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A Slippery Slope: How Much Global Warming Constitutes "Dangerous Anthropogenic Interference"?

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In a recent article (Hansen, 2004) I included a photograph taken by Roger Braithwaite with a rushing stream pouring into a hole in the Greenland ice sheet. The photo relates to my contention that disintegration of ice sheets is a wet, potentially rapid, process, and consequent sea level rise sets a low limit on the global warming that can be tolerated without risking dangerous anthropogenic interference with climate.

I asked glaciologist Jay Zwally if I would be crucified for a caption such as: "On a slippery slope to Hell, a stream of snowmelt cascades down a moulin on the Greenland ice sheet. The moulin, a near-vertical shaft worn in the ice by surface water, carries water to the base of the ice sheet. There the water is a lubricating fluid that speeds motion and disintegration of the ice sheet. Ice sheet growth is a slow dry process, inherently limited by the snowfall rate, but disintegration is a wet process, spurred by positive feedbacks, and once well underway it can be explosively rapid."

Zwally replied "Well, you have been crucified before, and March is the right time of year for that, but I would delete 'to Hell' and 'explosively'". I thought immediately of the fellow who went over Niagara Falls without a barrel. Wouldn't he consider that a joy ride, compared to slipping on the banks of the rushing melt-water stream, clawing desperately in the freezing water before being hurtled down the moulin more than a kilometer, and eventually being crushed by the giant grinding glacier? "A slippery slope to Hell" did not seem like an exaggeration.

On the other hand, I was using "slippery slope" mainly as a metaphor for the danger posed by global warming. So I changed "Hell" to "disaster".

What about "explosively"? Consider the situation during past ice sheet disintegrations. In melt-water pulse 1A, about 14,000 years ago, sea level rose about 20 meters in approximately 400 years (Kienast et al., 2003). That is an *average* of 1 meter of sea level rise every 20 years. The nature of glacier disintegration required for delivery of that much water from the ice sheets to the ocean would be spectacular (5 cm of sea level, the mean annual change, is about 15,000 cubic kilometers of water). "Explosively" would be an apt description, if future ice sheet disintegration were to occur at a substantial fraction of the melt-water pulse 1A rate.

Are we on a slippery slope now? Can human-made global warming cause ice sheet melting measured in meters of sea level rise, not centimeters, and can this occur in centuries, not millennia? Can the very inertia of the ice sheets, which protects us from rapid sea level change now, become our *bete noire* as portions of the ice sheet begin to accelerate, making it practically impossible to avoid disaster for coastal regions?

Ice sheet modeling: is something wrong with this picture? IPCC (2001) estimates sea level rise of between 9 and 88 cm in 110 years, for scenarios that include rapid, probably unrealistic, growth of climate forcings. This calculated sea level rise is due mainly to thermal expansion of ocean water, and secondarily to melting alpine glaciers, with the Greenland and Antarctic ice sheets calculated as being close to mass balance. For the heavily studied IS92a scenario, with 715 ppm of CO_2 in 2100, as well as large increases of CH_4, O_3 and black carbon (BC), the central estimate of sea level rise is 40-45 cm, with 30 cm from thermal expansion of ocean water, 10-15 cm from alpine glaciers, and practically no net change of the Greenland and Antarctic ice volume. More recent simulations with a high-resolution (T106) global climate model (Wild et al., 2003) result in both the Greenland and Antarctic ice sheets *growing* at a rate equivalent to *sea level fall* of 12 cm per century when doubled CO_2 (beyond today's level) is reached. These results, I argue, understate the potential for significant ice sheet disintegration.

Zwally et al. (2002) have shown empirically that ice sheet flow on Greenland speeds up in response to meltwater delivered to the ice sheet base via moulins. Parizek and Alley (2004) parameterize this melt-water basal lubrication in their two-dimensional ice sheet model, concluding that Greenland is likely to make a greater contribution to sea level rise than previously believed. However, their calculated sea level rise is still modest. For example, a scenario with CO_2 doubling by 2100 reduces the Greenland ice sheet volume less than 1% by 2100, yielding an 0.6-6.6 cm contribution to sea level rise, with the range depending upon uncertain model parameters.

Such a contribution to sea level rise seems almost innocuous. However, I suggest that the calculations do not yet fully and realistically incorporate important processes that will accelerate ice sheet disintegration.

