisms probably contributed to climate change through the Cenozoic era, it is clear that CO_2 change was the dominant cause of the early warming and the subsequent long-term cooling trend.

Plate tectonics today is producing relatively little subduction of carbonate-rich ocean crust (Edmund and Huh, 2003), consistent with low Pleistocene levels of CO_2 (170-300 ppm) and the cool state of the planet, with ice sheets in the polar regions of both hemispheres. Whether Earth would have continued to cool in the absence of humans[1], on time scales of millions of years, is uncertain. But that is an academic question. The rate of human-made change of atmospheric CO_2 amount is now several orders of magnitude greater than slow geological changes. Humans now control atmospheric composition, for better or worse, and surely will continue to do so, as long as the species survives.

The Cenozoic era contributes to assessment of the dangerous level of human interference with climate. However, implications become clearer after discussion of the precise empirical evaluation of climate sensitivity provided by recent Milankovic climate oscillations and consideration of potential rates of ice sheet disintegration.

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[1] Paleoanthropological evidence of Homo sapiens in Africa dates from about 200,000 years ago, i.e., over the last two glacial-interglacial cycles in Fig. 1c. Migration of Homo sapiens to other continents, 60,000 years ago, occurred at about the midpoint of the cooling after the penultimate (Eemian) interglacial period. Earlier human-like populations, such as Neanderthals and Homo erectus, date back at least 2,000,000 years, but, as is clear from Fig. 1a, even those species were present only in the recent time of ice ages.

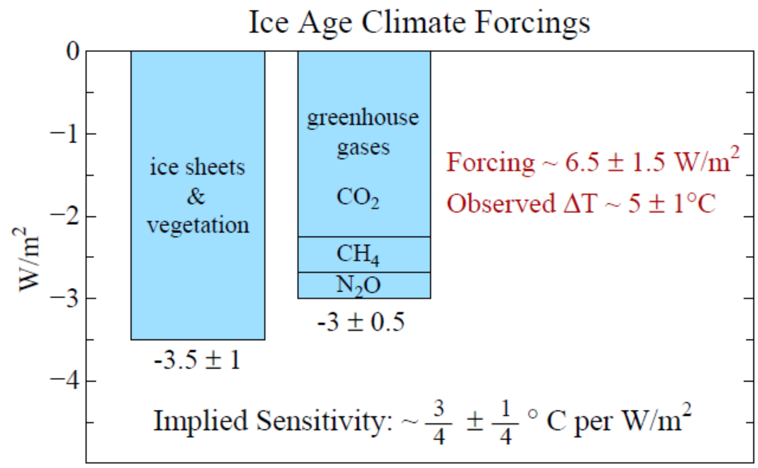

Fig. 2. Climate forcings during the ice age 20 ky ago relative to the pre-industrial Holocene.

3. Fast-Feedback Climate Sensitivity

Recent glacial-interglacial climate oscillations precisely define a specific climate sensitivity, yet this fact and its significance are not fully appreciated. Climate, averaged over a few millennia, must be in near-equilibrium during the last ice age (~20 ky ago) and in the current interglacial period prior to introduction of substantial human-made climate forcings. Any planetary energy imbalance was at most a small fraction of 1 W/m^2, as shown by considering the contrary: an imbalance approaching 1 W/m^2 would be sufficient to melt all ice on Earth or change ocean temperature a large amount, contrary to numerous paleoclimate data records.

Variability of solar luminosity on Pleistocene time scales is small. Therefore the changed boundary conditions that maintained observed climate change had to be changes on Earth's surface and changes of long-lived atmospheric constituents. These forcings, as summarized in Fig. 2, are both known with reasonably good accuracy. The largest uncertainty is the calculated 3.5 W/m^2 forcing due to surface changes (ice sheet area, vegetation distribution, shoreline movement) due to uncertainty in ice sheet sizes (Hansen et al., 1984; Hewitt and Mitchell, 1997).

Global temperature change of 5 ± 1°C between the last ice age and the Holocene[2] implies an equilibrium climate sensitivity of 5/6.5 ~ ¾°C for each watt of forcing. The fact that ice sheet and greenhouse gas boundary conditions are actually slow climate feedbacks is irrelevant for the purpose of evaluating the fast-feedback climate sensitivity (Hansen et al., 1984; Lorius et at., 1990).

This empirical climate sensitivity incorporates all fast response feedbacks in the real-world climate system, including changes of water vapor, clouds, aerosols, aerosol effects on clouds, and sea ice. In contrast to climate models, which can only approximate the physical processes and may exclude important processes, the empirical result includes all processes that exist in the real world – and the physics is exact.

The sensitivity ¾°C per W/m^2 corresponds to 3°C for doubled CO_2 forcing (4 W/m^2). If Earth were a blackbody without climate feedbacks the equilibrium response to 4 W/m^2 forcing would be about 1.2°C (Hansen et al., 1981, 1984). The water vapor increase and sea ice decrease

[2] A recent review (Shakun and Carlson, 2010) of the climate change between the last glacial maximum and the Holocene estimated the global temperature change as 4.9°C, but they suggested this was a minimum, because they were missing data from regions of sea ice and land ice that likely had the largest temperature change.

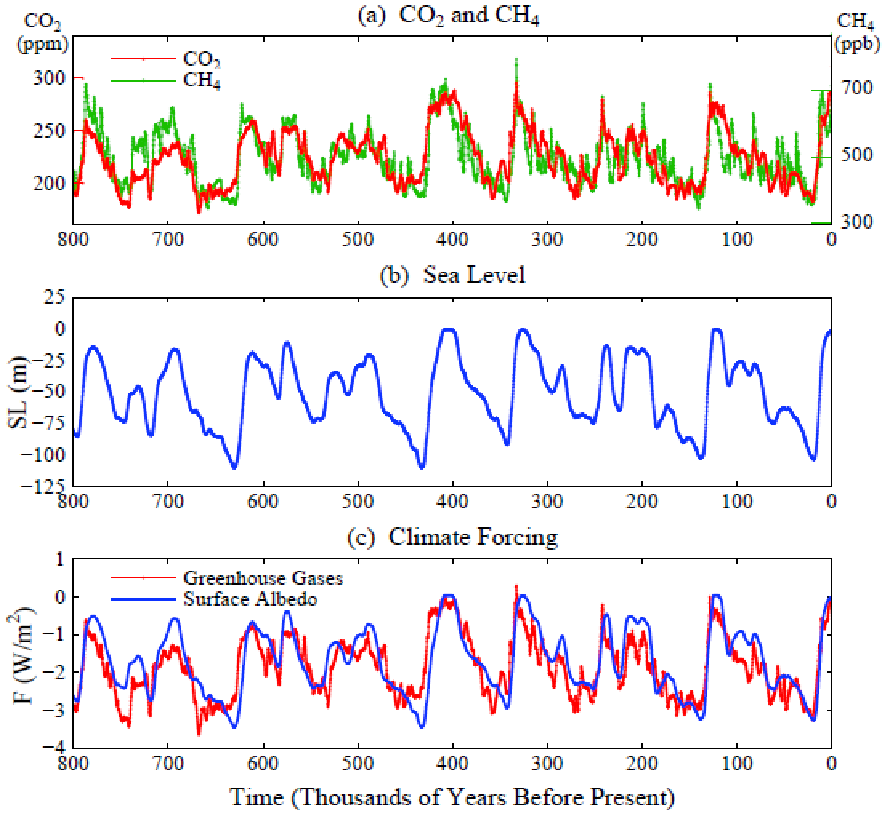

Fig. 3. CO_2 (Luthi et al., 2008), CH_4 (Loulergue et al., 2008), sea level (Bintanja et al., 2005) and resulting climate forcings (Hansen et al., 2008) for the past 800,000 years

that accompany global warming can be simulated reasonably well by climate models; together these two feedbacks approximately double the blackbody sensitivity. The further amplification is the net effect of all other processes, with aerosols, clouds, and their interactions probably being the most important of the remaining feedback processes.

