Is There Still Time to Avoid 'Dangerous Anthropogenic Interference' with Global Climate?*[#]

A Tribute to Charles David Keeling

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David Keeling altered our perspectives about global change with his painstaking observations of atmospheric carbon dioxide. The now famous 'Keeling curve', measuring both the pulse of Nature and a steadily rising human impact on atmospheric composition, is invariably hailed as our most rigorous and fundamental measure of global change. Carbon dioxide is joined by other key metrics that help define the causes and consequences of global climate change. The Earth's history provides our best indication of the levels of change that are likely to have deleterious effects on humans and wildlife, and constitute "dangerous anthropogenic interference" with nature.

The Earth's temperature, with rapid global warming over the past 30 years, is now passing through the peak level of the Holocene, a period of relatively stable climate that has existed for more than 10,000 years. Further warming of more than 1ºC will make the Earth warmer than it has been in a million years. "Business-as-usual" scenarios, with fossil fuel CO_2 emissions continuing to increase ~2%/year as in the past decade, yield additional warming of 2 or 3°C this century and imply changes that constitute practically a different planet.

I present multiple lines of evidence indicating that the Earth's climate is nearing, but has not passed, a tipping point, beyond which it will be impossible to avoid climate change with far ranging undesirable consequences. The changes include not only loss of the Arctic as we know it, with all that implies for wildlife and indigenous peoples, but losses on a much vaster scale due to worldwide rising seas. Sea level will increase slowly at first, as losses at the fringes of Greenland and Antarctica due to accelerating ice streams are nearly balanced by increased snowfall and ice sheet thickening in the ice sheet interiors. But as Greenland and West Antarctic ice is softened and lubricated by melt-water and as buttressing ice shelves disappear due to a warming ocean, the balance will tip toward ice loss, thus bringing multiple positive feedbacks into play and causing rapid ice sheet disintegration. The Earth's history suggests that with warming of 2-3°C the new equilibrium sea level will include not only most of the ice from Greenland and West Antarctica, but a portion of East Antarctica, raising sea level of the order of 25 meters (80 feet).

Contrary to lethargic ice sheet models, real world data suggest substantial ice sheet and sea level change in centuries, not millennia. The century time scale offers little consolation to coastal dwellers, because they will be faced with irregular incursions associated with storms and with continually rebuilding above a transient water level.

The grim "business-as usual" climate change is avoided in an alternative scenario in which growth of greenhouse gas emissions is slowed in the first quarter of this century, primarily via concerted improvements in energy efficiency and a parallel reduction of non-CO_2 climate forcings, and then reduced via advanced energy technologies that yield a cleaner atmosphere as well as a stable climate. The required actions make practical sense and have other benefits, but they will not happen without strong policy leadership and international cooperation. Action must be prompt, otherwise CO_2-producing infrastructure that may be built within a decade will make it impractical to keep further global warming under 1°C.

There is little merit in casting blame for inaction, unless it helps point toward a solution. It seems to me that special interests have been a roadblock wielding undue influence over policymakers. The special interests seek to maintain short-term profits with little regard to either the long-term impact on the planet that will be inherited by our children and grandchildren or the long-term economic well-being of our country.

The public, if well-informed, has the ability to override the influence of special interests, and the public has shown that they feel a stewardship toward the Earth and all of its inhabitants. Scientists can play a useful role if they help communicate the climate change story to the public in a credible understandable fashion.

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Is There Still Time to Avoid 'Dangerous Anthropogenic Interference' with Global Climate?

A. Introduction: CO_2 and Temperature Data

Chart 1. Is There Still Time to Avoid 'Dangerous Anthropogenic Interference' with Global Climate?
A Tribute to Charles David Keeling

I thank Ralph Keeling for inviting me to speak on climate change in honor of his father, which is a great privilege. This is a fitting time to take stock of how well we understand the message about climate change contained in the now famous 'Keeling curve' of increasing atmospheric carbon dioxide (CO_2). And to consider how well we have responded to that message.

The scientific CO_2-climate story began in earnest in the mid-19th century when the British physicist John Tyndall made laboratory measurements of infrared absorption by CO_2. He realized that CO_2 in the air, and water vapor that goes along with it, acts like a blanket, trapping the Earth's heat that was created by sunlight, and keeping the Earth's surface tens of degrees warmer than it otherwise would be without these 'greenhouse' gases. Tyndall also realized that the amount of CO_2 in the air could change, and he speculated, correctly as it turns out, that CO_2 changes may have been one of the principal agents involved in the waxing and waning of ice ages and warm interglacial periods. In the following 100 years a number of scientists[1] pondered the possible climate effects of CO_2 that humans were putting into the air by burning fossil fuels, coal, oil, and gas. [8-pitch text, including the two footnotes, was not used in the oral presentation]

Chart 2. The Keeling Curve.
Atmospheric CO_2 measured at Mauna Loa, Hawaii. Source: NOAA Climate Monitoring and Diagnostic Laboratory

Charles David Keeling was a stickler for precision. The measurements of CO_2 he began in the 1950s were an order of magnitude more accurate than previous measurements. In recognizing the value of a continuous record, and obtaining it, he brought a clarity to the problem that altered our perceptions about global change and the degree to which the Earth can absorb the human assault.

Dave Keeling had the focus and dedication of a scientist who realizes that he is onto an important problem and has the tools to address it. In the book "Thin Ice" Mark Bowan notes that when Dave got his tool working, although his life shows what a loving family man he was, he missed the birth of his first child, because he went out every four hours to measure CO_2.

What he found was that atmospheric CO_2 decreased in the daytime as plants assimilated CO_2 and increased at night as they respired. Plants in effect take one breath a day, and the Earth, as we see at this remote place in the middle of the Pacific, takes one breath a year.

I will discuss climate change, but first a few details about CO_2. This Keeling curve may look almost like a linear increase. It is not. CO_2 growth is closely related to fossil fuel use. We know two numbers accurately in the CO_2 story. One number is the annual global CO_2 increase, which we know for half a century, thanks to this record started by Dave Keeling.

Chart 3. Global Fossil-Fuel CO_2 Annual Emissions.
Fossil fuel CO_2 emissions based on data from Marland and Boden (DOE, Oak Ridge) and British Petroleum.
Source: Hansen and Sato, *PNAS*, **98**, 14778, 2001.

The second number is the global annual emissions of CO_2 from burning of fossil fuels. Coal was the only significant fossil fuel for a century. Oil overtook coal a few decades ago, at least

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[1] The early contributions of Tyndall (*Phil. Mag.*, **22**, 277, 1861) and Arrhenius (*Phil. Mag.*, **41**, 264, 1896) are well known. Arrhenius used infrared measurements by S. P. Langley of the moon, at varying angles in the sky and different seasons, to estimate absorption by atmospheric H_2O and CO_2, and he carried out calculations suggesting that doubling atmospheric CO_2 would raise the Earth's temperature about 5-6°C. An insightful paper by E. O. Hulburt (*Phys. Rev.*, **38**, 1876, 1931) has not received deserved attention. Hulburt recognized the role of convection in altering the atmospheric temperature profile and he carried out calculations having a much firmer basis than those of Arrhenius, inferring that doubling of CO_2 would raise the Earth's temperature about 4°C, given time to establish a new equilibrium, a climate sensitivity within the range of modern estimates. I thank Kerry Emanuel for drawing my attention to Hulburt's paper.

temporarily, and gas is now gaining. Total fossil fuel use increased about 4½ percent per year for a century, but since 1973 the growth rate has averaged about 1½ percent per year.

Chart 4. CO_2 airborne fraction.
CO_2 airborne fraction, i.e., ratio of annual atmospheric CO_2 increase to annual fossil fuel CO_2 emissions. Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

The ratio of the annual CO_2 increase in the atmosphere to the annual CO_2 emissions, the airborne fraction, varies a lot from year to year, but it has averaged about 58% for half a century with no obvious trend. The other 42% must be taken up by the ocean, the vegetation, and the soils. The ocean is thought to take up about 20-35%, leaving 5-20% as the net sink in vegetation and soil. Vegetation and soils are also a source of CO_2 via deforestation and biomass burning, so I refer to their net effect.

There is a concern that the sinks for CO_2 might tend to saturate or become less efficient. These data provide no empirical evidence of that. In absolute terms the sink has increased in proportion to the source. The sink is also approximately proportional to the difference between atmospheric CO_2 amount and pre-industrial CO_2 amount, with 1½% of that difference being taken up by the planet's surface each year. That proportionality will not necessarily continue.

If we wanted to stabilize atmospheric CO_2 for the next few years, we would need to cut fossil fuel emissions by about 60%. But, because of backpressure from CO_2 added to the ocean, in the long run the cut in emissions must be larger than 60% to stabilize atmospheric amount.

Chart 5. Global Fossil Fuel CO_2 Emissions.
Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land. Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

Here are the annual fossil fuel CO_2 emissions on a linear scale, to make the increase clear. Emissions grew 2%/year over the past decade, so annual emissions are now 7½ Gigatons. 58% of that means that the average atmospheric increase has climbed to 2 ppm per year.

Chart 6. Annual CO_2 Growth (ppm/year).
Growth rate of atmospheric CO_2 (ppm/year). Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

Finally, let's look at the annual CO_2 increase over a longer period. Ice core data provides an estimate for the prior century. The blue curve is the derivative of the Keeling curve. The current growth rate of 2%/year is similar to that in the IPCC A1FI and A1B scenarios. I will discuss scenarios more at the end of my talk.

Chart 7. Carbon Dioxide: Good News and Bad News.
Chart 7. CO_2 uptake is increasing, but a large cut in emissions is needed for stabilization and emissions are growing.

In summary, the good news about CO_2 is that about 40% of annual fossil fuel emissions continues to be soaked up. And if we decreased CO_2 emissions and improved reforestation and agricultural practices we could probably increase the percentage uptake. The bad news is that stabilization of atmospheric CO_2 amount may require reducing emissions by as much as 60-80%. But, on the contrary, emissions are still increasing.

Chart 8. Land-Ocean Temperature Index.
Global mean surface temperature change based on surface air measurements over land and SSTs over ocean.
Sources: Hansen *et al.*, *JGR*, **106**, 23947, 2001; Reynolds and Smith, *J. Climate*, **7**, 1994; Rayner et al., *JGR*, **108**, 2003.

The great interest in CO_2 is due to the realization that increasing CO_2, other things being equal, will cause global warming. CO_2 is a greenhouse gas. It absorbs the Earth's infrared radiation, reducing the emission of heat to space. This causes a temporary imbalance between the amount of solar energy absorbed by the Earth and the energy emitted to space. So the Earth will warm up until it restores energy balance.

Indeed, the Earth is getting warmer. Rapid warming in the past three decades coincides with the time in which greenhouse gas climate forcing became much larger than other climate forcings.

The temperature in 2005 so far is approximately the same as in 1998, which is remarkable because the 1998 temperature had jumped two standard deviations above the trend line, driven by the strongest El Nino of the century. Global warming in just the past 30 years is more than one-half degree Celsius, about 1 degree Fahrenheit in 30 years.

Chart 9. 1900-2005 Surface Temperature Change (°C).
Change of surface temperature index based on local linear trends using surface air measurements over land and SST over ocean. Sources: Hansen *et al.*, *JGR*, **106**, 23947, 2001; Reynolds and Smith, *J. Climate*, **7**, 1994; Rayner et al., *JGR*, **108**, 2003.

This is a map of estimated surface temperature change in the past century, areas of yellow, orange, red, brown being regions with significant warming. This is based on measurements of weather stations, ships, and recently satellites. It is confirmed by a large number of other direct and indirect measurements of temperature change. Local effects such as urban warming have been minimized and average near zero. Largest areas of warming are over the ocean and the greatest magnitude of warming is in regions remote from urban effects. The climate change is real and of a magnitude that it should now begin to be noticed by most people.

B. Climate Sensitivity

Chart 10. Climate Sensitivity: Empirical data … aided by models … □ precise evaluation.

Let's turn to climate sensitivity. Our most precise knowledge about climate sensitivity comes not from climate models per se, but from empirical information on climate change interpreted with the aid of climate models.

Climate sensitivity depends on the time scale of interest. The Charney definition of climate sensitivity is appropriate for the century time scale. This definition keeps ice sheet area fixed, but allows fast feedback processes such as clouds, water vapor, and sea ice to change in response to a specified "forcing" such as doubled atmospheric CO_2. Climate models per se yield an equilibrium warming of about 3°C for doubled CO_2, with a very large uncertainty bar.

Chart 11. Antarctic Time Series for CO_2, CH_4 and Temperature
CO_2, CH_4 and temperature records from Antarctic ice cores.
Sources: Petit *et al.*, *Nature*, **399**, 429, 1999 ; Vimeux *et al.*, *Earth Planet. Sci. Lett.*, **203**, 829, 2002.

We can evaluate climate sensitivity more accurately from paleoclimate data. These are records of CO_2, methane and temperature for the past 400,000 years extracted from Antarctic ice cores. [The ice sheet covering Antarctica was built from snow piling up year-by-year, which traps bubbles of air that preserve a record of atmospheric composition. Bubbles are sealed in ice only after there is enough weight of snow overhead, so the air is somewhat (typically ~ 1000 years) 'younger' than the ice that encloses it. The age difference depends on the snowfall rate, so the possible error in comparing ice age and air (CO_2/CH_4) age is of the order of 1000 years. The error in absolute age, which is obtained from the decay of carbon isotopes and other methods, is as much as several thousand years. The absolute age, or some common time scale, is needed for comparing the ice core data with other records, such as ocean sediment cores that are used to infer sea level changes. Thus in comparing time series from different sources the possible timing errors are often several thousand years or more. In some cases special events recorded in the ice cores or sediments allow synchronization to higher precision. These timing errors are of no consequence when we compare the planet's radiation balance averaged over the current interglacial period with that of the last ice age.] The Earth must be in radiation balance within a fraction of 1 W/m^2 averaged over 1000 years. For example, in say 1000 years 1 W/m^2 could melt enough ice to raise sea level 100 m or change ocean temperature by a large amount, which we know did not happen. So we can compare the energy balance of the current interglacial period (on the right) with the peak of the last ice age, 20,000 years earlier.

Chart 12. Ice Age Climate Forcings
Ice age forcings imply an equilibrium global climate sensitivity ¾°C per W/m^2.
Source: Hansen et al., *Natl. Geogr. Res. & Explor.*, **9**, 141, 1993.

The temperature change between full glacial and interglacial conditions is about 10ºC in Antarctica, about 3ºC at the Pacific Warm Pool on the equator, and 5±1ºC on global average. We know the change of surface conditions on the planet quite well, the ice sheet area being the dominant change. The total forcing of about 6½ W/m^2 implies a climate sensitivity of ¾ ± ¼ ºC per W/m^2 or 3 ± 1 ºC for doubled CO_2. This empirical climate sensitivity includes perfect cloud, water vapor, and sea ice physics, and any other processes operating in the real world. The result falls in the middle of the range found by climate models per se, but this empirical result is more accurate. And now this result can be put to an acid test…

Chart 13. Sea Level from Red Sea Analysis of Siddall et al.
Global sea level extracted, via a hydraulic model, from an oxygen isotope record for the Red Sea over the past 470 thousand years (concatenates Siddall's MD921017, Byrd, and Glacial Recovery data sets; AMS radiocarbon dating).
Source: Siddall et al., *Nature*, **423**, 853-858, 2003.

…because detailed sea level is available for the past 400,000 years. For reasonable assumptions about the shape of ice sheets, we can approximate the area covered by the ice sheet, and thus its climate forcing, as being proportional to the sea level change to the 2/3 power. Given the ice sheet forcing of 3½ W/m^2 20,000 years ago, when sea level was about 110 meters lower, we obtain an ice sheet forcing for the entire 400,000 year period.

Chart 14. Paleoclimate Forcings
Ice sheet forcing ~ (sea level)$^{2/3}$
GHGs = $CO_2 + CH_4 + N_2O$ (=0.15 forcing of $CO_2 + CH_4$)

We can calculate the CO_2 and CH_4 forcings very accurately. N_2O is not measured as well, but we know the magnitude of the total glacial to interglacial change and can take the time dependence as an average of that for CO_2 and CH_4, because it is a small term. The CH_4 forcing includes the fact that its efficacy is 140%. The ice sheet and greenhouse gas forcings are comparable in magnitude. Dating errors in comparing the Red Sea radiocarbon-dated sea level with ice core gases can be as much as several thousand years.