Energy balance and feedbacks. The Earth is now out of energy balance by close to +1 W/m^2, i.e., with that much more energy absorbed from sunlight than the energy emitted to space as thermal radiation (Hansen 2004). This large growing planetary energy imbalance has no known precedent, greatly exceeding the global mean energy imbalance associated with changes of the Earth's orbital elements that paced the natural building and decay of ice sheets.

The planetary energy imbalance is due mainly to rapid growth of greenhouse gases, especially CO_2 and CH_4, and the thermal inertia of the ocean. CO_2 and CH_4 amounts today are far outside the ranges that existed for hundreds of thousands of years (Figure 1). Although pre-human climate changes were paced by changes of the Earth's orbit, the climate change mechanisms functioned by altering atmospheric composition and surface properties. Humans now control the Earth's atmospheric composition and surface properties. The impact of the changing atmosphere and surface on the Earth's energy balance can be calculated with global climate models and verified with measurements of ocean heat storage (Levitus et al., 2000).

The planetary energy imbalance increased rapidly in recent decades. The imbalance in 1950 is estimated to have been about 0.2 W/m^2 (Sun and Hansen, 2003). The integrated planetary energy imbalance for the past century was about 15 W-years per square meter, if we approximate the imbalance in the first half of the 20^{th} century as a linear increase from zero in 1900 to 0.2 W/m^2 in 1950 and take the imbalance after 1950 from either Hansen et al. (2002) or Sun and Hansen (2003).

If the planetary energy imbalance of 15 W-years had gone entirely into melting of ice, sea level would have risen just over a meter in the past century (Box 4 of Hansen, 2004). Actual sea level rise in the 20^{th} century was 15±5 cm, and much of the change was probably caused by thermal expansion of ocean water and changes in water storage on land (IPCC, 2001). Thus, at most, of the order of 5-10% of the planetary energy imbalance went into melting of ice.

One might argue that the energy that goes into melting of ice will continue to be small, if the planet adjusts locally to the energy imbalance with a small increase in temperature. However, I suggest that the fraction of the planetary energy imbalance that goes into melting of ice will increase in the future for reasons summarized in Figure 2. The ice sheet area undergoing melt increases as the planet warms, and the melt season begins earlier and lasts longer. Analyses of satellite data (Abdalati and Steffen, 2001) show an increasing area of summer melt since 1979 in most Greenland regions. Increased melt-water itself contributes to sea level rise, but its prime effect is to seep into crevasses and moulins, contributing to the break-up and movement of ice toward the ocean.

The immediate repository of most of the energy from the planetary imbalance is the ocean mixed layer. However, as the global mixed layer temperature rises, the pathways for energy to reach the ice will expand. A primary pathway is transport and melting of icebergs, a heat flux that will increase as ice discharge accelerates. In this case, heat does not literally move to the ice sheet. Rather it is a case of bringing the mountain to Mohammed: the ocean disperses icebergs over a broad area, where they melt by drawing heat from the ocean mixed layer.

The dispersed ice mechanism that allows ice sheet disintegration to be orders of magnitude more rapid than ice sheet growth is thus: increased summer melt on the ice sheet initiates ice stream surges and massive iceberg discharges, leading to rapid “crushed ice” melting in the ocean, not unlike that occurring when one chews an ice cube to fine bits. In the geophysical case, the negative feedback as ice melts and cools the mixed layer is limited by the induced regional planetary energy imbalance; the cooled mixed layer reduces upward radiative, sensible and latent heat fluxes, thus increasing the flux of heat into the planetary system. This feedback provides the overall system with a practically unlimited energy source, which can drive the planet rapidly toward a new equilibrium. Dispersal of the ice into the ocean is needed to make the whole process explosively rapid, because it both speeds ice melt and spreads the cooling over a wide area, thus increasing the fraction of the planet with a positive energy imbalance.

This mechanism must account for the rapid ice sheet disintegration and subsequent warming that occurs with Heinrich (1988) events. The Heinrich events, associated with the culminations of the saw-toothed Bond climate cycles, witness vast iceberg armadas that emerge from North America and stretch across the Atlantic Ocean to the region of Spain (Bond et al., 1992; Hulbe et al., 2004). The rapid ice melt and reduced ice area cause the saw-toothed shape of these climate cycles. In order for ice sheet models to yield realistic disintegration times they presumably must include the effects of dispersed ice on regional and planetary energy imbalance as well as basal lubrication effects.