The empirical sensitivity 3°C for doubled CO_2 agrees with estimates of Charney (1979) and modern climate models. But the empirical result is more precise, and it includes all real-world processes. Moreover, by examining observed climate change over several Milankovic oscillations it is now possible to further reduce the uncertainty in this fast-feedback sensitivity.

Fig. 3 shows atmospheric CO_2 and CH_4 and sea level[3] for the past 800,000 years and resulting calculated climate forcings. Sea level implies the total size of the major ice sheets, which thus defines the surface albedo forcing as described by Hansen et al. (2008).

Multiplying the sum of greenhouse gas and surface albedo forcings by climate sensitivity ¾°C per W/m^2 yields the predicted temperature shown by blue curves in Fig. 4. This calculated global temperature change is compared with both Dome C Antarctic temperature change (Jouzel et al., 2007) and global deep ocean temperature change (Zachos et al., 2001, with temperature extracted from oxygen isotope data as described below and by Hansen et al., 2008).

[3] The sea level history of Bintanja et al. (2005) is dependent on an ice sheet model that is constrained to match the oxygen isotopic record, an approach that allows variable contributions of ice volume and temperature to oxygen isotope amount. Bintanja et al. (2005) found good agreement with other sea level reconstructions, and Hansen et al. (2008) made comparisons showing that the differences among sea level reconstructions are too small to alter the discussions in the present paper.

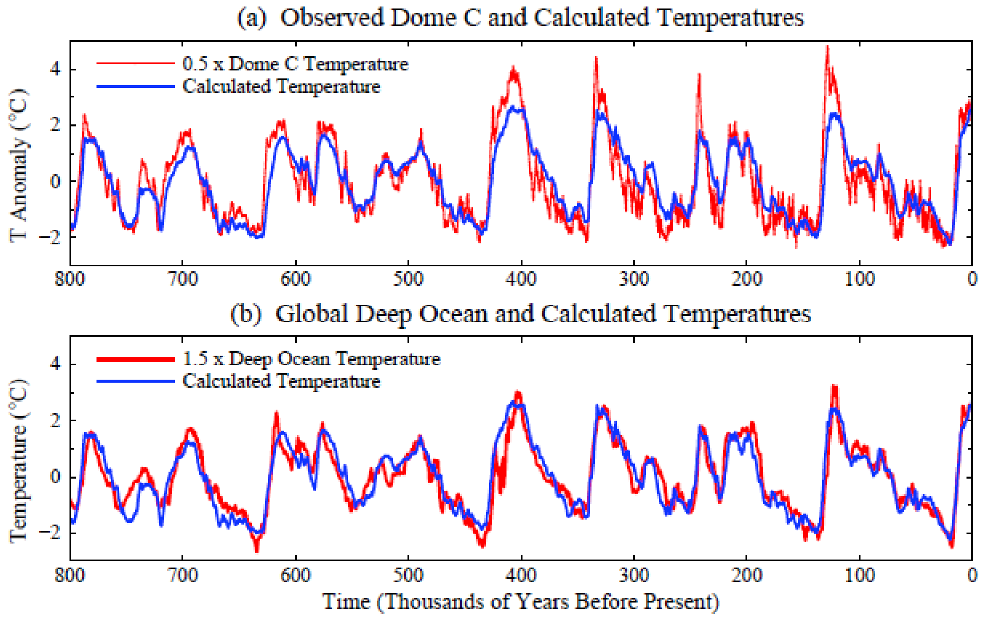

Fig. 4. Calculated global surface temperature change compared with (a) 0.5 × Dome C temperature, and (b) 1.5 × deep ocean temperature.

The estimate of observed global temperature change from the Antarctic ice core assumes global mean temperature change is half as large as Antarctic temperature change. The estimate of observed global temperature change based on the global compilation of deep ocean cores assumes that global temperature change is 1.5 times greater than deep ocean temperature change. These scale factors are chosen to yield global temperature change of about 5°C between the last ice age and the Holocene, the best documented glacial-interglacial climate change.

The good fit of calculations and deep ocean temperature for all interglacial periods, whether warmer or cooler than the Holocene, has profound implications about the dangerous level of human-made climate change. For this reason, we need to summarize how temperature is extracted from ocean cores.

4. Deep ocean temperature record

The isotopic composition of shells of microscopic benthic (deep ocean dwelling) animals (foraminifera, or 'forams') in ocean cores provides information on climate change throughout the Cenozoic Era. The proportions of the heavy oxygen isotope (^{18}O) and the common isotope (^{16}O) in a foram shell depend on both the temperature where the shell grew and on sea level at that time. Sea level is an indication of how much water is stored in continental ice sheets. As ice sheets grow the water molecules remaining in the ocean have a higher percentage of ^{18}O, because the lighter ^{16}O evaporates from the ocean more readily and accumulates in the ice sheets.

Hansen et al. (2008) compared two extreme sea level situations: (1) 35 My ago, just before a large ice sheet formed on Antarctica, when sea level was thus near its maximum height (about 75 m higher than today), and (2) 20 ky (thousand years) ago, during the last ice age, when sea level was about 180 m lower than during the nearly ice-free state at 35 My. Half of the oxygen isotope change between these extreme states is known to be due to the deep ocean temperature change and half to the accumulation of continental ice. Assuming that the amount of ice increases monotonically as the planet becomes colder, Hansen et al. (2008) made the approximation that oxygen isotope change was due in equal parts to temperature and ice volume for all intermediate climate states between 35 My and the Holocene.

In reality, the proportions of the isotope change due to temperature and ice volume are more complex, e.g., during the last glaciation deep water in the North Atlantic cooled more rapidly compared to the rate at which ice volume increased (Waelbroeck et al., 2002). An analysis by Bintanja et al. (2005) also finds that temperature change contributes most of the ^{18}O change in the early stages of ice sheet growth, while ice volume contributes more than half of the ^{18}O change near glacial maximum. However, Waelbroeck et al. (2002) found that Pacific deep water temperature change varied in proportion to sea level change. We use a global stack of ocean cores, which would be dominated by the Pacific Ocean, thus reducing the effect of more complex variability found in the North Atlantic.

But what is the relation of deep ocean temperature change to global mean surface temperature change? Deep ocean temperature depends on sea surface temperature at high latitudes in winter, the location and season at which surface water is most dense and sinks to the deep ocean. This leads us to infer that deep ocean temperature change is a useful approximation of global mean surface temperature change on millennial time scales. This fortuitous result is a consequence of substantial offset between the two principal factors that would make temperature change at the sites of deep water formation differ from global mean surface temperature change.

First, temperature change at high latitudes is amplified relative to global mean temperature change. But, second, temperature change is smaller over ocean than over land. These two competing factors substantially offset one another.[4] Both of these tendencies (polar temperature change amplification and ocean versus land temperature change dimunition) are present in observational data and models, and are well understood.