The planet must be in radiation balance on these time scales, so we can just multiply the sum of these two forcings by climate sensitivity, which is ¾ of a degree per W/m^2, to obtain an estimate for global temperature change, ...

Chart 15. Paleoclimate Temperature Change
Observations = Vostok □T/2. Calculated temperature = Forcing x 0.75°C/W/m^2

which is the blue curve. Observed temperature is taken here as one-half of the Vostok temperature. The agreement of observed temperature with that calculated from known forcings, without even making any time scale adjustments that could improve the fit, has important implications. These implications can be understood with the help of two more pieces of information.

Chart 16. Lag of Global Ice & CO_2 Relative to S.H. Temperature
Leads and lags of Vostok temperature and global ice volume relative to CO_2. Shaded bar is 1□ uncertainty. Temperature and ice are more contemporaneous at some terminations. Source: M. Mudelsee, quat. Sci. Rev., 20, 583, 2001.

First, careful examination of the leads and lags among temperature, ice volume or sea level, and CO_2, as carried out, for example, by Manfred Mudelsee, shows that temperature changes lead greenhouse gas changes, usually by about 1000 years or so. Overall, ice volume or sea level changes lag the temperature by several thousand years. But at terminations, when ice sheets disintegrate, the lags are more variable. At some terminations the ice and temperature changes are more nearly coincident. For example, Meltwater Pulse 1A, about 14,000 years ago, when sea level went up 20 meters at a rate of 1 meter every 20 years, seems to have been coincident with the Bolling warming within the resolution of certain measurements, which is a few hundred years (Kienast et al., *Geology*, **31**, 67, 2003).

Chart 17. CO_2, CH_4 and Temperature.
CO_2, CH_4 and estimated global temperature (Antarctic $\Delta T/2$ in ice core era). 0 = 1880-1899 mean.
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

Second, we need to realize that the greenhouse gas forcing that the climate system is being pushed by now is far greater than it has been in hundreds of thousands of years, and it will remain so for a long time because of the long lifetime of some of these gases. Also, in the past century, for which I have greatly expanded the time scale, the planet is not in energy balance with space, unlike the earlier part of the graph. In the present century the forcing was added so fast that the temperature has not yet had time to fully respond.

Chart 18. Implications of Paleo Forcings and Response

It follows that feedbacks – or you can describe greenhouse gas changes or ice sheet changes as indirect forcings, if you prefer, indirect forcings brought about by Earth orbital changes or other factors, but nevertheless they operate mainly via the temperature change – and it follows that these "feedback" mechanisms cause almost all of the paleo temperature change. Therefore climate change on these time scales is very sensitive to even small forcings. And the instigators of climate change, the pacemakers, must include Earth orbital variations, any other small forcings, and noise. Because of the human-made greenhouse gases, another "ice age" cannot occur unless humans become extinct. Even then, it would require thousands of years. Humans now control global climate, for better or worse.[2]

C. Climate Change in the Industrial Era

Chart 19. Effective Climate Forcings (W/m^2): 1750-2000.
Climate forcing agents in the industrial era. "Effective" forcing accounts for "efficacy" of the forcing mechanism.
Source: Hansen *et al.*, *JGR*, **110**, D18104, 2005.

Now let's turn to the industrial era. Humans have introduced an array of climate forcings, i.e., alterations of the planet's energy budget that tend to change the Earth's temperature. The forcings by greenhouse gases are known accurately, within about 15%. Forcing by aerosols, including their effects on clouds, is not known accurately, with an uncertainty of at least 50%. In recent decades the growth rate of aerosols has slowed, as some countries have tried to reduce particulate air pollution.

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[2] The above charts bear upon and support Bill Ruddiman's hypothesis (*Clim. Change*, **61**,261, 2003) that human's began to significantly affect atmospheric composition several thousand years prior to the industrial revolution. The increases of greenhouse gases (especially the CO_2 increase from 260 to 280 ppm) during the present interglacial, after full interglacial conditions were achieved, sea level had practically stopped rising, and temperature was stable or even declining, are indeed unique in the available ice core data record, including the EPICA extension. Curiously, a blip in CH_4 found in the EPICA ice core has been cited (Spahni *et al.*, *Science*, **310**, 1317, 2005) as if it were a strong refutation of Ruddiman's hypothesis, even though the blip did not occur during an interglacial period, sea level was far from a maximum, and thus ice sheet area was still changing.

The results in our charts do not support a secondary inference of Ruddiman, specifically that the pre-industrial human influence on atmospheric composition 'saved' the Earth from an impending ice age. It has been pointed out by numerous people that the Earth's orbital parameters during the current interglacial period resemble more closely the long (~30 kyr) interglacial period that occurred ~400 kyr ago, rather than subsequent briefer interglacials. Furthermore, we would expect that the net early human-made climate forcing would be one of cooling, not warming. Although, human-made greenhouse gas forcing is a positive (warming) forcing, the same (agricultural, deforestation) activities that increased greenhouse gases also increased atmospheric aerosols and increased the Earth's surface albedo. The aerosol effect is strongly non-linear, with human-made aerosols in a nearly pristine atmosphere being much more effective than those added to the present atmosphere. Even during the industrial era, up to about 1975, greenhouse gases and aerosols battled on comparable terms for control of global temperature. It is only in the past few decades, as technologies have reduced aerosol emission relative to greenhouse gases, that greenhouse gases have assumed overwhelming control of the net human-made climate forcing. Note in Chart 15 the discrepancy between simulated and observed temperatures during the past several thousand years, presumably a consequence of the fact that the computed temperature includes greenhouse gases, but not the (unmeasured) negative human-made forcings (land use and aerosol direct and indirect forcings).

Chart 20. Global Climate Forcings and Surface Temperature Change.
(A) Forcings used to drive climate simulations. (B) Simulated and observed surface temperature change.
Source: Hansen *et al*., *Science*, **308**, 1431, 2005.

Our best estimate for these forcings, shown in the upper graph, includes the sporadic cooling effect of volcanic aerosols, which is known rather well. The solar forcing is based on the estimate of Judith Lean in her 2000 JGR paper, which includes a modest positive trend over this period. The net forcing is about 1.85 W/m^2 in 2003 relative to 1880.

These forcings yield a global warming over the past century that is in good agreement with observations. We could have achieved comparable agreement if we had used a larger forcing in a model with smaller climate sensitivity, or conversely. However, the sensitivity of our model, 2.7°C for doubled CO_2 is close to that indicated by paleoclimate data.

Chart 21. Planetary Energy Imbalance and Ocean Heat Content.
(A) Net radiation at top of atmosphere in climate simulations. (B) Ocean heat gain in top 750 m of world ocean.
Source: Hansen *et al*., *Science*, **308**, 1431, 2005.

An important result of the climate simulations is that the planet should now be out of energy balance, if the forcings and model sensitivity are approximately correct. This energy imbalance is a direct result of greenhouse gases blocking outgoing radiation, so it is a fundamental test of the greenhouse effect. Given the large calculated imbalance in the past decade, and improved observations of ocean heat content, which must be the primary repository for the energy, we have an acid test of the theory. The agreement with observed ocean heat gain is a smoking gun that shows the greenhouse effect is the cause of observed warming. Continued precise ocean heat measurements are a critical metric, because this imbalance is the net climate forcing that is still acting on the planet.

Chart 22. Consistency Check and Implications.
Earth's energy imbalance implies further warming and sea level rise are "in the pipeline".
Source: Hansen *et al*., *Science*, **308**, 1431, 2005.

So of the 1.85 W/m^2 net forcing in 2003 relative to 1880, 1 W/m^2 was used up to produce the observed 0.7°C global warming. The remaining 0.85 W/m^2 remains to be responded to. Which means there is 0.6°C global warming still in the pipeline. The imbalance also confirms the long lag time of the climate system, which is a practical problem, because it means that, once we decide on the level of global warming that is dangerous, we must take anticipatory actions well before we get there. Another implication, I will argue, is that sea level rise is likely to accelerate.

D. Dangerous Anthropogenic Interference

Chart 23. United Nations Framework Convention on Climate Change.

Almost 15 years ago all nations, including the United States, agreed to the Framework Convention on Climate Change. The purpose and goal of the Convention is to stabilize greenhouse gas emissions at a level that prevents dangerous anthropogenic interference with the climate system.

Chart 24. IPCC Burning Embers.
Reasons for concern about projected climate change impacts.
Source: IPCC *Climate Change 2001: Impacts, Adaptation, and Vulnerability.*

A critical issue is then: what level of global warming would constitute "dangerous anthropogenic interference"? IPCC uses a burning embers diagram to quantify reasons for concern about climate change. The impression created is that 2 or 3 degrees Celsius warming, relative to the present is probably dangerous. The burning embers are usually interpreted with a probabilistic approach, which has certain merits. However, I suggest that the burning embers are a fuzzy concept that discourages action, action that is needed urgently, because we are on the precipice of climate system tipping points beyond which there is no redemption.

Chart 25. 21st Century Global Warming.
Climate simulations for IPCC 2007 report.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

Global mean temperature is a useful metric. The model that did a good job of simulating global temperature over the past century has been extended into the future for several scenarios. IPCC scenarios A2 and A1B have a growth rate for CO_2 emissions of about 2% per year over the next 50 years, similar to actual growth of the past 10 years. The Alternative scenario assumes slowly declining emissions, so that the added CO_2 forcing is about 1 W/m^2 in 50 years and 1.5 W/m^2 over 100 years. With that forcing, and climate sensitivities consistent with paleoclimate data, the warming is less than 1°C, but it is more than 2°C in the Business-as-Usual Scenarios, and still rising rapidly at the end of the century.

Chart 26. "Dangerous" Climate Change: Physical Climate System Approach
Outline of topics to be covered.

We know enough about the climate system that we can draw important conclusions. Sea level is the big global issue. It is helpful to break the sea level discussion into two parts: the equilibrium change for a given magnitude of global warming, and the question of how long it takes the ice sheets to respond to global warming. I will also address the question of what level of regional climate change is needed to reach "dangerous interference".

E. Global Temperature and Sea Level

Chart 27. CO_2, CH_4 and Temperature.
CO_2, CH_4 and estimated global temperature (Antarctic $\Delta T/2$ in ice core era). 0 = 1880-1899 mean.
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

Data from the past several hundred thousand years has limited ability to tell us about sea level in warmer climates, because it hasn't been much warmer than today. It would be hard to judge that from Antarctic data alone, but there is data for many other locations that suggests that at most global temperature reached a level about 1 degree warmer than today. In the last interglacial period, about 120,000 years ago, sea level was probably 5 or 6 meters higher than today. There are suggestions that it was still higher during the interglacial 400,000 years ago (Hearty et al., Geology, 27, 375, 1999). But to find a planet 2 or 3°C warmer than now, as it will be this century in "business-as-usual" scenarios, we must go back to the middle Pliocene, about 3 million years ago. At that time sea level was 25 ± 10 m greater than today.

Chart 28. Warm Pool SST (Equator, 160°E).
SST in Pacific Warm Pool (ODP site 806B, 0°N, 160°E) in past millennium. Time scale expanded in recent periods. Data after 1880 is 5-year mean.
Source: Medina-Elizade and Lea, *ScienceExpress*, 13 October 2005; data for 1880-1981 from Rayner et al., *JGR*, **108**, 2003, after 1981 on Reynolds and Smith, *J. Climate*, **7**, 1994.

The single most important place on Earth to check the temperature is probably the tropical ocean. Here is the Pacific Warm Pool temperature for the past million years. A few interglacial periods were warmer than today, by perhaps as much as 1°C. But with the warming of the past century, shown in an expanded scale on the right, it seems that we are rapidly approaching the warmest levels of the past million years. If we follow a "business-as-usual" scenario, we will shoot well above any of those levels this century.

Chart 29. Ice Sheet Response Time: Millennia or Centuries?
Evidence from paleoclimate, satellites, and ice sheet models.

A key question: what is the ice sheet response time? If it is centuries, and if we have business-as-usual CO_2 growth, then, since thermal expansion of ocean water and alpine glaciers would be expected to add half a meter of sea level, total sea level rise might be a couple of meters this century, and several more next century.

If climate warms 2-3°C, and ice sheets begin to adjust to an equilibrium size consistent with that climate, a time scale of centuries would offer no consolation to coastal dwellers, because they would be faced with irregular incursions associated with storms and thus needing to continually rebuild above a transient water level.

Some ice sheet modelers believe that it requires millennia for ice sheets to respond to forcing. I'm a modeler too, but I rate data higher than models.

Chart 30. Paleoclimate Sea Level Data.
Evidence from paleoclimate, satellite and field data, and ice sheet models.

Numerous recent studies show that when ice sheets begin to disintegrate sea level commonly rises at rates of a few meters per century. Perhaps even more important, several independent studies with independent methods, show that sea level does not change gradually with the Earth's orbital elements. Rather it exhibits rapid changes of 10 meters or more on sub-orbital time scales. I refer, for example, to studies of Siddall et al., Potter et al., Thompson and Goldstein, to name a few. Ice sheet models that move lethargically on millennial time scales do not produce these real-world changes, because they are missing critical physics.

Chart 31. Surface Melt on Greenland.
Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.
Source: Roger Braithwaite, University of Reading (UK)

Ice sheet growth may be a dry linear process, but ice sheet disintegration is a wet process that can become very non-linear. This is a moulin on the Greenland ice sheet. It's a natural process for summer melt to find a crevasse and make a hole to the base of the ice sheet. What isn't natural is the increase in melt that has occurred in recent years with increased warming.

Chart 32. Increasing Melt Area on Greenland.
Satellite-era record melt of 2002 was exceeded in 2005.
Source: Waleed Abdalati, Goddard Space Flight Center

The area on Greenland with summer melt fluctuates with the weather, but it has increased substantially in the period with measurements. I believe that this summer 2005 broke the prior record for melt area, but I didn't have time to verify that with Waleed.

Chart 33. Jakobshavn Ice Stream in Greenland.
Discharge from major Greenland ice streams is accelerating markedly.
Source: Konrad Steffen, Univ. Colorado

And it has been noted, by Jay Zwally and others, that ice streams draining the glaciers speed up notably in response to the increased melt, which lubricates the base of the ice sheet. This is the largest ice stream on Greenland. It's flux has almost doubled in recent years. The second largest ice stream and others have also sped up.

Chart 34. Satellites Reveal Changing Ice Sheets.
Rapid thinning is concentrated at outlet glaciers exiting deep (sub sea level) valleys.
Source: Robert Bindschadler, Goddard Space Flight Center.

Not all ice streams are accelerating, but acceleration of outlet glaciers is dominant. As Bob Bindschadler and others point out, most of the major accelerating ice streams, marked by red explosions in this map, have outlets that exit in submarine valleys. These ice stream are buttressed by ice shelves grounded on the ocean floor, ice shelves that are thinning because of the warming ocean. So greenhouse warming provides heat to melt the ice shelves, the submarine outlets provide a path from the ice sheets to the ocean, where the warmer ocean can melt the ice.

Global warming also increases snowfall, so the interiors of Greenland and Antarctica are getting thicker. Because of this competing effect, sea level changes slowly at first, but as global warming gets larger, as summer melt extends higher up the ice sheet, and as buttressing ice shelves melt away, multiple positive feedbacks come into play, and the nonlinear disintegration wins the competition hands down.

Chart 35. Summary: Ice Sheets.
"Business-as-usual" climate forcing could lead to continuing sea level change out of our control.

The potential human forcing with a "business-as-usual" scenario dwarfs the forcings that have existed during the past hundreds of thousands of years.

Chart 17. CO_2, CH_4 and Temperature.
CO_2, CH_4 and estimated global temperature (Antarctic □T/2 in ice core era). 0 = 1880-1899 mean.
Source: Hansen, *Clim. Change*, **68**, 269, 2005.

I remind you that the time scale is greatly expanded on the right. If we follow a business-as-usual scenario, we will be creating a hammer hitting the Earth faster and harder than it has ever been hit. Except perhaps when the Earth was hit by the asteroid that killed the dinosaurs.

Chart 35. Summary: Ice Sheets.
"Business-as-usual" climate forcing could lead to continuing sea level change out of our control.