Another mechanism transferring energy to the ice sheets will occur via increased atmospheric latent heat transport. Higher sea surface temperatures at low and middle latitudes will increase the intensity of rainfall on expanding areas of the ice sheets that are subject to summer rain. The process is episodic and the effects are highly non-linear with increasing temperature. An unusual weather event, analogous to the summer of 2003 in France, but rather in the form of heavy rains, perhaps of hurricane intensity, could have a huge long-lasting impact by “softening” the ice sheet and accelerating its movement and disintegration.

Ice sheet models cannot be used with confidence for assessing expected sea level change until they demonstrate an ability to reproduce ice sheet disintegration such as the Heinrich events, with realistic forcing yielding realistic rates of ice sheet demise. It will be interesting to examine the response of such a model to the incessant anthropogenic energy imbalance.

Another mechanism to consider is the effect of air pollution, especially soot, which accelerates ice melting (Hansen and Nazarenko, 2004), by absorbing sunlight, thus causing snow crystals to “age” (metamorphose into larger particles) and in turn causing the season with wet, dark snow to begin earlier and last longer. It is not known whether there is significant human-made soot on Greenland, although it is plausible that pollution from the Eastern United States could affect the important low altitude regions in southern Greenland, and soot from the Far East could conceivably reach Greenland. Even a few parts per billion of soot in snow can alter the reflectivity by 1% and thus have a significant effect (Warren and Wiscombe, 1980; Clarke et al., 1985, Hansen and Nazarenko, 2004).

The net effect of these processes, which eventually will include a positive feedback from lowering of the ice surface altitude, is the potential for a highly non-linear response, a process that could run out of control, possibly to the ultimate demise of the entire south dome (64°N) of the Greenland ice sheet, if the strong planetary forcing is maintained long enough. The question is: how long is "long enough"?

Time constants: the slippery slope. Three time constants play critical roles in creating a slippery slope for human society: T_1, the time required for climate, specifically ocean surface temperature, to respond to a forced change of planetary energy balance; T_2, the time it would take human society to change its energy systems enough to reverse the growth of greenhouse gases; T_3, the time required for ice sheets to respond substantially to a large relentless positive planetary energy imbalance. I define "substantially" to mean a total sea level rise of at least two meters, because that would be sufficient to flood large portions of Bangladesh, the Nile Delta, Florida, and many island nations, causing forced migration of tens to hundreds of millions of people. That criterion requires an ice melt contribution from Greenland and Antarctica of at least 1.5 meters, given the approximate half meter contribution expected this century from ocean thermal expansion and alpine glaciers.

T_1, the climate response time, is 50-100 years, as a result of the large thermal inertia of the ocean. T_2, the energy infrastructure time constant, also is perhaps 50-100 years. Although new technologies that reduce or eliminate greenhouse gases might be developed rapidly, these need to replace a huge fossil fuel infrastructure, and this technologic task is preceded by the time required to achieve world-wide agreement on the need for replacement.

T_3, the ice sheet response time, is the time constant of issue. I argue that T_3 is of the order of centuries, not millennia, as commonly assumed. Growth of ice sheets requires millennia, as growth is a dry process limited by the snowfall rate. Ice sheet disintegration, on the other hand, is a wet process that can proceed more rapidly, as evidenced by the saw-toothed shape of glacial-interglacial temperature and sea level records. For example, I referred above to the 20-meter sea level rise that occurred in about 400 years during deglaciation 14,000 years ago.

The ice sheets contributing to that deglaciation were at lower latitudes than the ice that remains today, and the period of rapid ice sheet disintegration was undoubtedly preceded by a period in which the ice was preconditioned for collapse. Balancing these considerations, and probably overwhelming them, are two counter considerations.

First, the growth of climate forcings in the anthropogenic era far exceeds that which spurred the natural deglaciations (Figure 1). CO_2 and CH_4 levels already dwarf any amounts that existed in the past hundreds of thousands of years. The most important consequence of this is the current planetary energy imbalance, which is now pouring energy into the Earth system at a rate sufficient to fuel rapid deglaciation once the process is set in motion.