But what if the location of deep water formation changes as the climate changes? As climate becomes colder and sea ice expands, deep water formation may move toward lower latitudes. Our interest is primarily in climates in the range from the Holocene toward warmer climates. We use a global set of ocean cores that is dominated by the Pacific, where the deep water temperature is determined by deep water formed around the Antarctic continent. As the climate warms beyond the Holocene, it is not likely that the location of deep water would move substantially closer to the Antarctic continent than it is at present.

However, deep ocean temperature change becomes less representative of global surface temperature change as the ocean temperature approaches the freezing point of water, because the deep ocean temperature is limited by the freezing point while the global mean surface can continue to cool. Observations are the most accurate way to quantify this constraint. We find that the amplitude of recent glacial-interglacial deep ocean temperature change (Fig. 1c) is only about two-thirds the amplitude of global mean surface temperature change.

5. Interglacial temperatures

Fig. 4 raises important questions. How warm were recent interglacial periods relative to the Holocene? Do ice cores or ocean cores yield a better estimate of global temperature change during those interglacial periods? Let us first remark on why these questions are important.

Broad-based assessments of the dangerous level of global warming, represented by the "burning embers" diagram in IPCC (2001, 2007), have suggested that major problems begin with global warming of 2-3°C relative to global temperature in year 2000. Sophisticated probabilistic

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[4] The very large polar amplification of surface air temperature that occurs in sea ice regions is not relevant, because we are concerned with water temperature, which does not fall below the freezing point.

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 IPCC analyses contributed to a European Union decision to support policies aimed at keeping global warming less than 2°C relative to pre-industrial times (1.3°C relative to year 2000).

The warmer interglacial periods can play a key role in discussions about the dangerous level of global warming, because some interglacials in the recent half of the ice core record were warmer than the Holocene. Most paleoclimate records indicate that the interglacials peaking near 125 ky ago (Eemian) and 400 ky ago (Holsteinian, Marine Isotope Stage 11) were the warmest. Sea level in those interglacial periods was higher than today by about 5m, possibly more, as discussed below.

The warmer interglacials were a prime consideration in definition of the "alternative scenario" of Hansen et al. (2000). Hansen et al. (2000) argued that these interglacials implied a lower threshold for "dangerous" global warming than suggested by the "burning embers" of IPCC (2001, 2007) and Schneider and Mastrandrea (2005). Thus the alternative scenario was designed to keep global warming less than 1°C relative to 2000, i.e., less than 1.7°C relative to pre-industrial times. This global warming target implied a CO_2 target of 450-475 ppm, with the exact CO_2 limit depending in part on success in controlling other trace gases.[5]

Subsequently, based on improving and more comprehensive paleoclimate analyses, as well as global observations of climate effects occurring in the first decade of the 21st century, we realized that additional global warming of 1°C above the 2000 level would push the planet well into the dangerous range (Hansen et al., 2007, 2008). We concluded that it will be necessary to reduce CO_2 eventually to some level less than 350 ppm to avoid unacceptable climate effects.

However, the need for a CO_2 target below the current CO_2 amount, and the rapid emissions reduction that such a target implies, has not been recognized and acted on by the international political community. Thus there is an urgency to extract and clarify the implications of paleoclimate data for human-made climate change.

Ice core and ocean core records each have limitations as a measure of global temperature. Here we point out constraints on both records and hypothesize a reason why these two records seem to differ during recent interglacial periods.

a. Ice cores

Ice core temperature analysis uses isotopes of ice core H_2O to determine the temperature when and where the snowflakes formed. We divide the ice core temperature change by two to obtain the estimated global mean temperature change in Fig. 4, because that factor brings the ice core temperature change between the Holocene and the last ice age into agreement with global temperature data available for this most recent glacial-interglacial climate change. Climate models also yield polar amplification of surface temperature change by about a factor of two.

Several adjustments to the ice core temperature record have been suggested with the aim of producing a more homogeneous record[6], i.e., a result that more precisely defines the surface

[5] Note that our numbers for CO_2, here and elsewhere, always refer to actual CO_2, not the less precise and sometimes confusing "CO_2 equivalent". Besides its imprecision, use of CO_2 equivalence has another major disadvantage: it promotes the concept of "offsets" to avoid the one essential near-term requirement, reduction of CO_2 emissions.

[6] A complex adjustment has been suggested to account for estimated glacial-interglacial change of the source region for the water vapor that eventually forms the snowflakes (Vimeux et al., 2002). The source location depends on sea ice extent. This correction reduces the magnitude of the interglacial warmth and thus works in the sense of reducing the discrepancy with the calculated interglacial temperatures in Fig. 4a.

air temperature change at a fixed location and fixed altitude. However, these adjustments are too small to remove the discrepancy between global temperature inferred from ice cores compared with either ocean core temperature change or our calculations based on greenhouse gas and albedo climate forcings (Fig. 4a).

The principal issue about temperature change on top of the ice sheet during the warmest interglacials is whether the simple (factor of two) relationship with global mean temperature change remains accurate during the warmest interglacials. That simple prescription works well for the Holocene and for all the glacial-interglacial cycles during the early part of the 800,000 year record, when the interglacials were no warmer than the Holocene.

We suggest that the warmest interglacial periods are different than interglacials in the period 800,000 to 450,000 ky ago or the pre-industrial Holocene. We suggest that the warmest interglacials moved into a regime in which there was less summer sea ice around the Antarctic and Greenland land masses, there was summer melting on the lowest elevations of the ice sheets, and there was summer melting on the ice shelves, which thus largely disappeared. In this regime, we expect warming on the top of the ice sheet to be more than twice global mean warming. Stated differently, even small global warming above the level of the Holocene begins to generate a disproportionate warming on the Antarctic and Greenland ice sheets.

Summer melting on lower reaches of the ice sheets and on ice shelves introduces the "albedo flip" mechanism (Hansen et al., 2007). This phase change of water causes a powerful local feedback, which, together with moderate global warming, can substantially increase the length of the melt season. Such increased summer melting has an immediate local temperature effect, and it also will affect sea level, on a time scale that is being debated, as discussed below.

We suggest that the warmest interglacials in the past 450,000 years were warm enough to bring the "albedo flip" phenomenon into play, while interglacials in the earlier part of the 800,000 year ice core record were too cool for surface melt on the Greenland and Antarctic ice sheets and ice shelves to be important. Increased surface melting, loss of ice shelves, and reduction of summer and autumn sea ice around the Antarctic and Greenland continents during the warmest interglacials would have a year-round effect on temperature, because the increased area of open water has its largest impact on surface air temperature in the cool seasons.

Further, we suggest that the stability of sea level during the Holocene is a consequence of the fact that global temperature remained just below the level required to initiate the "albedo flip" mechanism on Greenland and West Antarctica.

One implication of this interpretation is that the world today is on the verge of a level of global warming for which the equilibrium surface air temperature response on the ice sheets will exceed the global mean temperature increase by much more than a factor of two. Below we cite empirical evidence in support of this interpretation. First, however, we must discuss limitations of ocean core temperatures.