The equilibrium sea level response to 3°C global warming is about 80 feet, based on the history of the Earth. The fact that the ice sheet response time is probably hundreds of years is no solace to coastal dwellers, because they will be faced with irregular incursions associated with storms, and will need to continually rebuild above a transiently rising sea level.

F. Regional Climate Change

Chart 36. Regional Climate Change.
Outline for discussion of global warming effects on regional climate.

Let me turn to regional climate change, for which I will use a simple argument to make a general statement, and then look at some specific cases.

Chart 37. 2000-2100 Temperature Change in IPCC and Alternative Scenarios.
□ is interannual standard deviation of observed seasonal mean temperature for period 1900-2000.
Source: Hansen et al., *J. Geophys. Res., to be submitted*.

On the left, calculated with our climate model, is the change of Jun-Jul-Aug temperature by the end of the present century for two IPCC scenarios and the alternative scenario. The model has a middle-of-the-road sensitivity of 2.7°C for doubled CO_2, consistent with paleoclimate and the climate change of the past century, indeed, these are extensions of the runs that fit observed climate well.

On the right is the ratio of the mean warming to the local standard deviation of seasonal mean temperature in the 20th century. The standard deviation includes the effect of both year-to-year variations and long-term trend. I submit that changes in the mean by 5-10 standard deviations in the business-as-usual scenarios are prima facie evidence of dangerous human-made interference. Changes of 5 to 10 standard deviations mean that the environment and its inhabitants would be facing <u>average</u> local conditions that they had not experienced before even in the most extreme years.

Chart 38. Arctic Climate Impact Assessment.
Credits: Claire Parkinson and Robert Taylor.

The Arctic provides a good specific example of regional climate change. Like sea level, it has a potential tipping point, because of positive feedback. As ice melts the ocean absorbs more sunlight and becomes warmer. It is <u>not</u> a runaway feedback or instability, but it does mean that a moderate increase in forcings could melt all of the summer ice, destroying the habitat of many species and the way of life of indigenous peoples.

Chart 39. 1880-2003 Surface Temperature Change (°C).
Temperature change observed and simulated for different forcing mechanisms. Aerosol forcing (negative) is thought to be slightly excessive in the 'all forcing' simulation.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

The Arctic illustrates both the potential climate problem and a potential solution. The upper left is the observed global temperature change of the past century, and the upper right is what we calculated. The model didn't warm quite as much as observed at middle northern latitudes, and we now realize that we had somewhat excessive sulfate aerosols in our model. The main point that I want to make is shown by the second row. Although CO_2 can be blamed for a substantial fraction of the warming, the health-impacting pollutant tropospheric ozone and its precursor methane are equally responsible for the warming. There are other forcings that cause cooling. If we calculate the combined effect of ozone, methane, black and organic carbon aerosols and their indirect effect on clouds, these pollutants together probably contribute a somewhat greater Arctic warming than does CO_2, as shown in the lower right.

CO_2 is the most important forcing. What I am saying is that if we can achieve a significant decrease in methane, that would help decrease ozone, and if we kept the CO_2 growth close to the alternative scenario, the decreased pollutants would help balance the CO_2 warming effect. In this way it is possible to save the Arctic, to avoid crossing the tipping point. Such a scenario is practical, it has multiple benefits, and it makes good common sense.

Then why are we not doing it? I would like to address that question, which I will do at the end of my talk.

One comment on tropical storms, which Kerry Emanuel will discuss in the next talk. In our climate simulations, which I have already discussed, when we examine the tropical Atlantic, the region of hurricane formation, we find a warming in the period 1995-2005 relative to the preceding 25 years of 0.35°C. That's the mean result for a 5-run ensemble, which compares with an observed warming of 0.45°C in that region. So the categorical contention that recent hurricane intensification is due to a natural cycle of Atlantic ocean temperature in the region of hurricane formation and has nothing to do with global warming seems irrational and untenable. How can the hurricane distinguish between a natural warming and greenhouse gas warming? Not impossible, but would need to be explained. [– was not used, except in discussion]

Chart 36/40. Regional Climate Change.
Outline for discussion of global warming effects on regional climate.

In summary, with regard to regional climate: as with global climate and sea level, business-as-usual scenarios will produce basically another planet. How else can you describe climate change in which the Arctic becomes an open lake in the summer and fall, and most land areas on Earth experience mean warming this century that is 5-10 times larger than the standard deviation of the past century?

G. Greenhouse Gas Scenarios and Real World Trends

Chart 41. GHG Forcings (W/m^2).
Increase of greenhouse gas climate forcings since 1990.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

Let's look more closely at how greenhouse gas climate forcings are increasing. In the past few years the increase of forcing by all of the well-mixed greenhouse gases has fallen in between the IPCC and alternative scenarios. To understand that we need to look at the individual gases.

Chart 42. Greenhouse Gas Mixing Ratios.
Greenhouse gas amounts (a), growth rates (b), and resulting forcings (c) for IPCC, "alternative" and "2°C" scenarios compared with observational data.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

The principal thing that has happened, as shown in the second box on the top, is that methane has grown much more slowly than anticipated. Much slower than the IPCC scenarios and even slower than the alternative scenario. It serves to illustrate that the non-CO_2 forcings are important. It may be possible to do still better with the non-CO_2 forcings with a concerted effort, and I believe that is an important component of any strategy to avoid dangerous human-made interference with climate.

However, it must be realized that at best we can achieve a decrease of a few tenths of 1 W/m^2 from the non-CO_2 gases. It will be a challenge, and an accomplishment to keep the net change on non-CO_2 forcings at zero, because some constituents, such as N_2O are inevitably going to continue to increase for some time.

If we can get the CO_2 growth rate to level off and gradually decline, as in the alternative scenario, then a feasible decrease in the non-CO_2 forcings could keep the total increase in forcing at the level of about 1½ W/m^2 that is needed to keep further global warming less than 1°C. But if we follow a business-as-usual path for CO_2, then it won't help much to slow the other gases, and it will be harder to control these gases because, as the paleoclimate data shows, as the planet gets warmer the sources of CH_4 and N_2O increase.

Chart 43. Annual CO_2 Growth (ppm/year).
Growth rate of atmospheric CO_2 (ppm/year). Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

The observed growth of CO_2 in the air, the blue curve, fluctuates a lot, but recently it is headed in the direction of IPCC business-as-usual. This becomes clearer, if we note that the CO_2 growth rate, and thus CO_2 emissions, would need to decline moderately this half century to achieve the alternative scenario. But in reality…

Chart 44. Global Fossil Fuel CO_2 Emissions.
Global fossil fuel CO_2 emissions divided according to country or region of emissions. Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

…global CO_2 emissions are increasing rapidly, 2% per year in the past decade. Is continued growth of this sort inevitable, or is there a feasible alternative course? On the long run, satisfying energy needs while decreasing CO_2 emissions will require development of renewable energies, sequestration of CO_2 produced at power plants, and perhaps a new generation of nuclear power. But a flattening out of emissions can be achieved now with improved energy efficiency. It is important that the United States, as a technology leader and as the largest producer of CO_2 in the world, take a leadership role.

H. Can We Still Avoid Dangerous Climate Change?

Chart 45. U.S. Auto & Light Truck CO_2 Emissions.
"Moderate Action" is NRC "Path 1.5" by 2015 and "Path 2.5" by 2030.
Source: *On the Road to Climate Stability*, Hansen, J., D. Cain and R. Schmunk,, *to be submitted.*

Industrial emissions of CO_2 are declining. The two problem areas are emissions from power plants and emissions from vehicles. Solution in both cases depends critically on improved energy efficiency. Power plants, because we need to avoid building a fossil fuel power plant infrastructure unless and until CO_2 sequestration is a reality. For vehicles, efficiency is critical because of the rapidly growing global number of vehicles. It is false to say that hydrogen technology will solve this in the future. It takes energy to make hydrogen. Efficiency will always be needed. It could be achieved now if we seriously pursued it, and if it were pursued we could get onto an 'alternative' scenario track.

Chart 46. U.S. Auto & Light Truck CO_2 Emissions.
"Moderate Action" is NRC "Path 1.5" by 2015 and "Path 2.5" by 2030.
Source: *On the Road to Climate Stability*, Hansen, J., D. Cain and R. Schmunk,, *to be submitted.*

My education-outreach team of students and teachers showed that in the U.S., even though the number of vehicles on the road increases every year, we could get off the path of increasing emissions by accepting even the moderate recommendations of the NRC, which calls for phasing in improvements in efficiency that would amount to about 30% by 2030. This would be based on available technology and it gives the automakers ample time to phase it in. It does require that they stop opposing efficiency requirements in court and stop pressuring lawmakers to oppose efficiency.

The accrued benefit in 35 years, of just this moderate action, even without addition of hydrogen-powered vehicles, is a savings of oil equal to more than seven times the amount of oil that the U.S. Geological Survey estimates to be available in the Arctic National Wildlife Refuge.

Chart 47. Oil Savings (barrels/day, $B/year).
United States annual savings (at $50/barrel, today's dollars) in 2030 for alternative automobile efficiency improvements.
Source: *On the Road to Climate Stability*, Hansen, J., D. Cain and R. Schmunk,, *to be submitted*.

The savings of this moderate action, at $50 per barrel of oil, is $100B <u>per year</u>. These savings increase each year, even without additional efficiency improvements. And as you know, $100B here, $100B there, pretty soon you are talking about real money. The U.S. has an opportunity to address a number of issues including energy independence.

Chart 48. 2004 Portions of CO_2 Emissions.
Fossil fuel CO_2 emissions by source country in 2004.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

Climate is a global problem and CO_2 emissions are a global problem. The U.S. is the largest emitter, but China and India are growing more rapidly. But they have been growing rapidly the past decade, and the 2%/year growth of emissions could be halted with sensible actions. China and India, overall, are even less efficient than the U.S. There will be a tremendous market for improved efficiency, which we should be pursuing much more vigorously, for our own good as well as for the planet's.

Chart 49. Workshop at East-West Center.
Technical cooperation offers large mutual benefits to developed and developing countries.
Source: Hansen et al., *J. Geophys. Res., to be submitted.*

The goal of keeping further global warming under 1°C requires two things: first, flattening out and then decreasing the rate of growth of CO_2 emissions, and second an absolute decrease in emissions of non-CO_2 climate forcings, particularly methane and carbon monoxide, and therefore tropospheric ozone, and black carbon (soot) aerosols. There are multiple reasons to do this, with benefits for developed and developing countries, and for the planet and future generations. But these are not things that will simply happen because they make sense. There has to be leadership.

Chart 50. Summary: Is There Still Time? Yes, but:

So, in summary, is there still time to avoid dangerous human-made interference with climate? I believe the evidence shows with reasonable clarity that the level of additional global warming that would put us into dangerous territory is about 1°C, not 2 or 3°C. We will need to refine our estimate as more data comes in, but I am quite confident of this assertion.

Yes, it is technically possible to avoid the grim "business-as usual" climate change, to follow an alternative scenario in which growth of greenhouse gas emissions is slowed in the first quarter of this century, primarily via concerted improvements in energy efficiency and a parallel reduction of non-CO_2 climate forcings, and then reduced via advanced energy technologies that yield a cleaner atmosphere as well as a stable climate. The required actions make practical sense and have other benefits, but they will not happen without strong policy leadership and international cooperation. Action must be prompt, otherwise CO_2-producing infrastructure that may be built within a decade will make it impractical to keep further global warming under 1°C.

I refer especially to the large number of coal-fired power plants that China, the United States, and India are planning to build without CO_2 sequestration.

I said that I would return to the question of why, if an alternative scenario is practical, has multiple benefits, and makes good common sense, why are we not doing it?

There is little merit in casting blame for inaction, unless it helps point toward a solution. It seems to me that special interests have been a roadblock wielding undue influence over policymakers. The special interests seek to maintain short-term profits with little regard to either the long-term impact on the planet that will be inherited by our children and grandchildren or the long-term economic well-being of our country.

The public, if well-informed, has the ability to override the influence of special interests, and the public has shown that they feel a stewardship toward the Earth and all of its inhabitants. Scientists can play a useful role if they help communicate the climate change story to the public in a credible, understandable fashion.

Is There Still Time to Avoid ‘Dangerous Anthropogenic Interference’ with Global Climate?

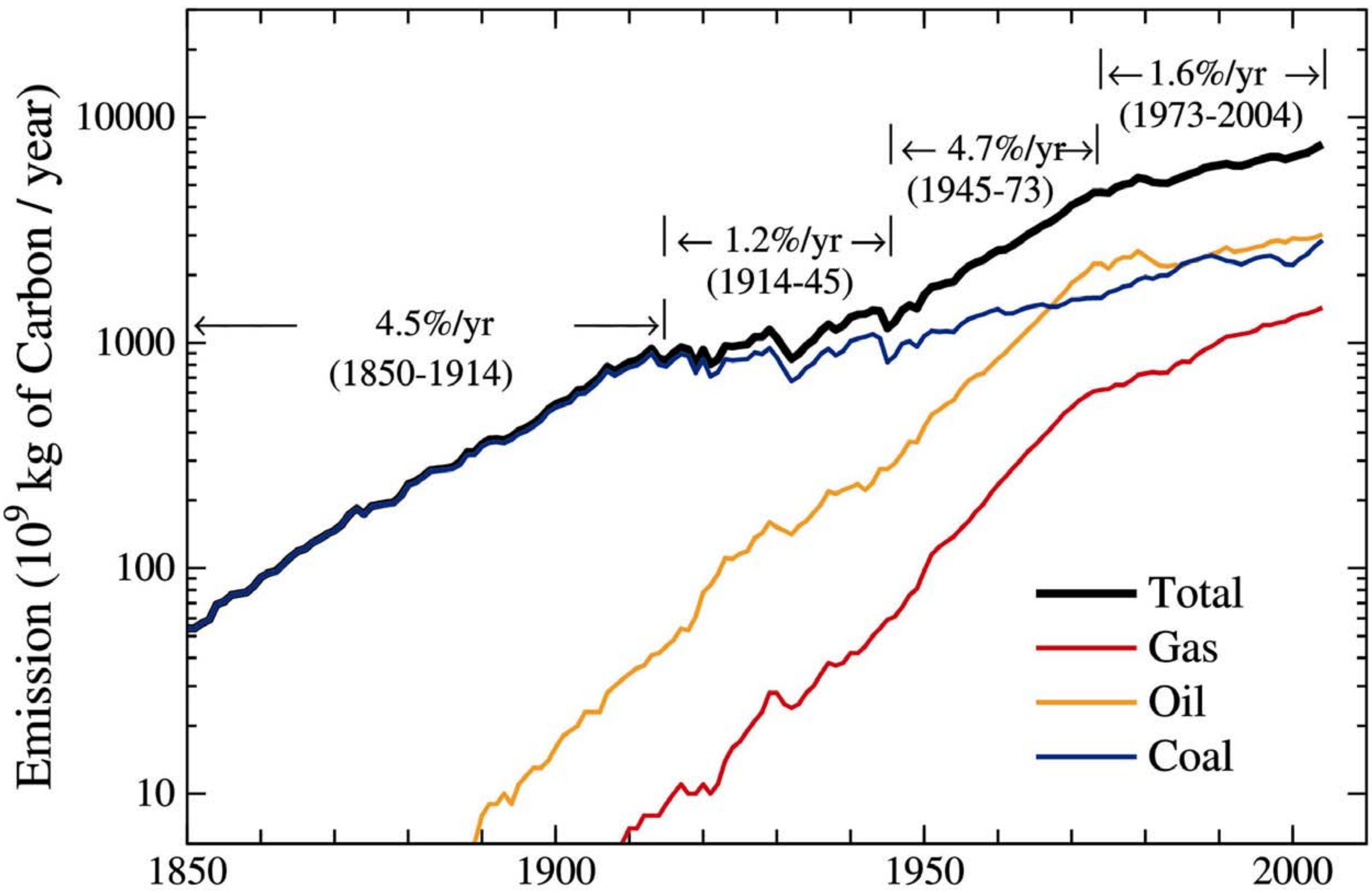
A Tribute to Charles David Keeling

Presentation on 6 December 2005 by James E. Hansen
American Geophysical Union, San Francisco, California

Atmospheric CO_2 measured at Mauna Loa, Hawaii.