Second, a 20-meter sea level rise is not required to wreak havoc with civilization today. Three-quarters of a meter each from Greenland and Antarctica would do the job quite well.

It seems inescapable to me that the time constant T_3 is measured in centuries, not millennia. I would be surprised if T_3 exceeded 1-3 centuries. Ice sheet models will not be capable of providing a good assessment of T_3 until they are driven by all anthropogenic forcings, incorporate realistically all significant processes and feedbacks, including those discussed above, and demonstrate the ability to simulate realistically rapid nonlinear ice sheet disintegration as occurred during meltwater pulse 1A.

The likelihood that T_3 is comparable to $T_1 + T_2$ has a staggering practical implication. $T_3 >> T_1 + T_2$ would permit a relatively complacent "wait and see" attitude toward ice sheet health. If, in the happy situation $T_3 >> T_1 + T_2$, we should confirm that human forcings were large enough to eventually alter the ice sheets, we would have plenty of time to reverse human forcings before the ice sheets responded.

Unfortunately, $T_3 \sim T_1 + T_2$ implies that once ice sheet changes pass a critical point, it will be impossible to avoid substantial ice sheet disintegration. The reason for this is evident in the definition of the time constants. The comparability of these time constants, together with the planetary energy imbalance, make the ice sheets a ticking time bomb.

If, as I have argued, T_3 indeed is not very much larger than $T_1 + T_2$, it becomes of high priority to detect as early as possible beginnings of ice sheet disintegration. High precision measurements of ice motion and sea level change are needed for early detection of any acceleration in the global rates of ice movement and sea level rise.

It might be argued that, should we pass the critical point when ice sheet disintegration begins to accelerate, we can seek an "engineering" solution. That may be true, but the difficulty of the task should not be underestimated. Physical barriers to corral the ice sheets are implausible. Could we pump water to the ice sheet summit, where it would freeze and thus lower sea level? That would require an enormous throughflow of water over an increasingly mobile surface. I have an image of engineers on the ice sheet desperately trying to repair rupturing pipelines as the ice sheet moves faster and faster. Perhaps the best that engineers could do is build dykes to protect regions such as Manhattan and the Netherlands, albeit for a limited time.

Potential implications of the human-made planetary energy imbalance for the response time of ice sheets are not yet fully appreciated, I believe. No known paleoclimate analogue exists. Except for a possible brief period following the next large volcanic eruption, the Earth's positive energy imbalance is now continuous, relentless, and still growing.

Surely the most practical way to defuse this time bomb, and maintain ice volumes, is to limit the anthropogenic climate forcing. But what limit must we achieve?

Climate forcing scenarios: what constitutes "dangerous anthropogenic interference"? I summarize here an argument made elsewhere (Hansen, 2004). Its elements are: (1) with the ~0.5°C warming of the past 50 years, global temperature now (Figure 1) approximately matches the peak level of the current (Holocene) interglacial period, which occurred about 6,000-9,000 years ago, (2) the global mean temperature during the penultimate (Eemian) and the several previous interglacial periods was not more than about 1°C greater than the peak Holocene temperature, (3) the Earth is now out of energy balance with space by at least 0.5-1W/m^2, implying that an additional global warming of close to 0.5°C is already "in the pipeline", and (4) the greater warmth in some previous interglacial periods led to sea level being several meters higher than today.

The first two assumptions, about global mean temperature at the peaks of the Holocene and preceding interglacial periods, are important, but I argue that they are unlikely to be far off the mark, and our argument is not sensitive to the precise values. Although some local ice sheet temperatures have larger variations, climate simulations show that 1°C global mean warming above current levels is already a large climate change, so it is unlikely that recent interglacial periods could have been much warmer than that globally. Temperatures inferred from ocean cores support this conclusion (cf. references below). Nevertheless, improved reconstructions of global temperature during previous interglacials are needed.

The third assumption, that the Earth is out of energy balance, is confirmed by observed increase of ocean heat content (Levitus et al., 2000). The fourth assumption, that sea level was higher than today during some prior interglacial periods, and that this was due to global warming, is harder to prove. Sea level at some locations was several meters higher than today during the Eemian period, although Lambeck and Nakada (1992) argue that this could have been a regional effect of isostatic uplift. Beach deposits and elevated reef terraces suggest that sea level in the interglacial period that occurred about 400,000 years ago (called stage 11) when global temperature was not much greater than in the Holocene (King and Howard, 2000; Droxler et al., 2003), may have stood as much as 20 m higher than today (Hearty et al., 1999), although a range of evidence suggests that sea level may have been only a few meters higher (Kennett, 2003). Additional uncertainty is caused by the difficulty in dating beach terraces of that age and the possibility that tectonic processes could change the volume of the ocean basin.