Another adjustment has been suggested to account for change of the altitude of the ice sheet's upper surface (Masson-Delmotte et al., 2010). They find an increase in the peak homogenized (fixed altitude) temperature during the warmest interglacials. The correction is based on ice sheet models, which yield a greater altitude for the central portion of the ice sheet during these interglacials, even though sea level was higher and thus the ice sheet volume was smaller. This counter-intuitive result is possible because the snowfall rate is higher during the interglacials, which could make the central altitude greater despite the smaller ice sheet volume, but we note that the correction is based on ice sheet models that may be "stiffer" than real-world ice sheets.

b. Ocean cores

Ocean core temperatures, when used to estimate global temperature change, have their own issues. Although ocean core temperatures are based on many sites around the world ocean, deep ocean temperature depends mainly on ocean surface temperature at high latitudes where deep water forms. So we must be concerned that locations of deep water formation might move as climate changes. As climate becomes colder, for example, sea ice expands equatorward and the location of deep water formation may move equatorward. Fortunately, the climates of most interest to us have global temperature ranging from that of the Holocene toward warmer climates. There is little expectation that the present sites of deep water formation would move substantially in response to moderate additional global warming.

A second problem with ocean cores is that deep ocean temperature change is limited as ocean water nears its freezing point. That is why deep ocean temperature change between the last ice age and the Holocene was only two-thirds as large as global average surface temperature change.[7] However, in using a constant adjustment factor (1.5) in Fig. 4, based on the range of climates from the ice age to the Holocene, we overstate the magnification at interglacial temperatures and understate the magnification at the coldest climates, thus maximizing the possibility for the deep ocean temperature to reveal (and exaggerate) large interglacial warmth. Yet no interglacial warm spikes appear in the ocean core record of temperature change (Fig. 4b).

A third issue concerns the temporal resolution of ocean cores. Bioturbation, mixing of ocean sediments by worms, smoothes the ocean core record, especially at locations where ocean sediments accumulate slowly. However, the length of the interglacial periods of primary concern, the Eemian and Holsteinian, exceeded the resolution of most ocean cores.

We conclude that ocean cores provide a better measure of global temperature change than ice cores during those interglacial periods that were warmer than the pre-industrial Holocene.

c. The Holocene

How warm is the world today relative to peak Holocene temperature? The Altithermal, the time of peak Holocene warmth, is usually placed at about 8,000 years ago, but it varies from one place to another. Our present interest is in global mean temperature, not regional variations.

Earth orbital (Milankovic) parameters have favored a cooling trend for the past several thousand years, which would be expected to start in the Northern Hemisphere. For example, Earth is now closest to the sun in January, which favors warm winters and cool summers in the Northern Hemisphere, thus favoring growth of glaciers and ice caps in the Northern Hemisphere. However, that tendency is very weak during the current interglacial period because another more slowly varying orbital parameter, the eccentricity of Earth's orbit, happens to be small during this interglacial period[8]. Thus paleoclimatologists have debated in recent years whether, in the absence of humans, a new ice age would have begun within the next few thousand years or whether the Holocene interglacial period would have continued for another 20,000 years or so until the next time that conditions favor growth of Northern Hemisphere ice. That debate is purely academic, as human-made climate forcings now dwarf Milankovic effects.

[7] This empirical result is consistent with modeling results of Bintanja et al. (2005), who found that ice volume change provided most of the oxygen isotope change as the planet approached glacial maximum.

[8] When the eccentricity is near zero Earth's orbit is almost perfectly circular, so the date at which Earth is closest to the sun becomes irrelevant. The remaining Milankovic parameter, the tilt of Earth's spin axis relative to the plane of the orbit, is now at an intermediate value, headed toward minimum tilt that will occur in about ten thousand years. Minimum tilt favors growth of ice sheets in the polar regions of both hemispheres.

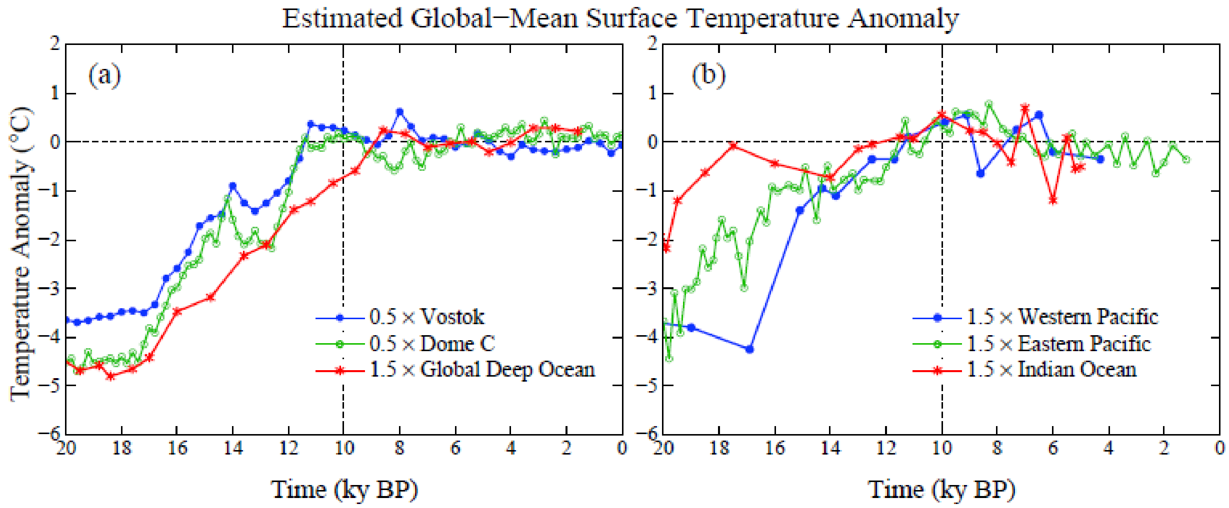

Fig. 5. Estimates of global temperature change inferred from Antarctic ice cores (Vimeux et al., 2002; Jouzel et al., 2007) and ocean sediment cores (Medina-Elizade and Lea, 2005; Lea et al., 2000, 2006; Saraswat et al., 2005). Zero-point temperature is the mean for the past 10 ky.

Fig. 5 compares several temperature records for the sake of examining Holocene temperature change. Zero temperature is defined as the mean for the past 10,000 years. The records are made to approximate global temperature by dividing polar temperatures by two and multiplying deep ocean and tropical ocean mixed layer[9] temperature by a factor 1.5. Fig. 5 indicates that global temperature has been relatively stable during the Holocene.

So how warm is it today relative to peak Holocene warmth? Fig. 5, especially the red curve in Fig. 5a for the global deep ocean temperature, makes it clear that the world did not cool much in the Holocene. Consistent with our earlier study (Hansen et al., 2006), we conclude that, with the global surface warming of 0.7°C between 1880 and 2000 (Hansen et al., 2010), global temperature in year 2000 had returned, at least, to approximately the Holocene maximum.

d. Holocene versus prior interglacial periods and the Pliocene

How does peak Holocene temperature compare with prior warmer interglacial periods, specifically the Eemian and Holsteinian interglacial periods, and with the Pliocene?

Fig. 6 shifts the temperature scale so that it is zero at peak Holocene warmth. The temperature curve is based on the ocean core record of Fig. 1 but scaled by the factor 1.5, which is the scale factor relevant to average conditions between the Holocene and the last ice age. Thus for climates warmer than the Holocene, Fig. 6 may exaggerate actual temperature change.