Source: NOAA Climate Monitoring and Diagnostic Laboratory

Global Fossil-Fuel CO_2 Annual Emissions

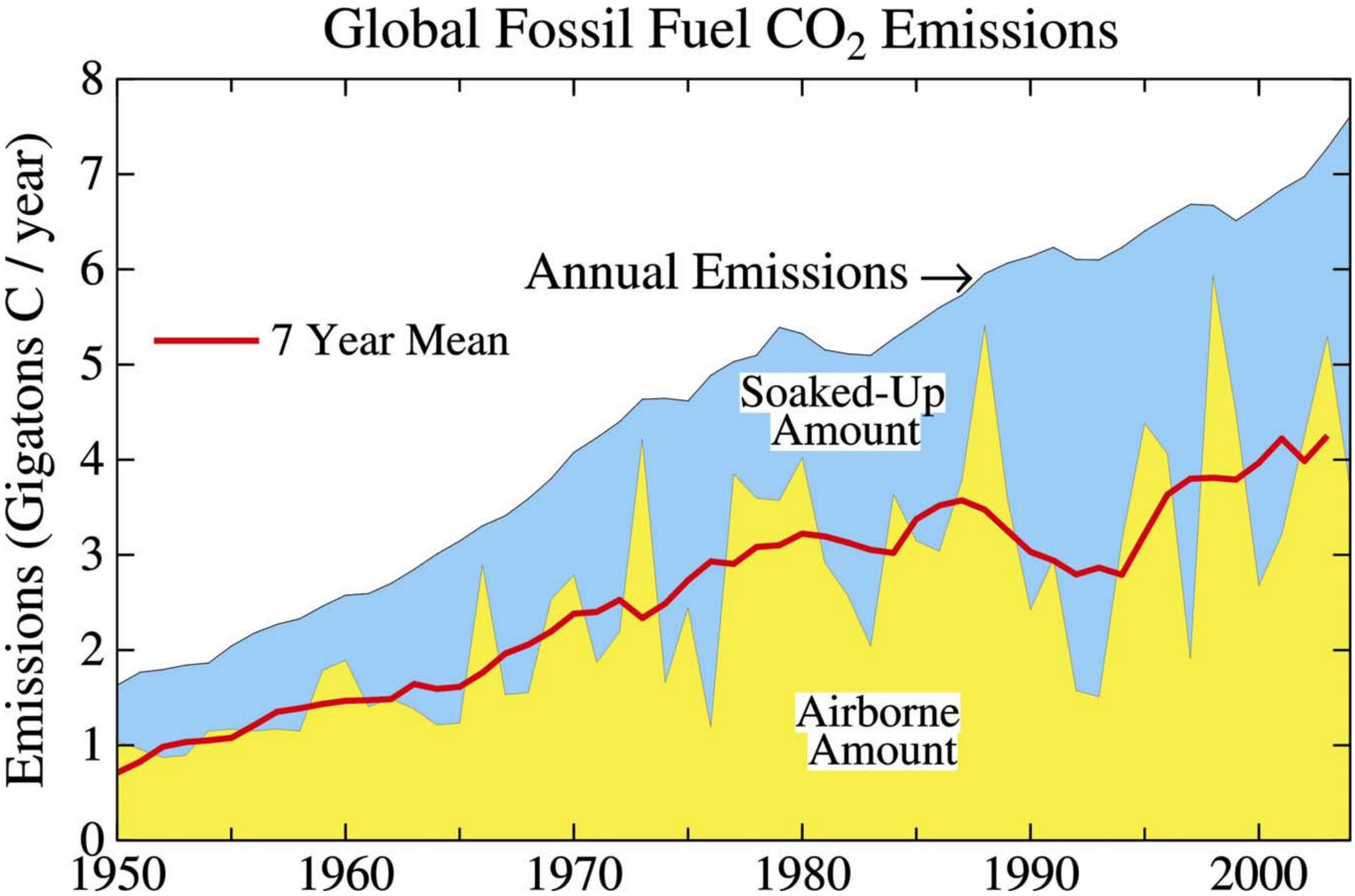


Fossil fuel CO_2 emissions based on data of Marland and Boden (DOE, Oak Ridge) and British Petroleum.

Source: Hansen and Sato, *PNAS,* **98**, 14778, 2001.

CO_2 airborne fraction, i.e., ratio of annual atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS,* **101**, 16109, 2004.

Growth rate of atmospheric CO_2 (ppm/year).

Source: Hansen and Sato, *PNAS,* **101**, 16109, 2004.

Carbon Dioxide

Good News:

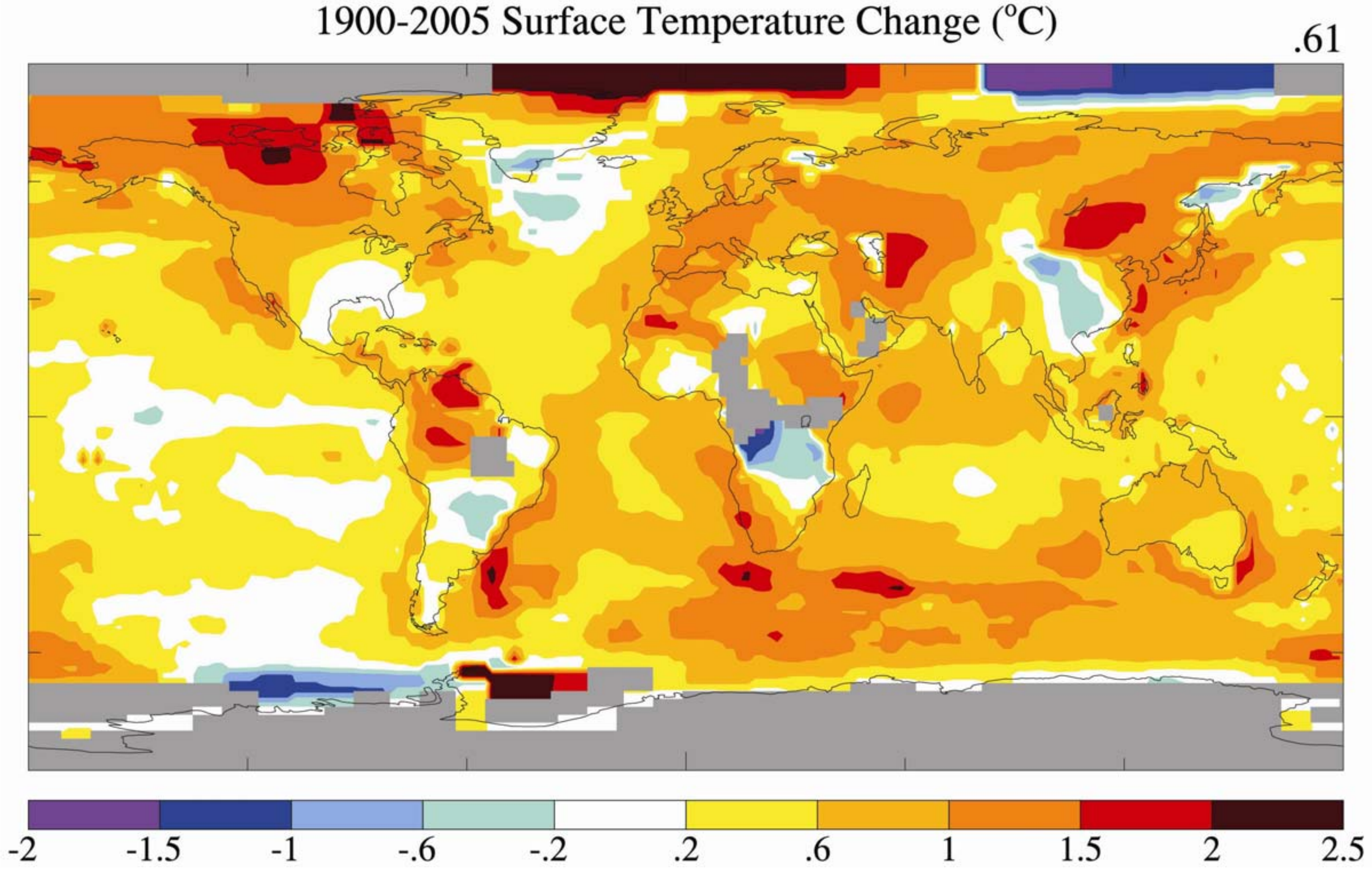
1. ~42% of annual fossil fuel emissions continues to be "soaked up" by ocean, soil, vegetation
2. Uptake % could increase if emissions decreased, or via improved forestation/agricultural practices

Bad News:

1. Stabilization of atmospheric CO_2 may require eventual reduction of emissions by 60-80%
2. Fossil fuel emission are increasing ~2% per year

Global mean surface temperature change based on surface air measurements over land and SSTs over ocean

Source: Update of Hansen et al., *JGR,* **106**, 23947, 2001; Reynolds and Smith, *J. Climate,* **7**, 1994; Rayner et al., *JGR,* **108**, 2003.



Change of surface temperature index based on local linear trends using surface air temperature over land and SST over ocean.

Sources: Hansen et al., *JGR*, **106**, 23947, 2001; Reynolds and Smith, *J. Climate*, **7**, 1994; Rayner et al., *JGR*, **108**, 2003.

Climate Sensitivity

Empirical data

…aided by models…

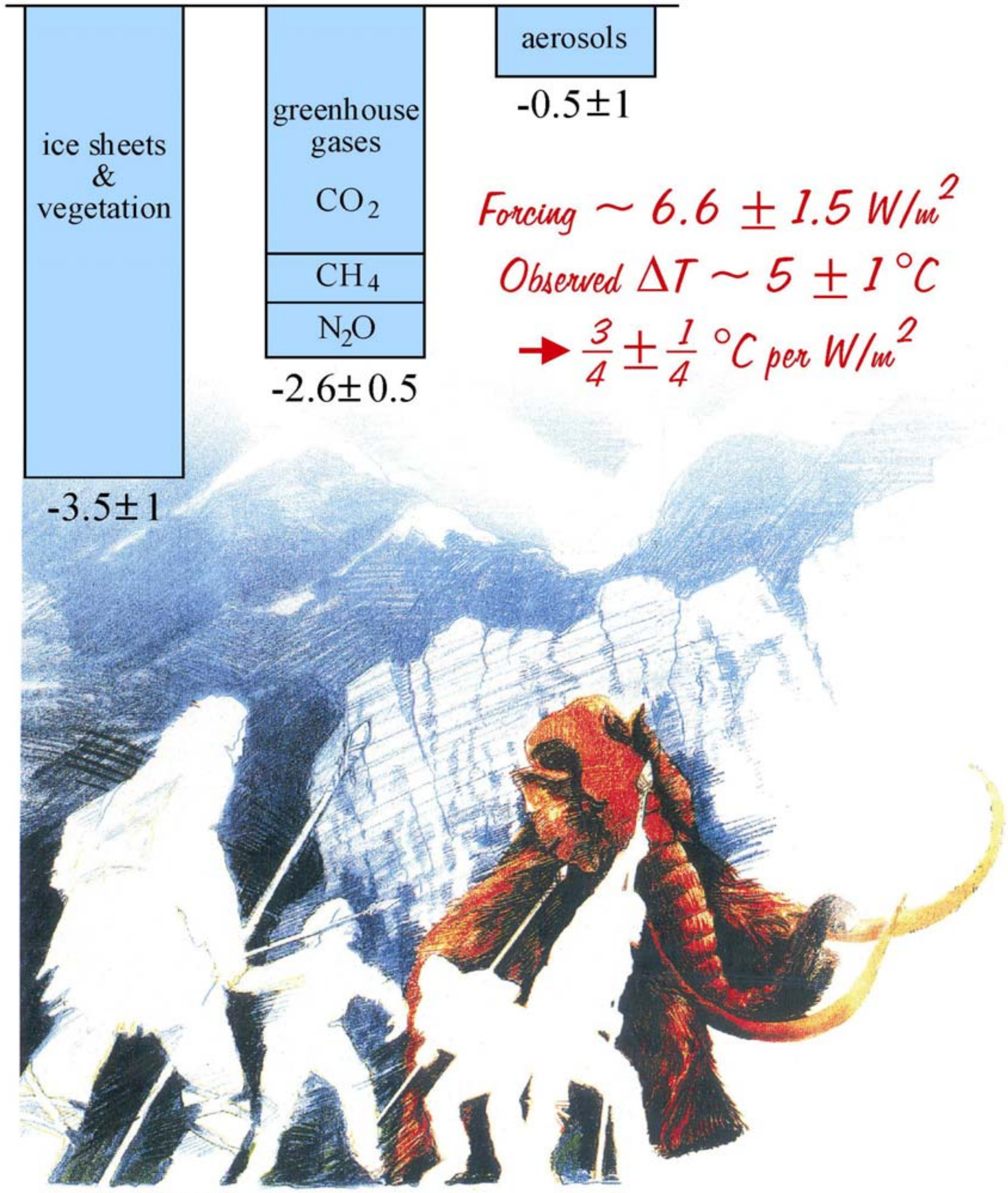
→ precise evaluation

CO_2, CH_4 and temperature records from Antarctic ice core data

Source: Petit et al., Nature, 399, 429, 1999

Ice Age Forcings Imply Global Climate Sensitivity ~ ¾°C per W/m².

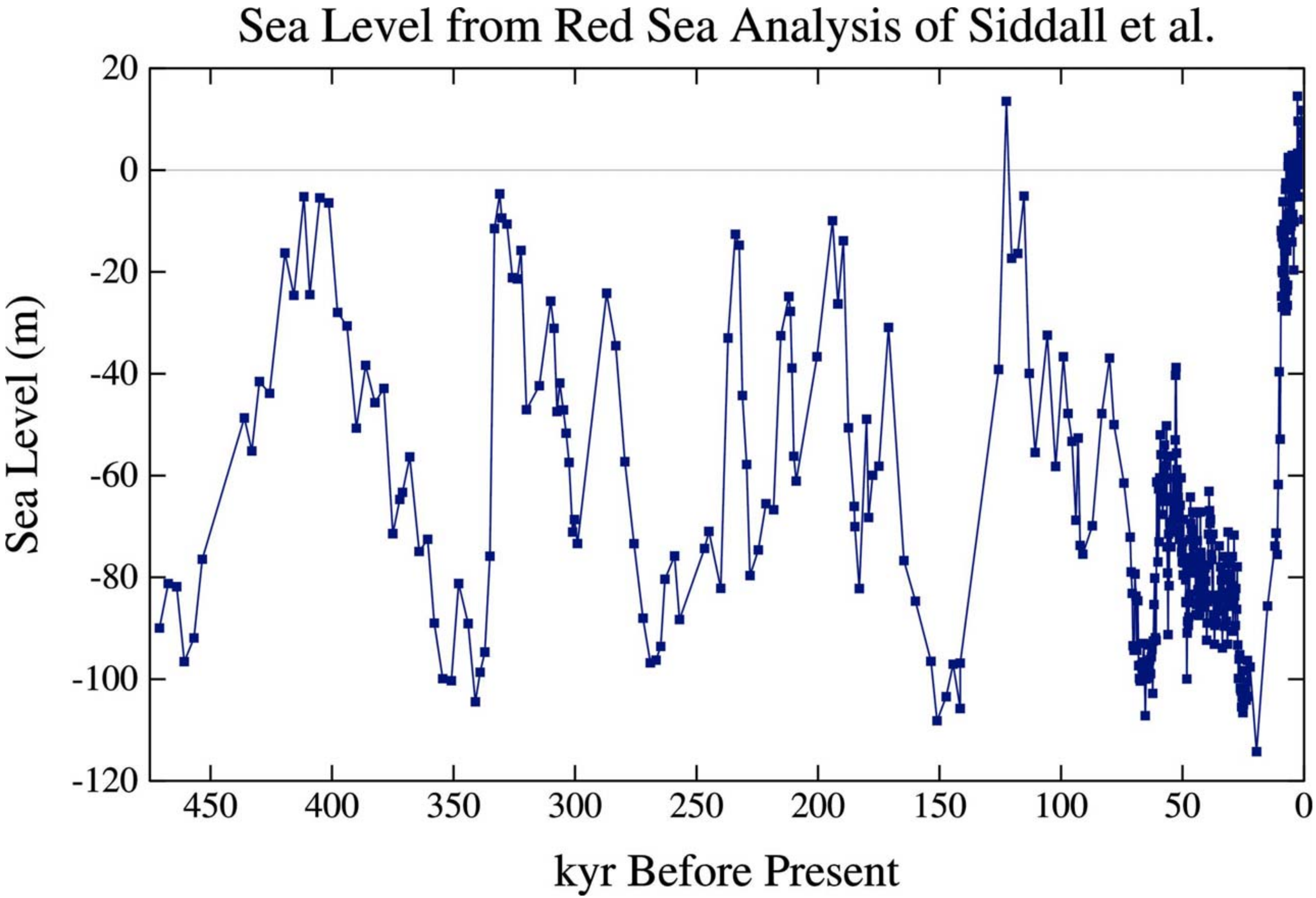
Ice Age Climate Forcings (W/m^2)