Although it is hard to establish precise global temperature and sea level during prior interglacial periods, it is reasonably clear that the Earth was not more than about 1°C warmer (global mean) than today during recent interglacials, sea level has changed substantially and almost synchronously with changes in global temperature, and there is no basis to expect that sea level should be capped at its present level. These conclusions, together with the discussion above about time constants, imply that global warming of more than 1°C above today's global temperature would likely constitute "dangerous anthropogenic interference" with climate. In turn, given the current planetary energy imbalance and empirical modeling evidence that climate sensitivity is about ¾°C per W/m^2, this implies that we should seek to keep long-term additional climate forcings from exceeding about 1 W/m^2.

Such limits on additional global warming and climate forcing are well below any IPCC (2001) scenario, even for CO_2 alone (Figure 3), let alone the air pollutants black carbon (BC) and tropospheric ozone (O_3), and the O_3 precursor CH_4, all of which IPCC (2001) has at higher levels in 2050 than in 2000. The "alternative scenario" (Hansen et al., 2000; Hansen, 2004) has CO_2 peaking at ~475 ppm in 2100. CH_4 peaks at 1787 ppb in 2014, decreasing to 1530 in 2050. O_3 and BC decrease moderately in this scenario. This scenario has peak added forcing ~1.4 W/m^2 in 2100, with the forcing declining slowly thereafter. Because of the climate system's thermal inertia, the maximum warming does not exceed ~1°C.

Given the extreme nature of the alternative scenario (by the standards of IPCC) and the fact that some scientists may argue that global warming greater than 1°C is permissible, Hansen and Sato (2004) have also defined a "2°C" scenario (for climate sensitivity 3/4°C per W/m^2) in which CO_2 peaks at 560 ppm in 2100. However, the 2°C scenario cannot be recommended as a responsible target, as it almost surely takes us well into the realm of dangerous anthropogenic interference with the climate system.

I hope that I am wrong about the level of climate forcings that will constitute dangerous anthropogenic interference, because, despite the technical feasibility of the alternative scenario, there is not much action being taken to achieve it. The most difficult part of that scenario is to get CO_2 emissions to flatten out and eventually decline. Global fossil fuel emissions continue to climb by 1-1.5% per year and annual CO_2 growth over the past 10 years (through 2003) averaged 1.7 ppm/year, which is the starting point for the 21st century CO_2 growth rate in the alternative scenario. However, in three of the past six years (1998, 2002, 2003) the annual CO_2 increment exceeded 2 ppm/year, and the background CO_2 growth rate is now 1.9 ppm/year (Hansen and Sato, 2004).

I have pointed out that the growth rate of climate forcings in the real world is notably less than in typical IPCC scenarios, and I have argued that practical actions with multiple benefits could slow and eventually stop the global warming process (Hansen, 2004). However, I do not imply that such a slowdown can occur without strategic planning and strong concerted actions. If our assessment of the level of "dangerous anthropogenic interference" is anywhere near the mark, urgent actions are needed for both CO_2 and non-CO_2 climate forcings.

Philosophy. Richard Feynmann liked to remind us how science works. We must continually question our conclusions, presenting all sides of an argument equally, and changing our conclusions when the evidence warrants it.

I have been told that my discussion (Hansen, 2004) is too critical of IPCC. This, I believe, is a misreading of the spirit of my discussion. I aim to be no more or less critical of IPCC than of my own papers.

However, I disagree with the implication of Allen et al. (2001) that conclusions about climate change should wait until IPCC goes through a ponderous process, and that verdicts reached by IPCC are near gospel. IPCC conclusions, even after their extensive review and publication, must be subjected to the same scientific process as all others.

In the case at hand, I realize that I am no glaciologist and could be wrong about the ice sheets. Perhaps, as IPCC (2001) and more recent global models suggest, the ice sheets are quite stable and may even grow with doubling of CO_2. I hope those authors are right. But I doubt it.