One conclusion deserving emphasis is that global mean temperatures in the Eemian and Holsteinian were less than 1°C warmer than peak Holocene global temperature. Therefore, these interglacial periods were also less than 1°C warmer than global temperature in year 2000.

Fig. 6 also suggests that global temperature in the early Pliocene, when sea level was about 25 m higher than today (Dowsett et al., 1994), was only about 1°C warmer than peak Holocene temperature, thus 1-2°C warmer than recent (pre-industrial) Holocene. That

[9] Indian and Pacific Ocean temperatures in Fig. 5 are derived from forams that lived in the upper ocean, as opposed to benthic forams used to obtain global deep ocean temperature. The Eastern Pacific temperature in Fig. 5b is the average for two locations, north and south of the equator, which are shown individually by Hansen et al. (2006).

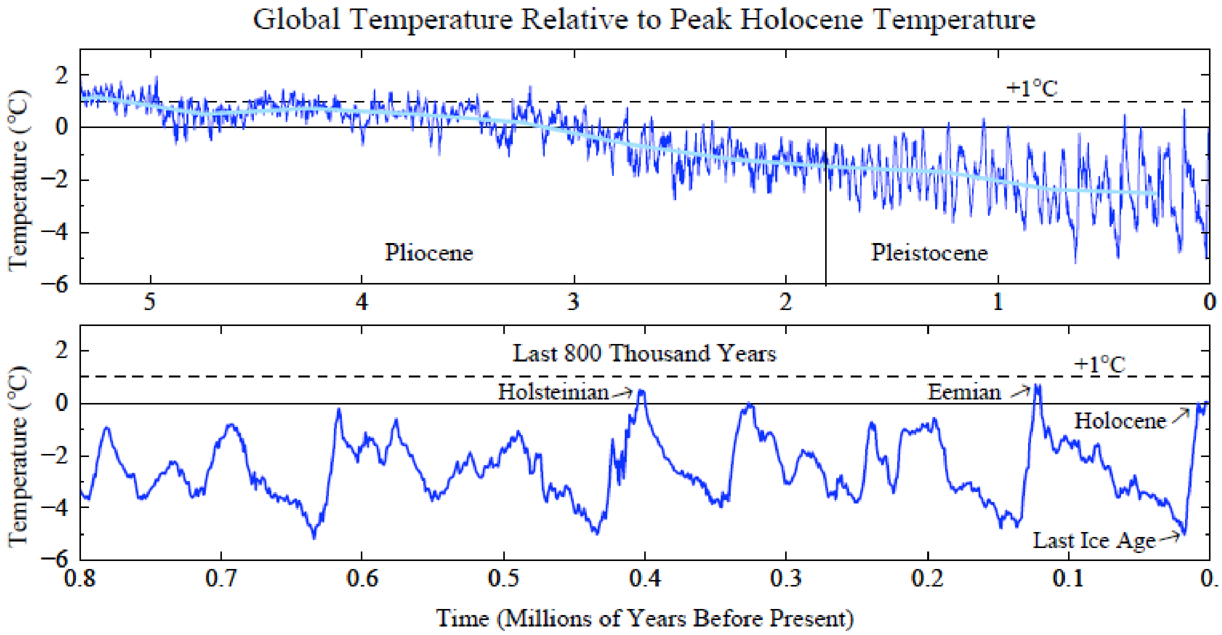

Fig. 6. Global temperature relative to peak Holocene temperature, based on ocean core records as in Fig. 1, but with temperature change amplified by factor 1.5. For climates warmer than the Holocene, such as the Eemian, the indicated temperature change probably exaggerates the actual temperature change, because the 1.5 amplification factor should not be required for warmer climates.

conclusion requires a caveat about possible change of location of deepwater formation, stronger than the same caveat in comparing recent interglacial periods. Substantial change in the location of deep water formation is more plausible in the Pliocene because of larger Arctic warming at that time (Dowsett et al., 1999); also ocean circulation may have been altered in the early Pliocene by closure of the Panama Seaway, although the timing of that closure is controversial (Haug and Tiedemann, 1998).

Is such small Pliocene warming inconsistent with PRISM (Pliocene Research, Interpretation and Synoptic Mapping Project) reconstructions of mid-Pliocene (3-3.3 My ago) climate (Dowsett et al., 1996, 2009 and references therein)? Global mean surface temperatures in climate models forced by PRISM boundary conditions yield global warming of about 3°C (Lunt et al., 2010) relative to pre-industrial climate. However, it must be borne in mind that "PRISM's goal is a reconstruction of a 'super interglacial', not mean conditions" (Dowsett et al., 2009), which led to (intentional, as documented) choices of the warmest conditions in a variety of data sets that were not necessarily well correlated in time.

Perhaps the most striking characteristic of Pliocene climate reconstructions is that low latitude ocean temperatures were very similar to temperatures today. High latitudes were much warmer than today, the ice sheets smaller, and sea level about 25 m higher (Dowsett et al., 2009 and references therein). Atmospheric CO_2 amount in the Pliocene is poorly known, but a typical assumption, based on a variety of imprecise proxies, is 380 ppm (Raymo et al., 1996). It is likely that both elevated CO_2 and increased poleward heat transports by the ocean and atmosphere contributed to large high latitude warming with little change at low latitudes, but Pliocene climate has not been well simulated from first principals by climate models.

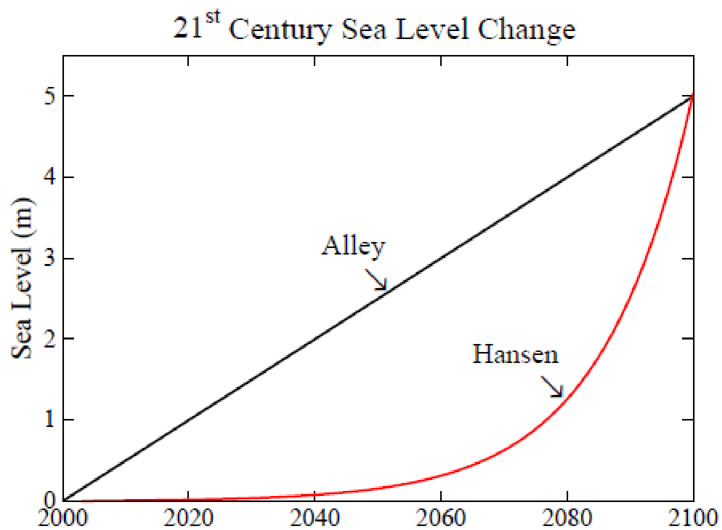

Fig. 7. Five-meter sea level change in 21st century under assumption of linear change (Alley, 2010) and exponential change (Hansen, 2007), the latter with a 10-year doubling time.

We conclude that Pliocene temperatures probably were no more than 1-2°C warmer on global average than peak Holocene temperature. And regardless of the precise temperatures in the Pliocene, the extreme polar warmth and diminished ice sheets are consistent with the picture we painted above. Earth today, with global temperature having returned to at least the Holocene maximum, is poised to experience strong amplifying polar feedbacks in response to even modest additional global mean warming.

6. Sea level

Sea level rise potentially sets a low limit on the dangerous level of global warming. Civilization developed during a time of unusual sea level stability. Much of the world's population and infrastructure is located near current sea level.