Forcing ~ 6.6 ± 1.5 W/m^2
Observed ΔT ~ 5 ± 1 °C
→ $\frac{3}{4} \pm \frac{1}{4}$ °C per W/m^2

Reports to the Nation • Fall 1997

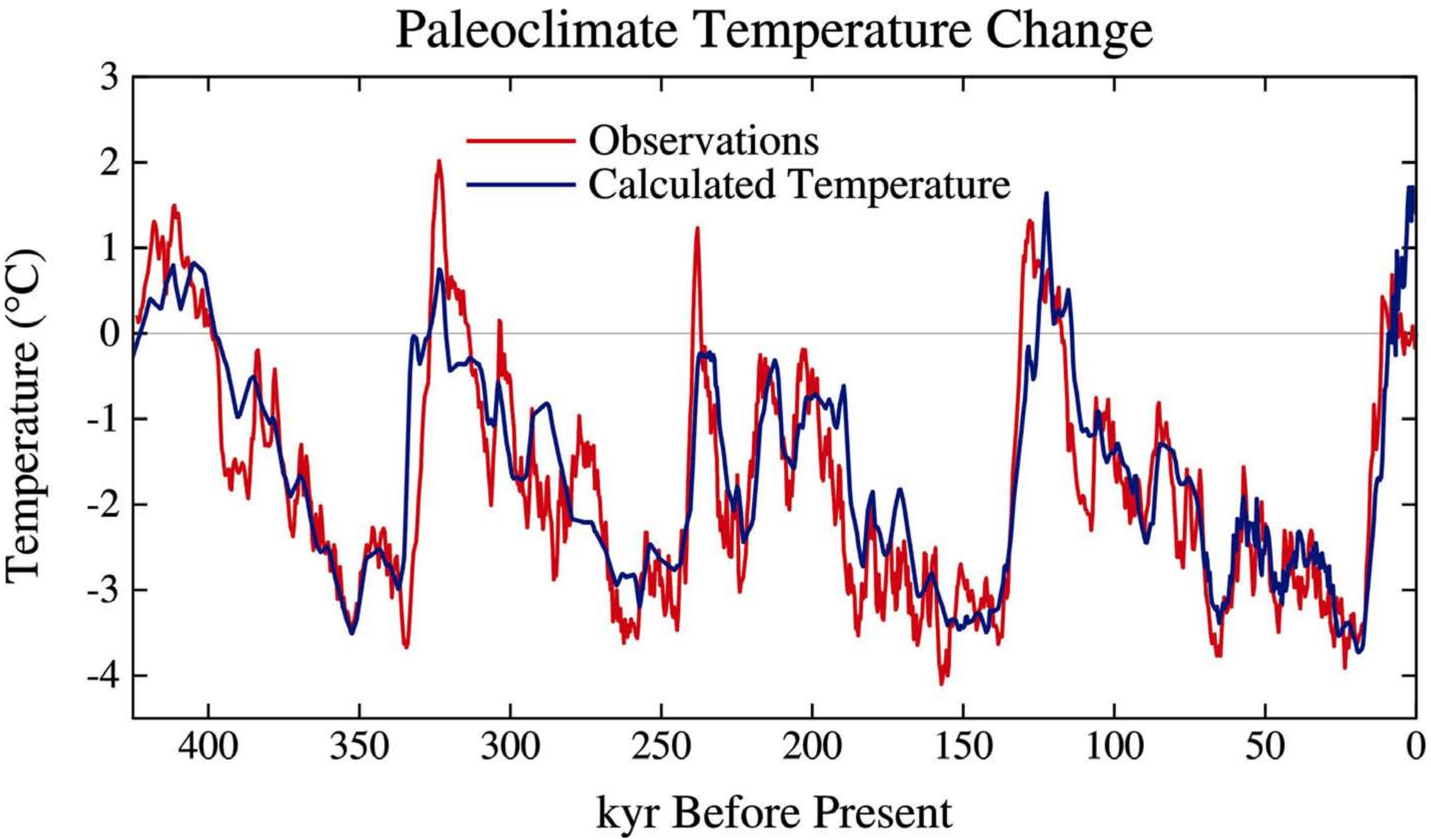
Source: Hansen et al., *Natl. Geogr. Res. & Explor.*, **9**, 141, 1993.



Global sea level extracted, via a hydraulic model, from an oxygen isotope record for the Red Sea over the past 470 kyr (concatenates Siddall's MD921017, Byrd, & Glacial Recovery data sets; AMS radiocarbon dating).

Source: Siddall et al., *Nature*, **423**, 853-858, 2003.

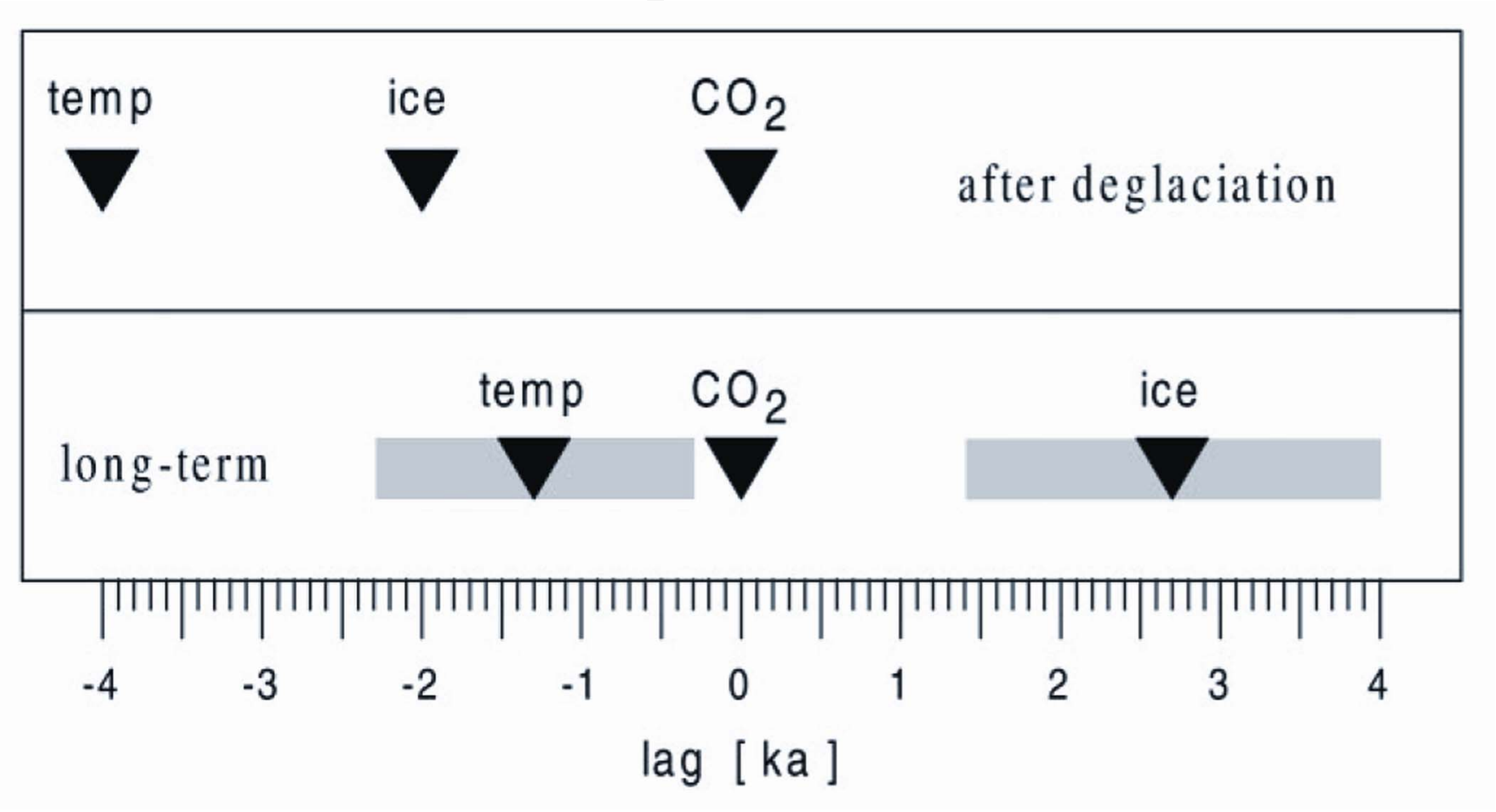
Ice sheet forcing $\cong$ (sea level)$^{2/3}$
GHGs = CO_2 + CH_4 + N_2O (0.15 forcing of CO_2 + CH_4)



Observations = Vostok ΔT/2.

Calculated temperature = Forcing x 0.75°C /W/m^2

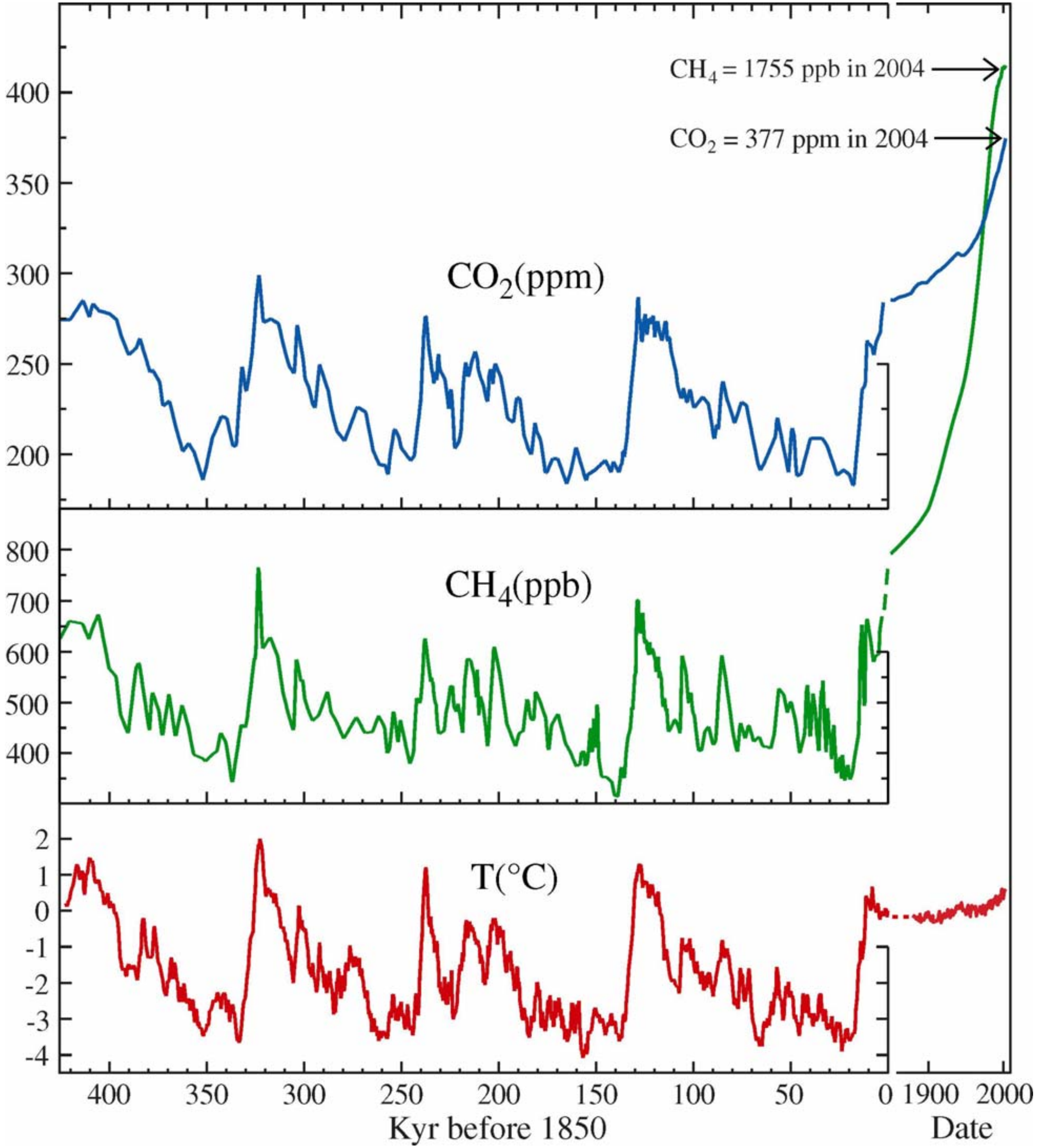
Lag of Global Ice & CO_2 Relative to S.H. Temperature



Leads and lags of Vostok temperature and global ice volume relative to CO_2. Shaded bar is 1σ uncertainty. Temperature and ice are more contemporaneous at some terminations.

Source: M. Mudelsee, Quat. Sci. Rev., **20**, 583, 2001.

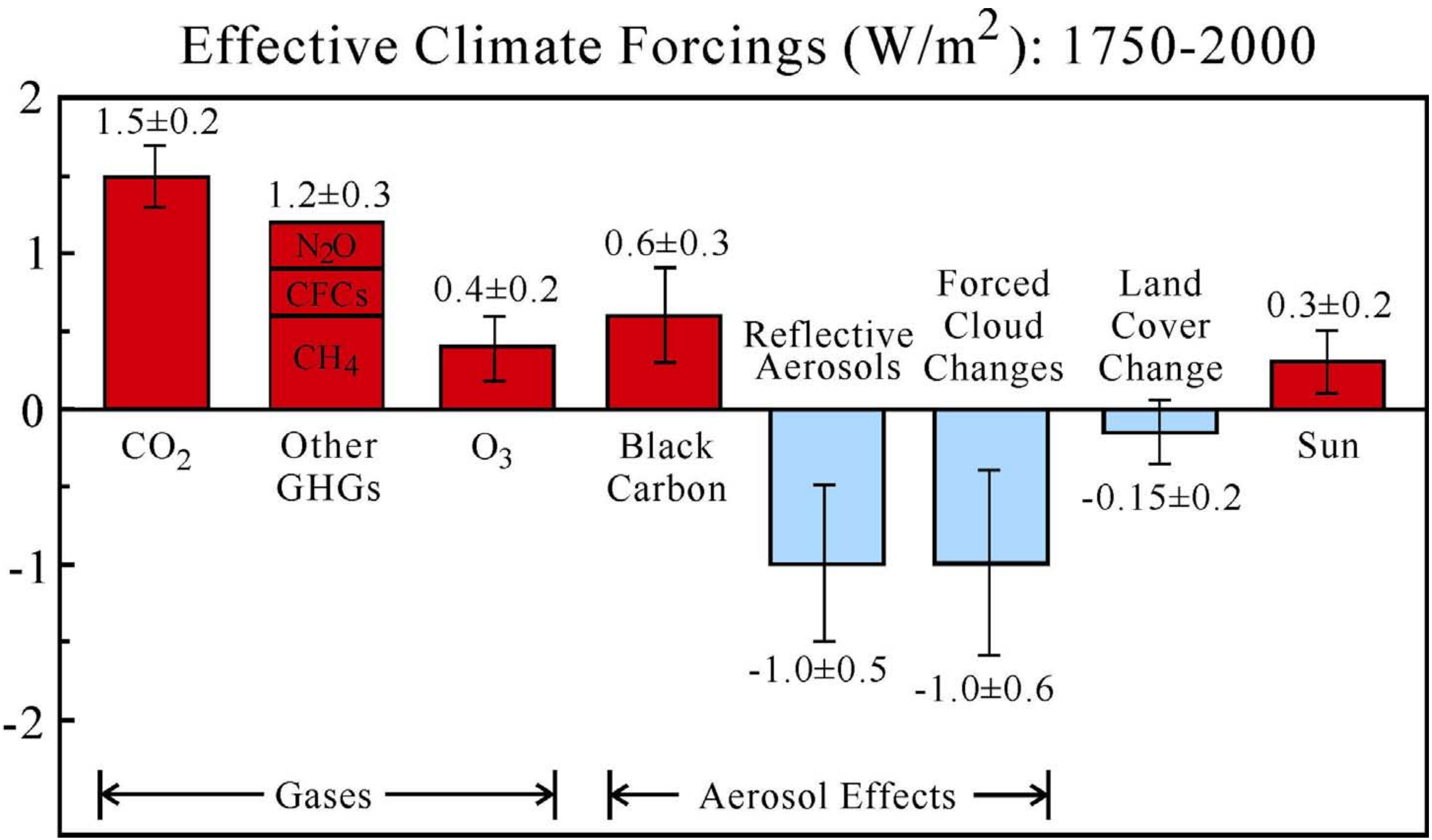
CO_2,CH_4 and estimated global temperature
(Antarctic ΔT/2
in ice core era)
0 = 1880-1899 mean.