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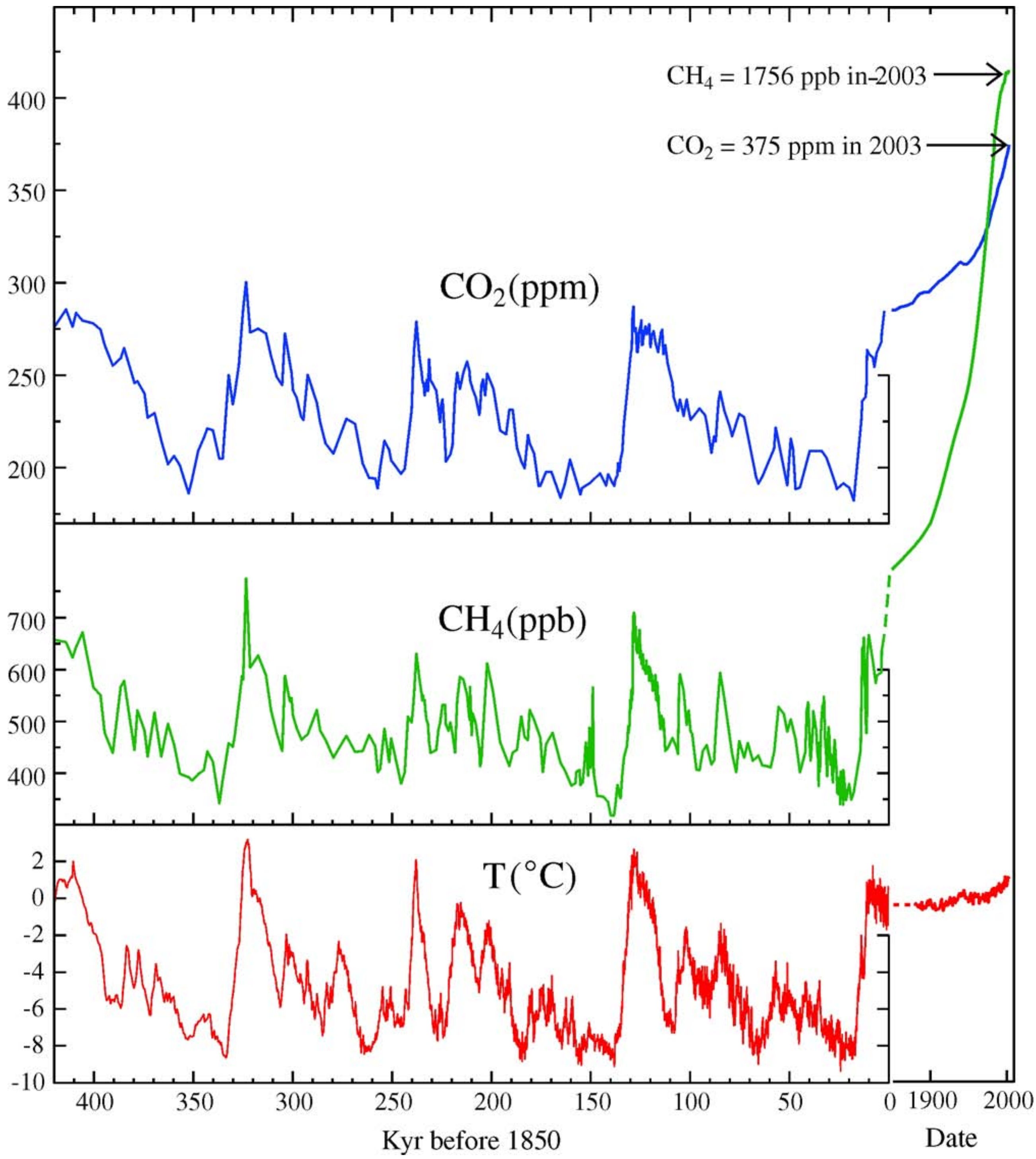
Figures

Figure 1. Record of atmospheric CO_2, CH_4, and temperature extracted from Antarctic ice core by Petit et al. (1999) and from in situ and other data for the past century. The temperature change for the past century, for comparability to the ice core record for earlier times, is twice the global mean temperature change of Hansen et al. (2001). The temperature zero-point is the mean for1880-1899.