Earth's paleoclimate history shows that eventual sea level rise of many meters should be anticipated with the global warming of at least several degrees Celsius that is expected under business-as-usual (BAU) climate scenarios (IPCC, 2001, 2007; Hansen et al., 2000, 2007). Yet the danger of sea level rise has had little or no impact on global energy and climate policies.

The explanation, at least in part, must be belief that ice sheets respond only slowly to climate change. Thus the IPCC (2007) projection of about 29 cm (midrange 20-43 cm, full range 18-59 cm) sea level rise by the end of this century was more reassuring than threatening.

IPCC projections did not include contributions from ice sheet melt, on the grounds that we do not understand ice sheet physics well enough. That is reasonable, but if ice sheets pose the danger of sea level rise far exceeding other mechanisms, then it deserves to be front and center in communication with policymakers. Given the near impossibility of getting policymakers to consider far future effects, the practical question then becomes: how much can ice sheets contribute to sea level rise on the time scale of a century?

Rahmstorf (2007) made an important contribution to the sea level discussion by pointing out that even a linear relation between global temperature and the rate of sea level rise, calibrated

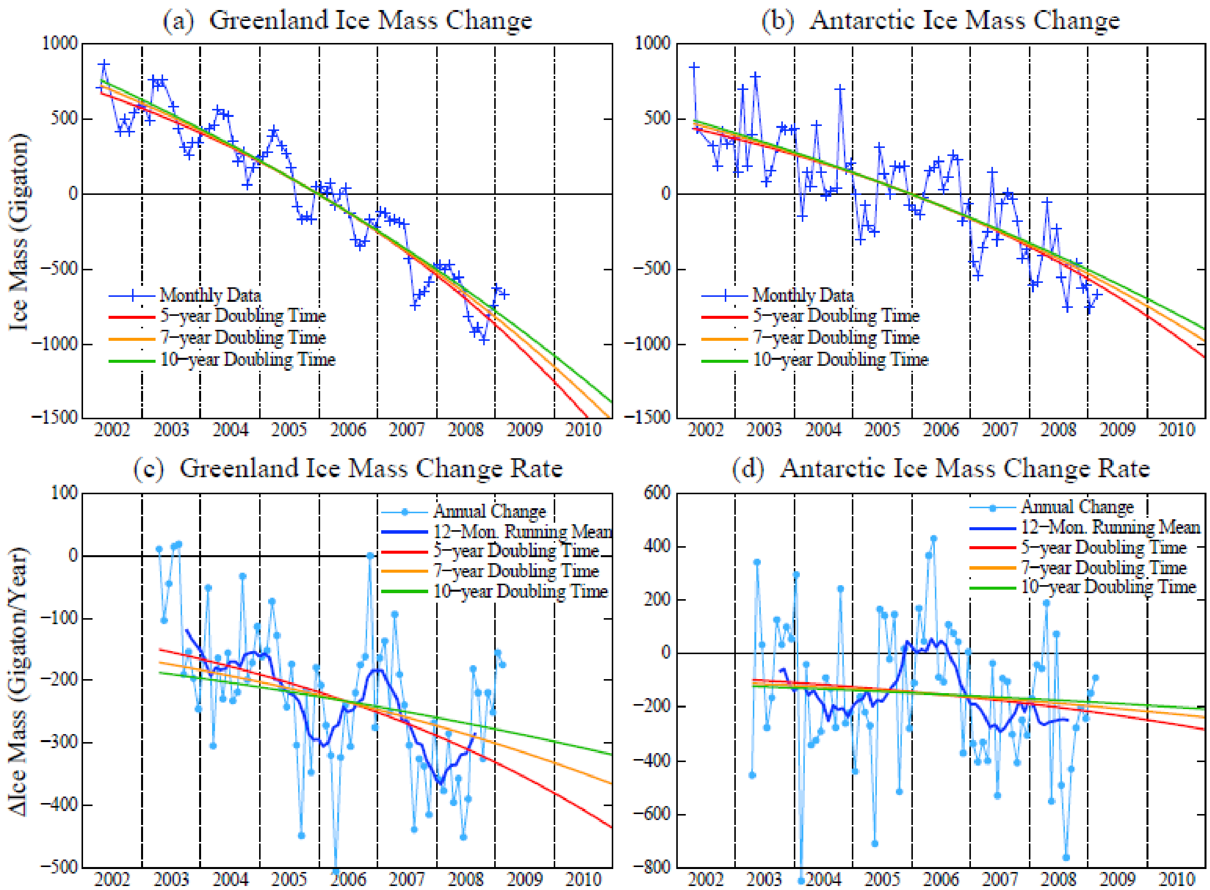

Fig..8. Greenland (a) and Antarctic (b) mass change deduced from gravitational field measurements by Velicogna (2009), as read by one of us (MS) from her graph, and the derivative of these curves, i.e., annual changes of the Greenland (c) and Antarctic (d) ice sheet masses.

with 20th century data, implies a 21st sea level rise of about a meter, given expected global warming for BAU greenhouse gas emissions. Vermeer and Rahmstorf (2009) extended Rahmstorf's semi-empirical approach by adding a rapid response term, projecting sea level rise by 2100 of 0.75-1.9 m for the full range of IPCC climate scenarios. Grinsted et al. (2010) fit a 4-parameter linear response equation to temperature and sea level data for the past 2000 years, projecting a sea level rise of 0.9-1.3 m by 2100 for a middle IPCC scenario (A1B). These projections are typically a factor of 3-4 larger than the IPCC (2007) estimates, and thus they altered perceptions about the potential magnitude of human-caused sea level change.

Alley (2010) reviewed projections of sea level rise by 2100, showing several clustered around 1 m and one outlier at 5 m, all of which he approximated as linear. The 5 m estimate is what Hansen (2007) suggested was possible, given the assumption of a typical IPCC's BAU climate forcing scenario. Alley's graph is comforting, making the suggestion of a possible 5 m sea level rise seem to be an improbable outlier, because, in addition to disagreeing with all other projections, a half-meter sea level rise in the next 10 years is preposterous.

However, the fundamental issue is linearity versus non-linearity. Hansen (2005, 2007) argues that amplifying feedbacks make ice sheet disintegration necessarily highly non-linear. In a non-linear problem, the most relevant number for projecting sea level rise is the doubling time for the rate of mass loss. Hansen (2007) suggested that a 10-year doubling time was plausible, pointing out that such a doubling time from a base of 1 mm per year ice sheet contribution to sea level in the decade 2005-2015 would lead to a cumulative 5 m sea level rise by 2095.

Non-linear ice sheet disintegration can be slowed by negative feedbacks. Pfeffer et al. (2008) argue that kinematic constraints make sea level rise of more than 2 m this century physically untenable, and they contend that such a magnitude could occur only if all variables quickly accelerate to extremely high limits. They conclude that more plausible but still accelerated conditions could lead to sea level rise of 80 cm by 2100.

The kinematic constraint may have relevance to the Greenland ice sheet, although the assumptions of Pfeffer at al. (2008) are questionable even for Greenland. They assume that ice streams this century will disgorge ice no faster than the fastest rate observed in recent decades. That assumption is dubious, given the huge climate change that will occur under BAU scenarios, which have a positive (warming) climate forcing that is increasing at a rate dwarfing any known natural forcing. BAU scenarios lead to CO_2 levels higher than any time since 32 My ago, when Antarctica glaciated. By mid-century most of Greenland would be experiencing summer melting in a longer melt season. Also some Greenland ice stream outlets are in valleys with bedrock below sea level. As the terminus of an ice stream retreats inland, glacier sidewalls can collapse, creating a wider pathway for disgorging ice.