Source: Hansen, *Clim. Change*, **68**, 269, 2005.

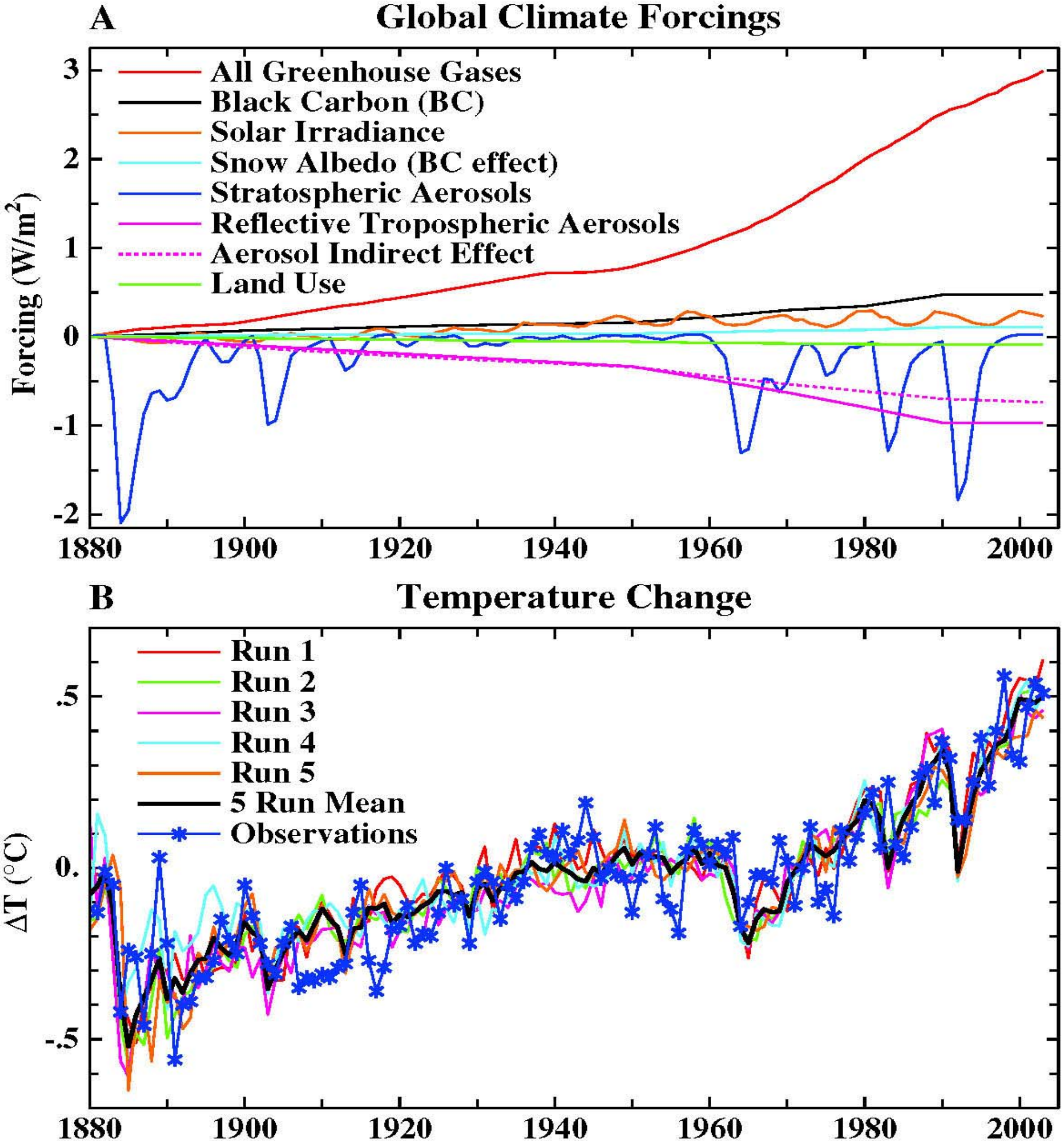
Implications of Paleo Forcings and Response

1. “Feedbacks” (or indirect forcings) cause almost all paleo temperature change.
2. Climate on these time scales is very sensitive to even small forcings.
3. Instigators of climate change must include: orbital variations, other small forcings, noise.
4. Another “ice age” cannot occur unless humans become extinct. Even then, it would require thousands of years. Humans now control global climate, for better or worse.



Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

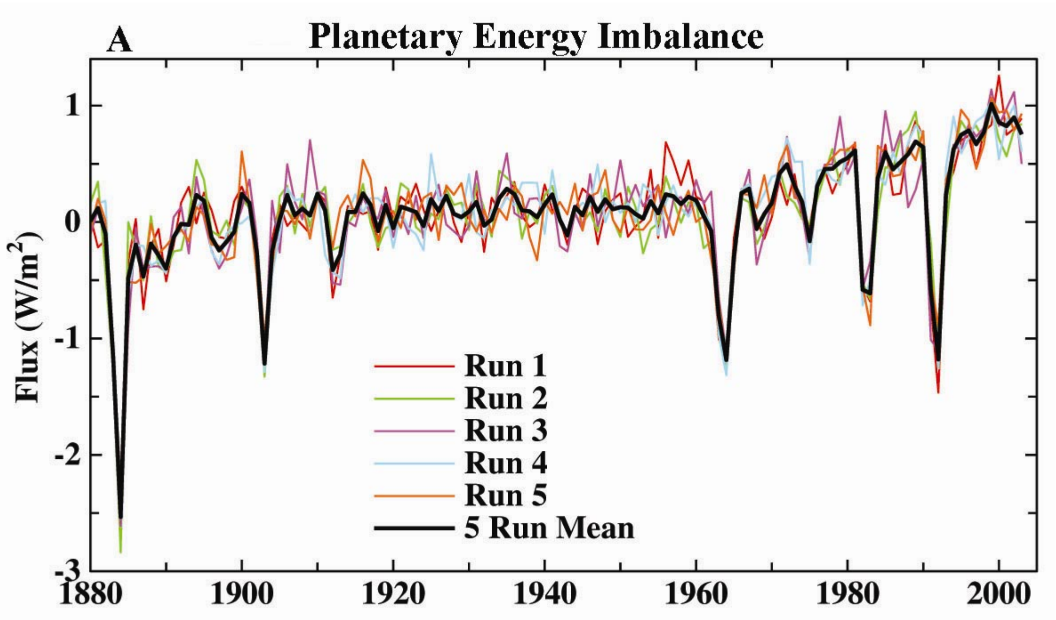


(A) Forcings used to drive climate simulations.

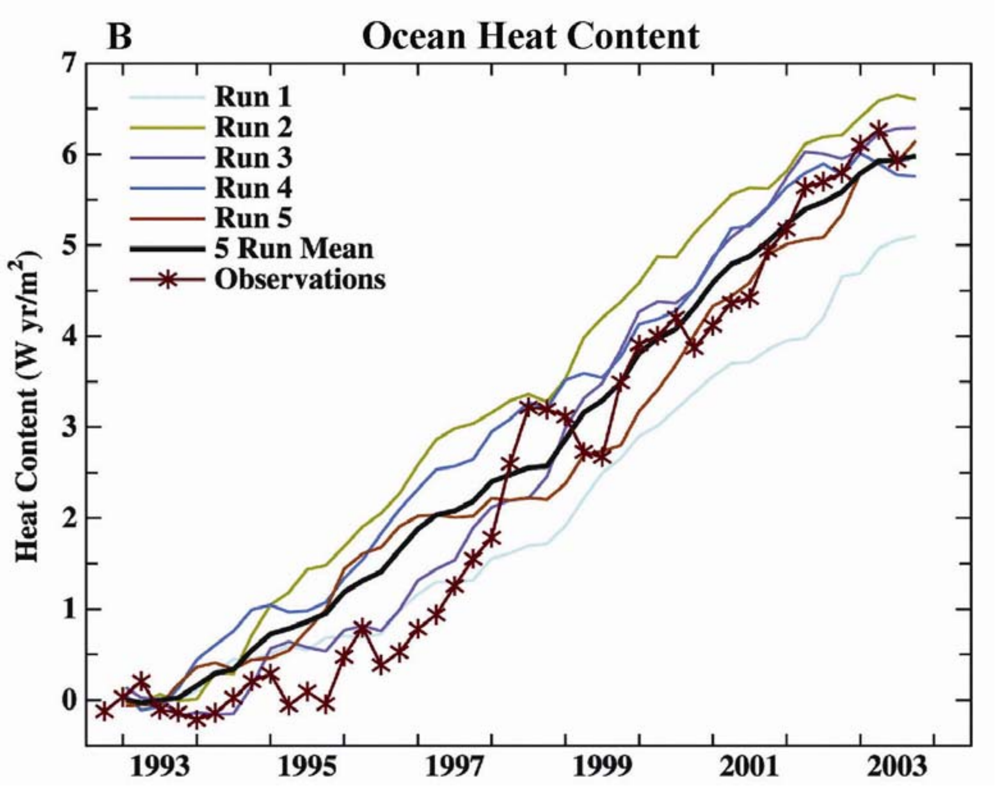
(B) Simulated and observed surface temperature change.

Source: Earth's energy imbalance: Confirmation and implications. *Science* **308**, 1431, 2005.

(A) Net Radiation at top of atmosphere in climate simulations.



(B) Ocean heat gain in the top 750 m of world ocean.



Source: Hansen et al.,
Science, **308**, 1431, 2005.

Consistency Check

1.85 W/m^2 = 1880-2003 forcing

1.00 W/m^2 = used for observed 2/3°C warming

0.85 W/m^2 = remains, not yet responded to

Implications

1. 0.6°C more warming in the pipeline
2. Confirms climate system lag

   → Need anticipatory actions to avoid any specified level of "dangerous" change
3. Acceleration of sea level rise is likely

Source: Hansen et al., *Science*, **308**, 1431, 2005.

United Nations
Framework Convention on Climate Change

Aim is to stabilize greenhouse gas emissions…

"…at a level that would prevent dangerous anthropogenic interference with the climate system."

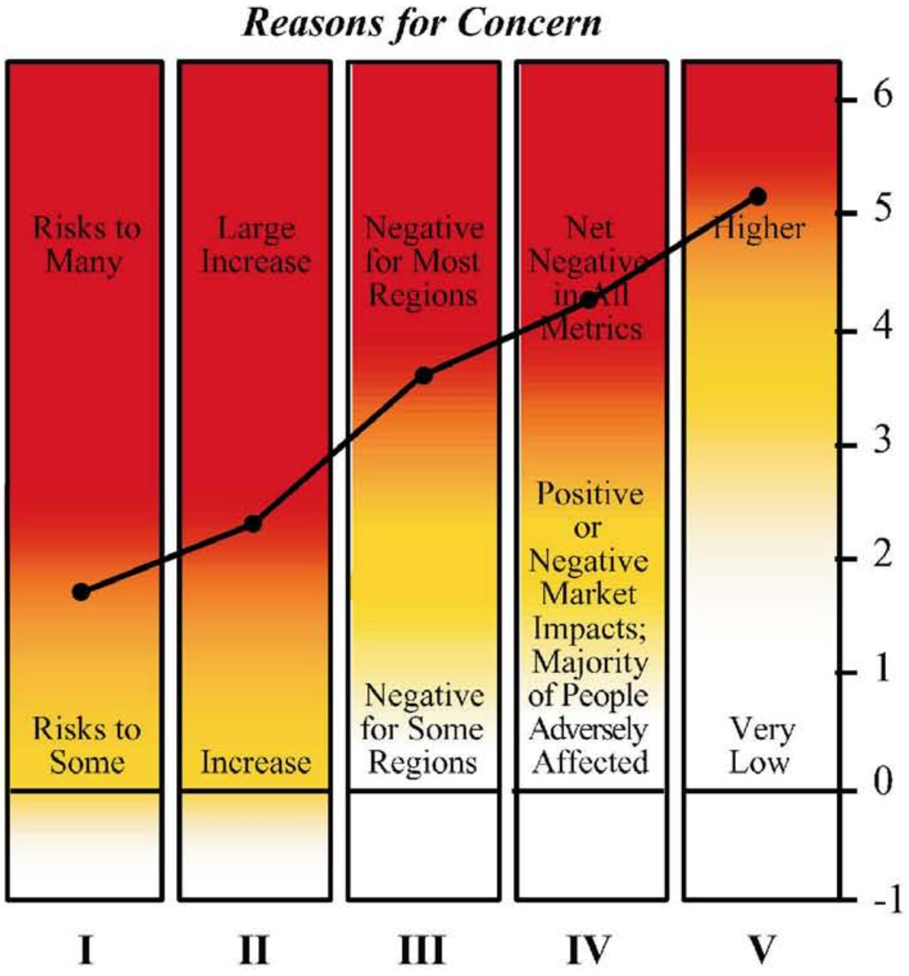
IPCC Burning Embers

White: neutral or small positive or negative impacts

Yellow: negative impacts for some systems or low risks

Red: negative impacts or risks that are more widespread and/or greater in magnitude

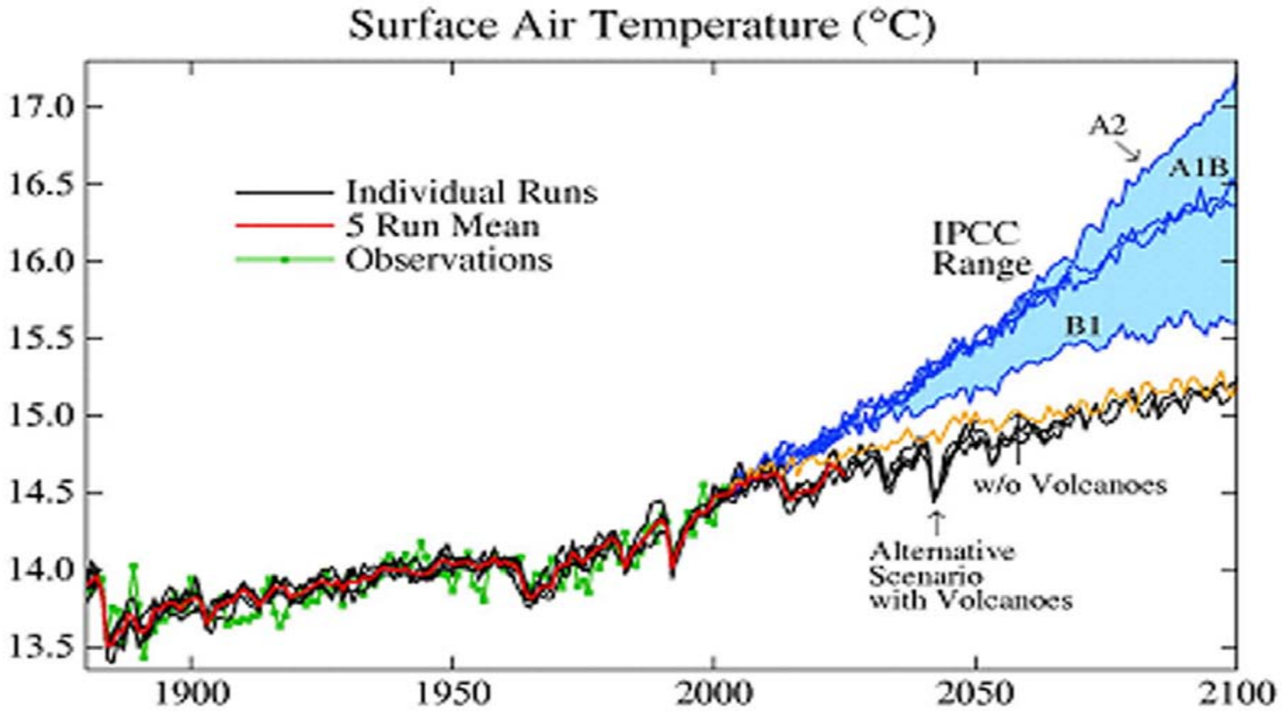
I	Risks to Unique and Threatened Systems
II	Risks from Extreme Climate Events
III	Distribution of Impacts
IV	Aggregate Impacts
V	Risks from Future Large-Scale Discontinuities



Reasons for concern about projected climate change impacts

Source: IPCC *Climate Change 2001;* S. Schneider & M. Mastrandrea, *PNAS,* **102**, 15728, 2005.