Figure 2. The human-made planetary energy imbalance is now an incessant ~1 W/m^2. This energy divides primarily into warming the ocean and melting ice. If ocean temperature held fixed, so that the energy imbalance went entirely into melting ice, the 1 W/m^2 imbalance would cause sea level to rise at a rate of about 1 meter every 12 years. The fraction of the energy imbalance that goes into melting, which was small in the 20^{th} century, will increase as the atmosphere becomes moister and transports energy more efficiently to the ice, and especially as ice streams accelerate and more ice is rafted to warmer regions. The armadas of ice cool the ocean, thus maintaining or increasing the planetary energy imbalance. High precision measurements of ice motion and sea level change are needed for early detection of any acceleration in the rates of ice movement and sea level rise.

Figure 3. Atmospheric CO_2 amount in the “alternative”, “2°C”, and the range of IPCC (2001) scenarios. Scenario A1B is similar to the IS92a scenario in previous IPCC reports.



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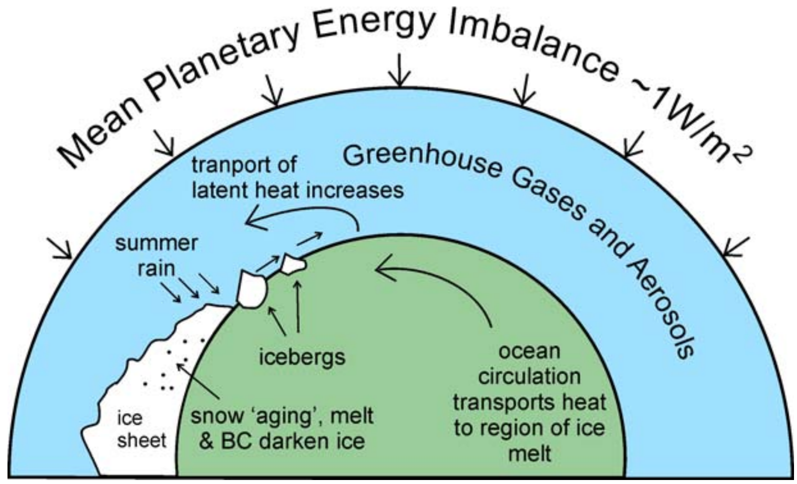

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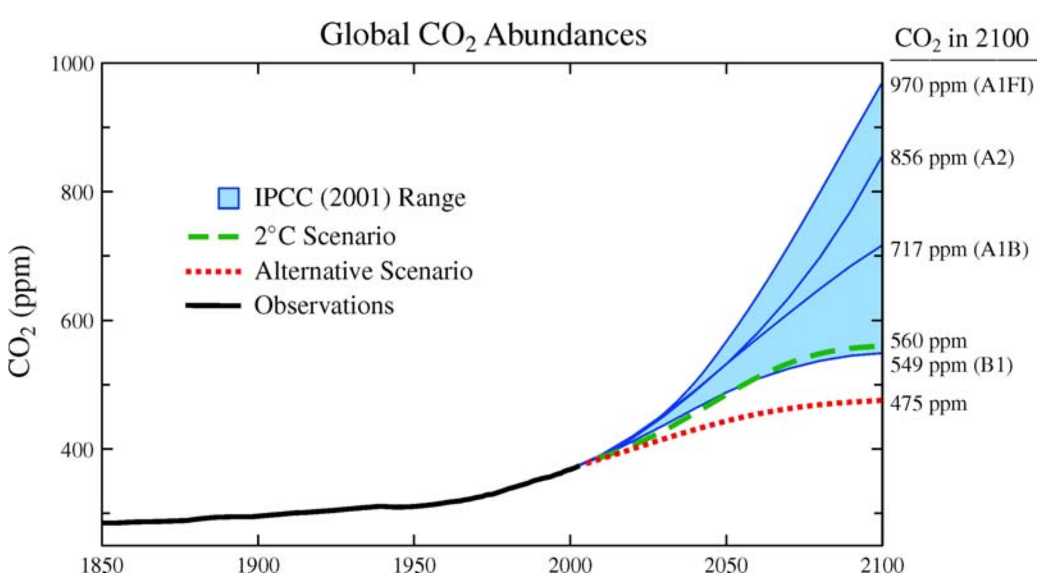

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