However, the primary flaw with the kinematic constraint concept is the geology of Antarctica, where large portions of the ice sheet are buttressed by ice shelves that will not survive BAU climate scenarios. West Antarctica's Pine Island Glacier (PIG) illustrates nonlinear processes coming into play. The floating ice shelf at PIG's terminus has been thinning in the past two decades as the ocean around Antarctica warms (Shepherd et al., 2004). Thus the grounding line of the glacier has moved inland by 30 km into deeper water, allowing potentially unstable ice sheet retreat. PIG's rate of mass loss has accelerated almost continuously for the past decade (Wingham et al., 2009) and may account for about half of the mass loss of the West Antarctic ice sheet, which is of the order of 100 km^3 per year (Sasgen et al., 2010).

PIG and neighboring glaciers in the Amundsen Sea sector of West Antarctica, which are also accelerating, contain enough ice to contribute 1-2 m to sea level. Most of West Antarctica, with at least 5 m of sea level, and about a third of East Antarctica, with another 15-20 m of sea level, are grounded below sea level. This more vulnerable ice may have been the source of the 25 ± 10 m sea level rise of the Pliocene (Dowsett et al., 1990, 1994). If human-made global warming reaches Pliocene levels this century, as expected under BAU scenarios, these greater volumes of ice will surely begin to contribute to sea level change. Indeed, satellite gravity and radar interferometry data reveal that the Totten Glacier of East Antarctica, which fronts a large ice mass grounded below sea level, is already beginning to lose mass (Rignot et al., 2008).

It is clear that there will be sufficient available ice to produce multi-meter sea level rise this century under BAU greenhouse gas scenarios. "Available ice" is the difference between current ice sheet mass and equilibrium ice sheet size for expected 21st century global temperature. The question is: how fast will that ice mass be converted to sea level rise given realistic nonlinear physics of ice sheet disintegration?

The most reliable indication of the imminence of multi-meter sea level rise may be provided by empirical evaluation of the doubling time for ice sheet mass loss. Mass loss by the Greenland and Antarctic ice sheets can be deduced from satellite measurements of Earth's gravity field. Fig. 8 shows mass loss reported by Velicogna (2009). The most important curves are the 12-month running means of the annual mass change of the Greenland and Antarctic ice sheets (heavy blue lines in Figs. 8c and 8d), which average out the annual cycle.

These data records are too short to provide a reliable evaluation of the doubling time, but, such as they are, they yield a best fit doubling time for annual mass loss of 5-6 years for both Greenland and Antarctica., consistent with the approximate doubling of annual mass loss in the period 2003-2008. There is substantial variation among alternative analyses of the gravity field data (Sorensen and Forsberg, 2010), but all analyses have an increasing mass loss with time, providing at least a tentative indication that long-term ice loss mass will be non-linear.

We conclude that available data for the ice sheet mass change are consistent with our expectation of a non-linear response, but the data record is too short and uncertain to allow quantitative assessment. The opportunity for assessment will rapidly improve in coming years if high-precision gravity measurements are continued.

Finally, we note the existence of a strong negative feedback described by Hansen (2009) that comes into play when the rate of sea level rise approaches the order of a meter per decade. Such an iceberg discharge rate temporarily overwhelms greenhouse warming, cooling high latitude atmosphere and ocean mixed layer below current levels. Ice sheet mass loss may slow in response to this cooling, but, as described qualitatively by Hansen (2009), it will be no consolation to humans. Stronger storms driven by increased latitudinal temperature gradients, combined with multi-meter sea level rise, will produce global havoc.

7. Summary Discussion

Paleoclimate records can help reveal likely consequences of a given level of global warming. However, we suggest that there have been some substantial misinterpretations about the level of global warming required to initiate large climate impacts.

Discussions of potential sea level change often assume that prior interglacial periods were much warmer than today. For example, from "Sea-Level Rise and Variability: Synthesis and Outlook for the Future" (Church et al., 2010): "The climatic conditions most similar to those expected in the latter part of the 21^{st} century occurred during the last interglacial, about 125000 years ago. At that time, some paleodata (Rohling et al., 2008) suggest rates of sea-level rise perhaps as high as 1.6 ± 0.8 m/century and sea level about 4-6 m above present-day values (Overpeck et al., 2006), with global temperature about 3-5°C higher than today (Otto-Bliesner et al., 2006)." Rohling et al. (2008) begin their paper "The last interglacial period, Marine Isotope Stage (MIS) 5e, was characterized by global mean surface temperature at least 2°C warmer than present (Otto-Bliesner et al., 2006)." However, the referenced Otto-Bliesner work is a climate model study and in fact the model does not actually yield global mean warming of 3-5°C, or 2°C, or even 1°C (Otto-Bliesner, 2006; Otto-Bliesner, 2011 personal communication).

Estimates of temperature in the Eemian and other periods should be based mainly on observations. As we show, observations suggest that moderate global warming above the Holocene level will have large effects at high latitudes and on global sea level.

Milankovic climate oscillations, the glacial-interglacial climate changes driven primarily by perturbations of Earth's orbit about the sun, allow extraction of our most accurate knowledge of equilibrium climate sensitivity. Paleoclimate records for changes of long-lived greenhouse gases and ice sheet area determine a global climate forcing, from which a fast-feedback climate sensitivity can be extracted, including the effects of changing water vapor, clouds, aerosols and sea ice cover. But the changes of ice sheet area and long-lived greenhouse gases in Milankovic climate oscillations are themselves slow climate feedbacks in response to perturbations of Earth's orbit that alter the seasonal and geographical distribution of sunlight. The fact that both fast and slow climate feedbacks are amplifying feedbacks and substantial in magnitude accounts for the remarkably high sensitivity of Earth's climate to the weak Milankovitch perturbations. We have discussed this topic extensively elsewhere (Hansen et al., 2008).

Our discussion here will focus not on equilibrium climate response, but rather the time-dependent climate response to human-made climate forcing. Paleoclimate data include no known analog to the human-made climate forcing, which is a strong positive (warming) forcing that is so rapid that the planet is out of energy balance today. However, paleoclimate data and satellite observations together yield valuable insights about likely climate effects.

a. Global temperature in prior warm periods

Ice cores and ocean cores are valuable complementary sources of climate information. Fig. 4 shows that they provide similar pictures of Milankovic glacial cycles, with one exception. Ice cores suggest that the Eemian and Holsteinian interglacials were warmer than the Holocene by 2°C or more. In contrast, ocean cores suggest that these earlier interglacials were warmer than the Holocene by at most one degree, perhaps by only tenths of a degree Celsius.

Ocean cores and ice cores each are limited as a measure of global temperature change. Ocean cores suffer from ambiguity in the contributions of ice volume and temperature. We use the global stack of ocean cores of Zachos et al. (2001), which gives greatest weight to Pacific Ocean deep water, to minimize effects of spatial and temporal variability.

Ocean cores have a systematic difficulty as a measure of temperature change when the deep ocean temperature approaches the freezing point, as quantified by Waelbroeck et al. (2002). However, by using the known surface temperature change between the last glacial maximum and the Holocene for empirical calibration, we maximize (i.e., we tend to exaggerate) the ocean core estimate of global surface warming during warmer interglacials relative to the Holocene.