21st Century Global Warming



Climate Simulations for IPCC 2007 Report

► **Climate Model Sensitivity ~ 2.7°C for 2xCO_2**
(consistent with paleoclimate data & other models)

► **Simulations Consistent with 1880-2003 Observations**
(key test = ocean heat storage)

► **Simulated Global Warming < 1°C in Alternative Scenario**

Conclusion: Warming < 1°C if additional forcing ~ 1.5 W/m^2

Source: Hansen et al., *to be submitted to J. Geophys. Res.*

Metrics for “Dangerous” Change

Physical Climate System Approach

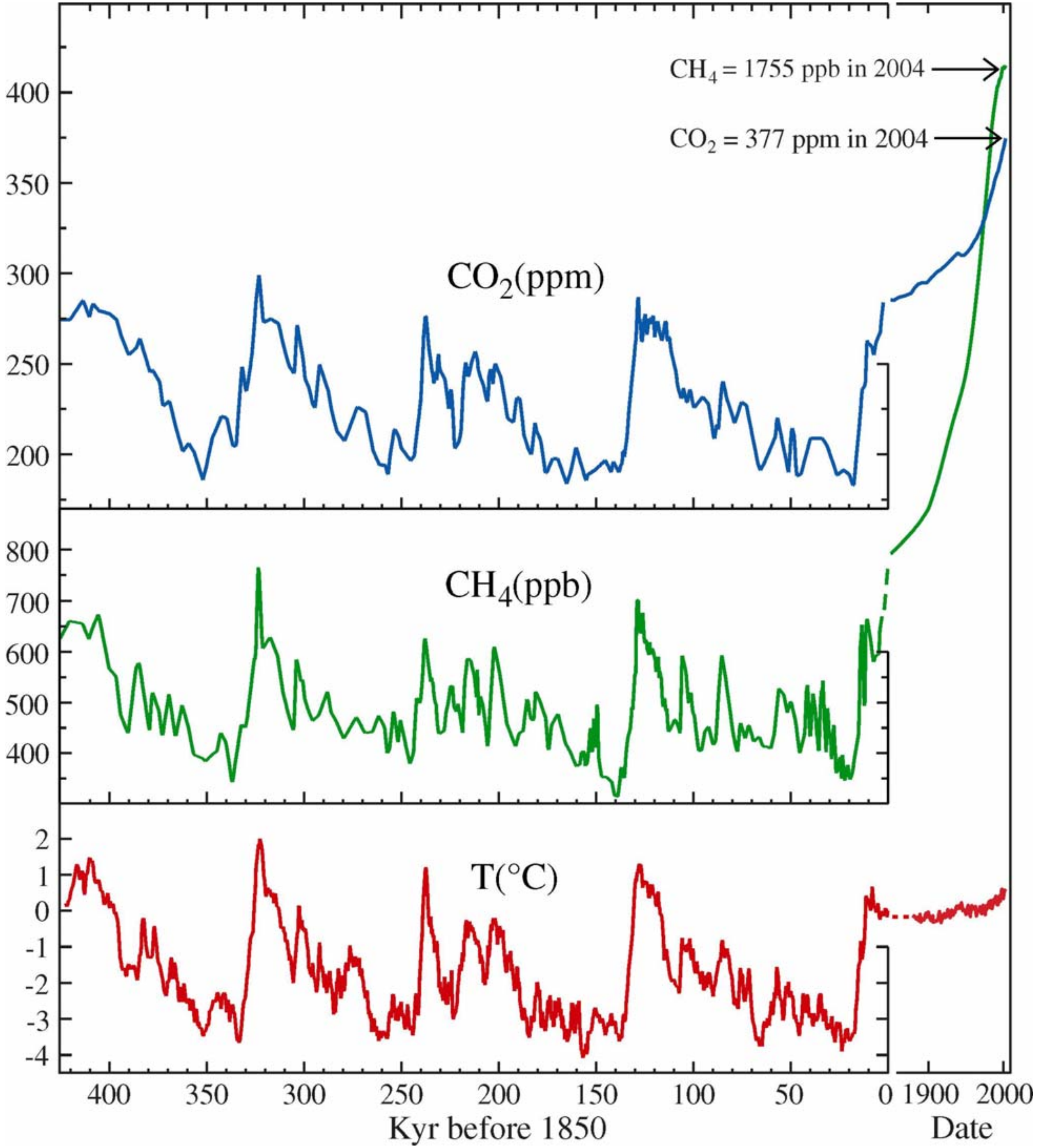
Global Sea Level

1. Long-Term Change: Paleoclimate Data
2. Ice Sheet Response Time

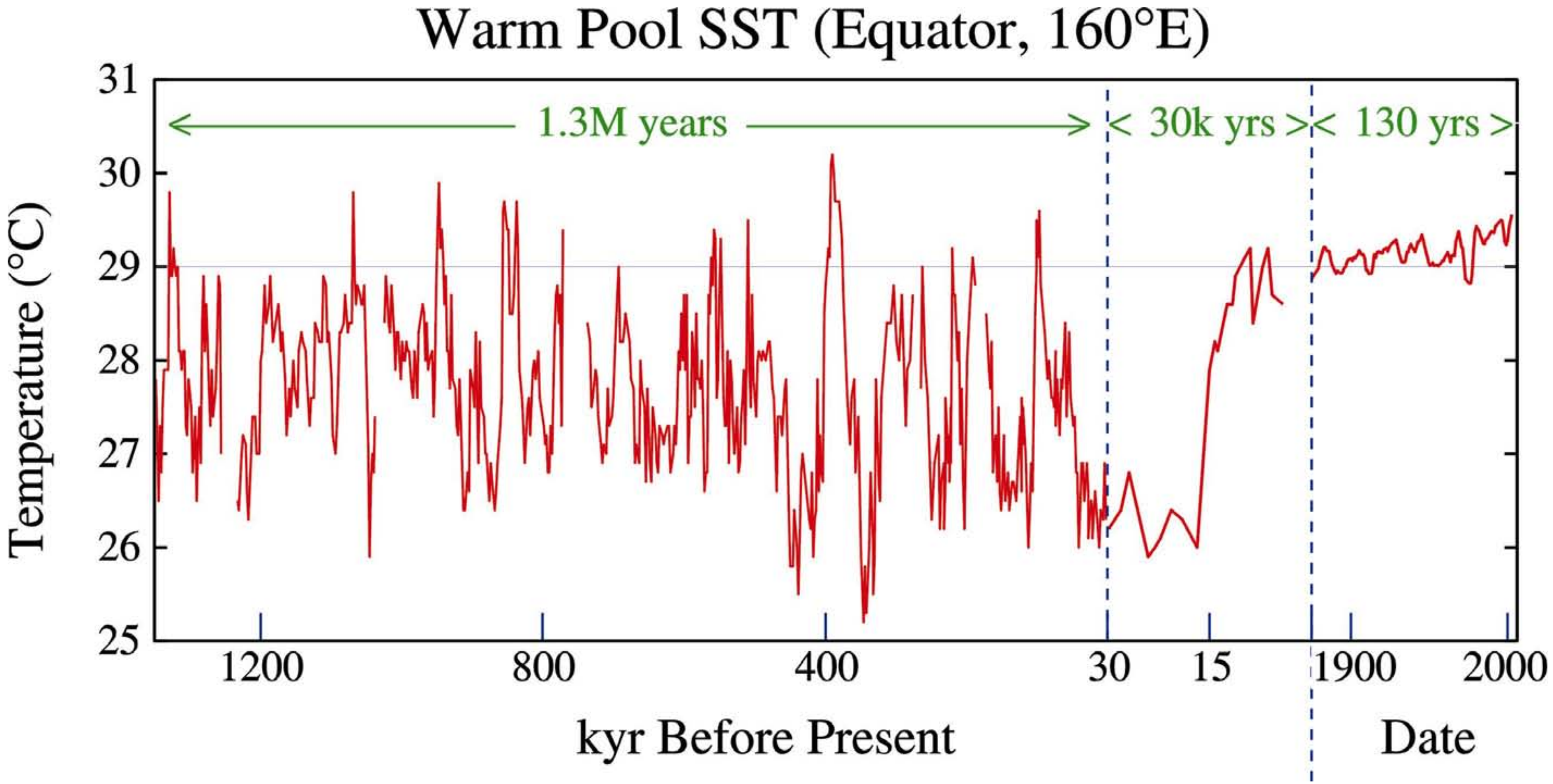
Regional Climate Change

1. General Statement
2. Specific Cases

CO_2,CH_4 and estimated global temperature (Antarctic ΔT/2 in ice core era)
0 = 1880-1899 mean.



Source: Hansen, *Clim. Change*, **68**, 269, 2005.



SST in Pacific Warm Pool (ODP site 806B, 0°N, 160°E) in past millennium. Time scale expanded in recent periods. Data after 1880 is 5-year mean.

Source: Medina-Elizalde and Lea, ScienceExpress, 13 October 2005;data for 1880-1981 based on Rayner et al., *JGR*, **108**, 2003, after 1981 on Reynolds and Smith, *J. Climate*, **7**, 1994.

Ice Sheet Response Time: Millennia or Centuries?

1. **Paleoclimate Data**

   Dated “Terminations”

   ~10 m “Sub-orbital” Sea Level Change

2. **Satellite & Field Data**

   Linear Growth, Nonlinear Disintegration

3. **Ice Sheet Models**

   Fail paleoclimate & satellite tests

Paleoclimate Sea Level Data

1. Rate of Sea Level Rise

   - Data reveal numerous cases of rise of several m/century (e.g., MWP 1A)

2. "Sub-orbital" Sea Level Changes

   - Data show rapid changes ~ 10 m within interglacial & glacial periods

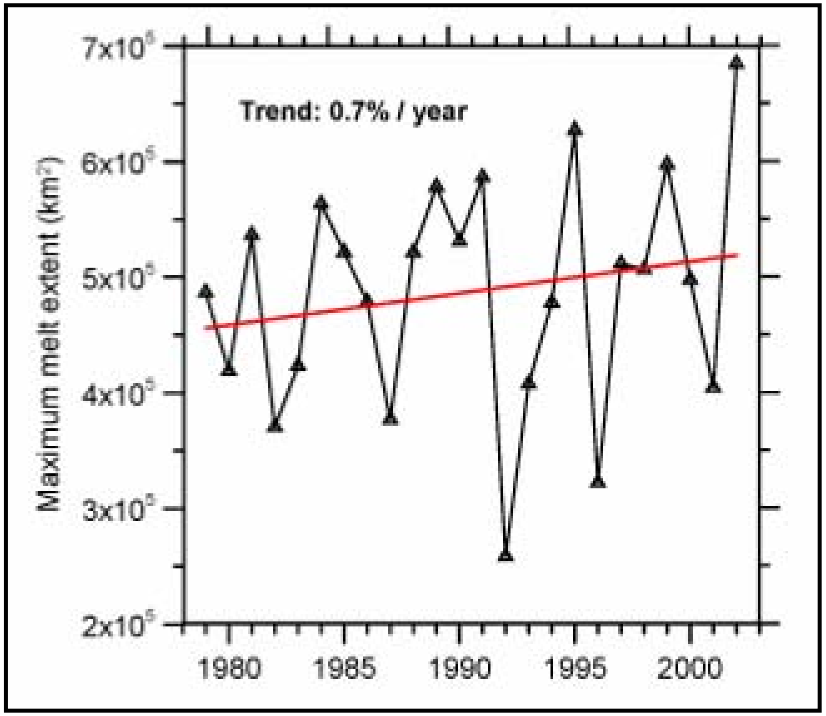
Ice Sheet Models Do Not Produce These

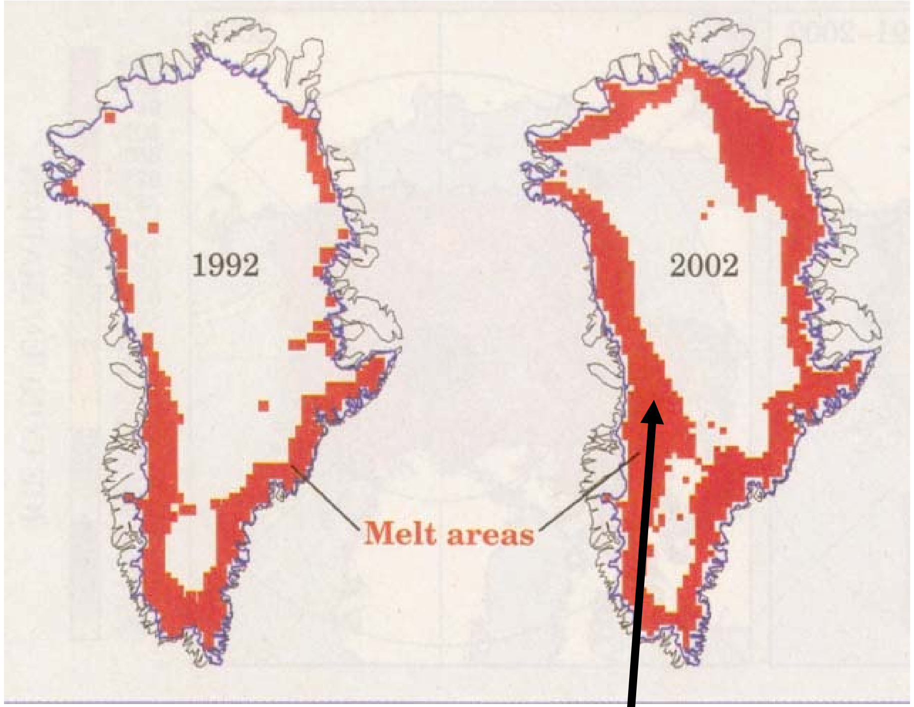
Surface Melt on Greenland

Melt descending
into a moulin,
a vertical shaft
carrying water
to ice sheet base.

*Source: Roger Braithwaite,
University of Manchester (UK)*

Increasing Melt Area on Greenland





- 2002 all-time record melt area
- Melting up to elevation of 2000 m
- 16% increase from 1979 to 2002

70 meters thinning in 5 years

Satellite-era record melt of 2002 was exceeded in 2005.