Ice cores and ocean cores have uncertainty due to variability of measurement location. However, plausible changes of ice sheet altitude cannot account for discrepancies in Fig. 4. And the interglacial location of deep water formation around Antarctica, which affects deep Pacific Ocean temperature, is limited by the Antarctic geography and is unlikely to be far removed during slightly warmer interglacial periods.

Fig. 4 provides unambiguous discrimination between ice and ocean core measures of global temperature change. Climate sensitivity cannot vary much from one interglacial period to another. The climate forcings are known accurately. Ocean core temperatures give a consistent climate sensitivity for the entire 800,000 years. In contrast, the ice core temperature (Fig. 4a) leads to the illogical result that climate sensitivity depends on time.

We conclude that the ocean core data are correct in indicating that global temperature was only slightly higher in the Eemian and Holsteinian interglacial periods than in the Holocene, at most by about 1°C, but probably by only several tenths of a degree Celsius. Large Eemian warming occurred in Antarctica, but global warming was modest.

b. Phase change feedback mechanisms

Polar warmth during the Eemian was not limited to Antarctica. Central Greenland during the Eemian was 5°C warmer than in the Holocene (NGRIP, 2004).

Glacial-interglacial global temperature change is almost entirely accounted for by greenhouse gas and surface albedo changes, as shown by Fig. 4. Milankovic orbital parameters are a prime instigator of changes in those two forcings, but the additional direct effect of changes in the seasonal/geographical distribution of sunlight is modest. The direct reason that both poles were so warm in the Eemian, and sea level was high, is because the global mean temperature was slightly higher in the Eemian than it has been in the Holocene.

There is a simple explanation for why the Eemian and Holsteinian were only marginally warmer than the Holocene and yet had (both) poles several degrees Celsius warmer. Earth at peak Holocene temperature is poised such that additional warming instigates large amplifying high-latitude feedbacks. Mechanisms on the verge of being instigated include loss of Arctic sea ice, shrinkage of the Greenland ice sheet, loss of Antarctic ice shelves, and shrinkage of the Antarctic ice sheets. These are not runaway feedbacks, but together they strongly amplify the impacts in polar regions of a positive (warming) climate forcing.

Augmentation of peak Holocene temperature by even 1°C would be sufficient to trigger powerful amplifying polar feedbacks, leading to a planet at least as warm as in the Eemian and Holsteinian periods, making ice sheet disintegration and large sea level rise inevitable.

Empirical evidence supporting these assertions abounds. Global temperature increased 0.5°C in the past three decades (Hansen et al., 2010) to a level comparable to the prior Holocene maximum, or a few tenths of a degree higher. Satellite observations reveal rapid reduction of Arctic sea ice (Stroeve et al., 2007) and surface melt on a large growing portion of the Greenland ice sheet (Steffen et al., 2004; Tedesco et al., 2011).

Arctic response to human-made climate forcing is more apparent than Antarctic change, because the response time is quicker due to the large proportion of land area and Greenland's temperature, which allows a large expansion of the area with summer melting.

However, we must expect ice sheet mass balance changes will occur simultaneously in both hemispheres. Why? Because ice sheets in both hemispheres were in near-equilibrium with Holocene temperatures. That is probably why both Greenland and Antarctica began to shed ice in the past decade or so, because global temperature is just rising above the Holocene level.

Ice sheet disintegration in Antarctica depends on melting the underside of ice shelves as the ocean warms, a process well underway at the Pine Island glacier (Scott et al., 2009). The glacier's grounding line has retreated inland by tens of kilometers (Jenkins et al., 2010) and thinning of the ice sheet has spread inland hundreds of kilometers (Wingham et al., 2009).

c. Linear versus non-linear ice sheet disintegration

The asymmetry of glacial-interglacial climate cycles, with rapid warming and sea level rise in the warming phase and a slower descent into ice ages, suggests that amplifying feedbacks can make the "wet" ice sheet disintegration process relatively rapid (Hansen et al., 2007). But how rapid?

Paleoclimate records include cases in which sea level rose several meters per century, even though known natural positive forcings are much smaller than the human-made forcing. This implies that ice sheet disintegration can be a highly nonlinear process.

We suggest that a nonlinear process spurred by an increasing forcing and amplifying feedbacks is better characterized by the doubling time for the rate of mass disintegration, rather than a linear rate of mass change. If the doubling time is as short as a decade, multi-meter sea level rise could occur this century. Observations of mass loss from Greenland and Antarctica are too brief for significant conclusions, but they are not inconsistent with a doubling time of a decade or less. The picture will become clearer as the measurement record lengthens.

What constraints or negative feedbacks might limit nonlinear growth of ice sheet mass loss? An ice sheet sitting primarily on land above sea level, such as most of Greenland, may be limited by the speed at which it can deliver ice to the ocean via outlet glaciers. But much of the West Antarctic ice sheet, resting on bedrock below sea level, is not so constrained.

Hansen (2009) points out a negative feedback that comes into play as ice discharge approaches a level of the order of a meter per decade: cooling of the upper ocean by the ice. That negative feedback would be cold comfort. The high latitude cooling and low latitude warming would drive more powerful mid-latitude cyclonic storms, including more frequent cases of hurricane force winds. Such storms, in combination with rapidly rising sea level, would be disastrous for many of the great world cities and devastating for the world's economic wellbeing and cultural heritage.

d. Scenarios and predictions

Predictions of future sea level change are inherently difficult because, we assert, ice sheet disintegration is fundamentally a non-linear process. However, in addition, the climate forcing scenario is uncertain. When predictions are made, or statements that can be construed as predictions, it is important to be clear what climate forcing scenario is being considered.

IPCC BAU (business-as-usual) scenarios assume that greenhouse gas emissions will continue to increase, with the nations of the world burning most of the fossil fuels including unconventional fossil fuels such as tar sands.

An alternative extreme, one that places a substantial rising price on carbon emissions, would have CO_2 emissions beginning to decrease within less than a decade, as the world moves on energy systems beyond fossil fuels, leaving most of the remaining coal and unconventional fossil fuels in the ground. In this extreme scenario, let's call it fossil fuel phase-out (FFPO), CO_2 would rise above 400 ppm but begin a long decline by mid-century (Hansen et al., 2008).

The European Union 2°C scenario, call it EU2C, falls in between these two extremes.

BAU scenarios result in global warming of the order of 3-6°C. It is this scenario for which we assert that multi-meter sea level rise on the century time scale are not only possible, but almost dead certain. Such a huge rapidly increasing climate forcing dwarfs anything in the peleoclimate record. Antarctic ice shelves would disappear and the lower reaches of the Antarctic ice sheets would experience summer melt comparable to that on Greenland today.

The other extreme scenario, FFPO, does not eliminate the possibility of multi-meter sea level rise, but it leaves the time scale for ice sheet disintegration very uncertain, possibly very long. If the time scale is several centuries, then it may be possible to avoid large sea level rise by decreasing emissions fast enough to cause atmospheric greenhouse gases to decline in amount.

What about the intermediate scenario, EU2C? We have presented evidence in this paper that prior interglacial periods were less than 1°C warmer than the Holocene maximum. If we are correct in that conclusion, the EU2C scenario implies a sea level rise of many meters. It is difficult to predict a time scale for the sea level rise, but it would be dangerous and foolish to take such a global warming scenario as a goal.

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