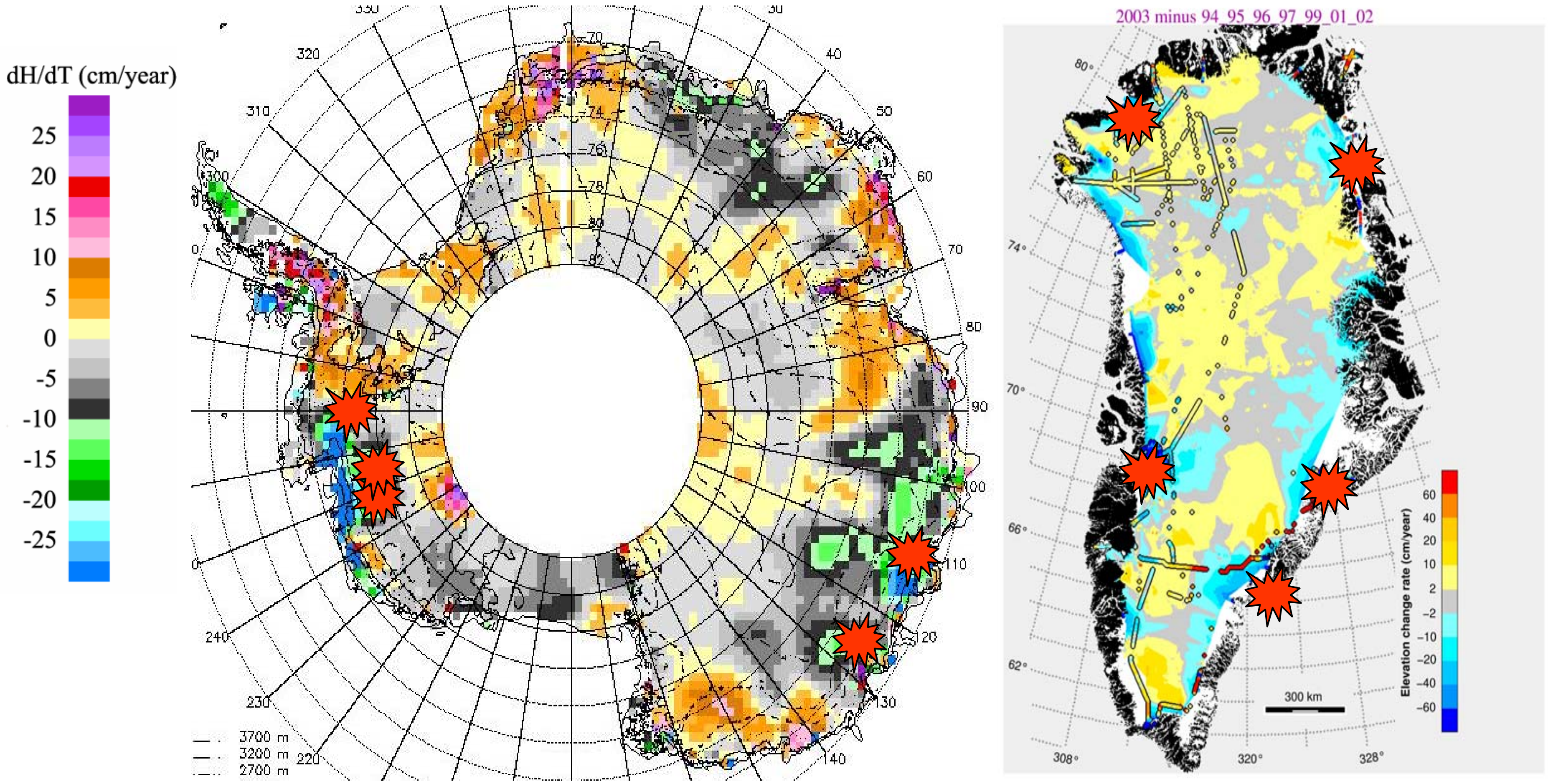
Source: Waleed Abdalati, Goddard Space Flight Center

Jakobshavn Ice Stream in Greenland

Discharge from major Greenland ice streams is accelerating markedly.

Source: Prof. Konrad Steffen, Univ. of Colorado

Satellites Reveal Changing Ice Sheets



Rapid thinning is concentrated at outlet glaciers exiting deep (sub sea level) valleys

Source: Robert Bindschadler, Goddard Space Flight Center

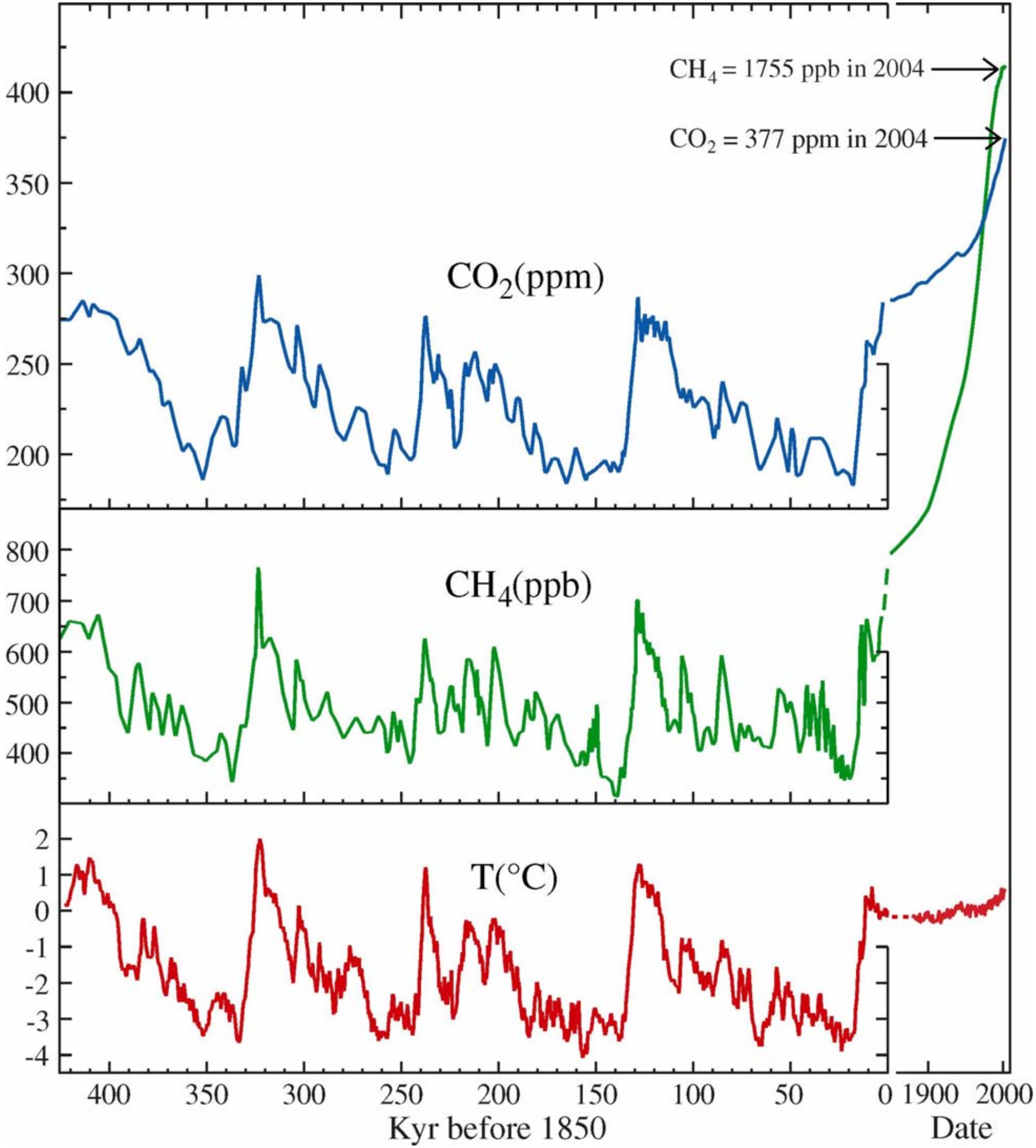
Summary: Ice Sheets

1. Human Forcing Dwarfs Paleo Forcing

2. Sea Level Rise Starts Slowly as Interior Ice Sheet Growth Temporarily Offsets Ice Loss at the Margins

3. Equilibrium Sea Level Response for ~3C Warming (25±10 m = 80 feet) Implies Potential for a System Out of Our Control

CO_2,CH_4 and estimated
global temperature
(Antarctic ΔT/2
in ice core era)
0 = 1880-1899 mean.



Source: Hansen, *Clim. Change*, **68**, 269, 2005.

Regional Climate Change

1. **General Statement**

   Magnitude of Change vs Scenario

2. **Specific Cases**

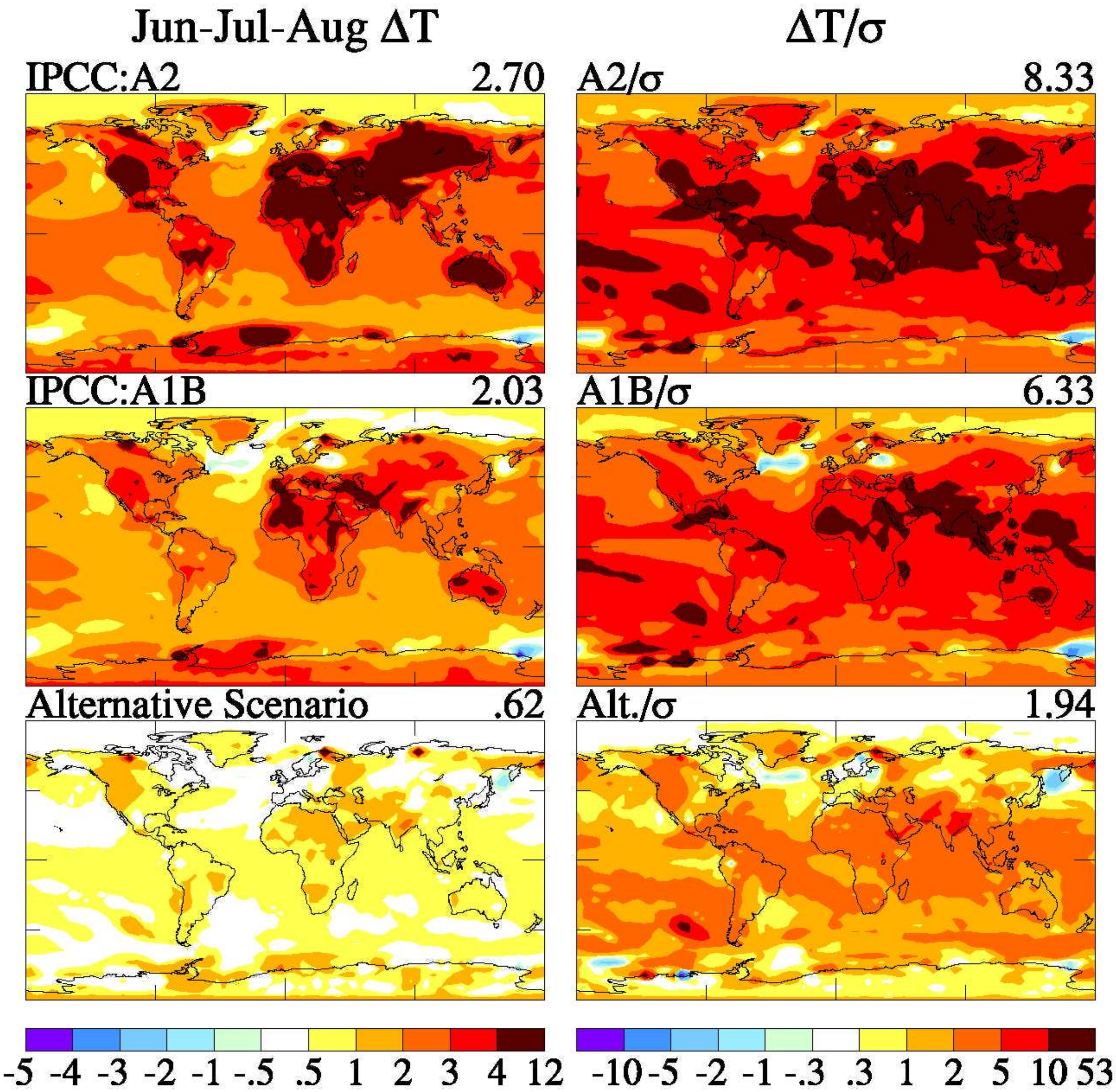
   Arctic

   Tropical Storms

   Ocean Effect on Ice Shelves

Simulated 2000-2100 Temperature Change

σ is interannual standard deviation of observed seasonal mean temperature for period 1900-2000.



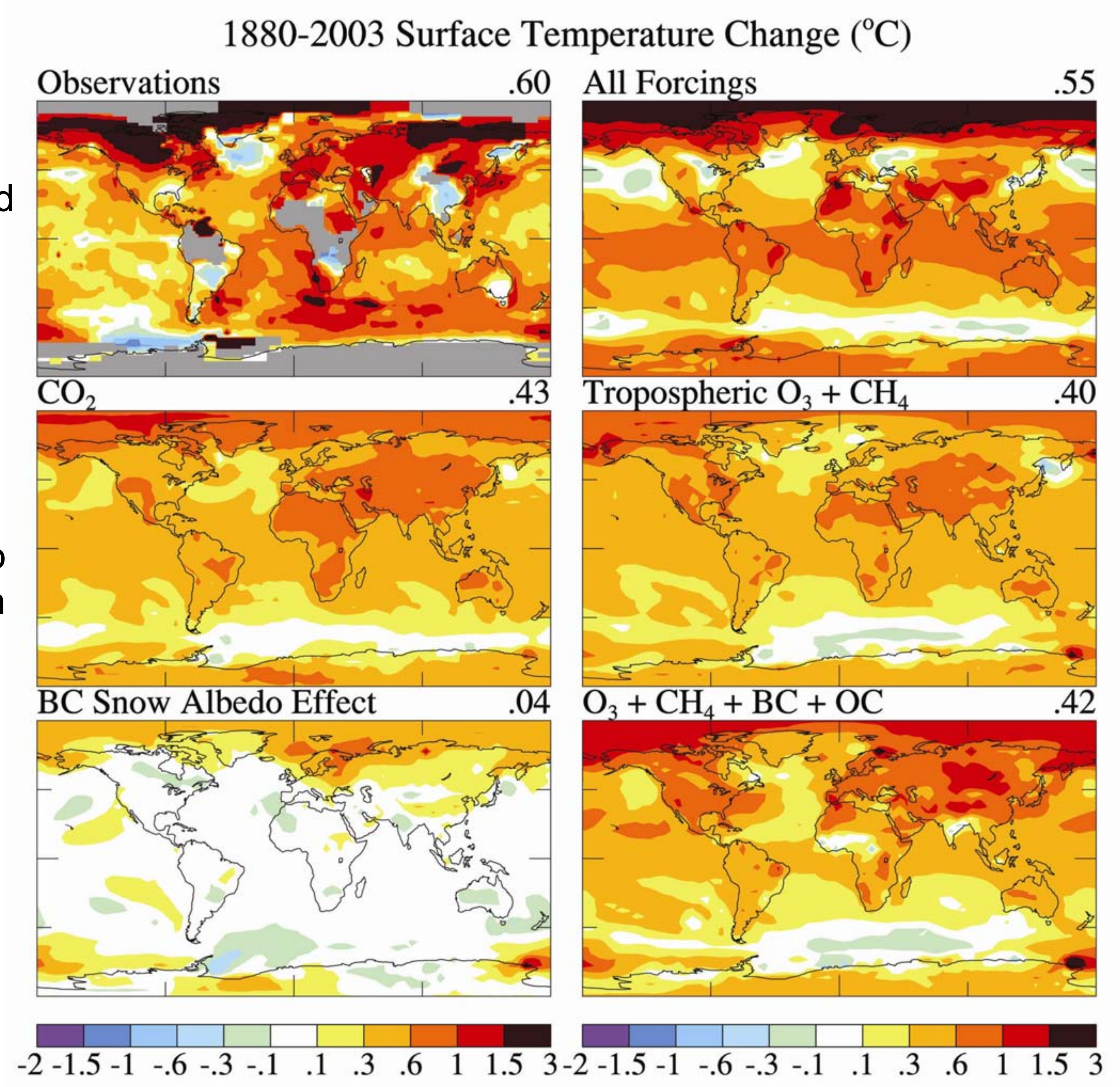
Source: Hansen et al., *J. Geophys. Res.*, to be submitted.

Arctic Climate Impact Assessment (ACIA)

- 140-page synthesis report released in November 2004.
- Main science report imminent (chapters available electronically at www.acia.uaf.edu).
- Concerns over wide-ranging changes in the Arctic.
  - Rising temperatures
  - Rising river flows
  - Declining snow cover
  - Increasing precipitation
  - Thawing permafrost
  - Diminishing late and river ice
  - Melting glaciers
  - Melting Greenland Ice Sheet
  - Retreating summer sea ice
  - Rising sea level
  - Ocean salinity changes
- Species at risk include polar bears, seals, walruses, Arctic fox, snowy owl, and many species of mosses and lichens

Sources: Claire Parkinson and Robert Taylor

Temperature change observed and simulated for different forcing mechanisms.



Aerosol forcing (negative) is thought to be slightly excessive in in the ‘all forcing’ simulation.

Source: Hansen et al., *J. Geophys. Res.*, to be submitted.

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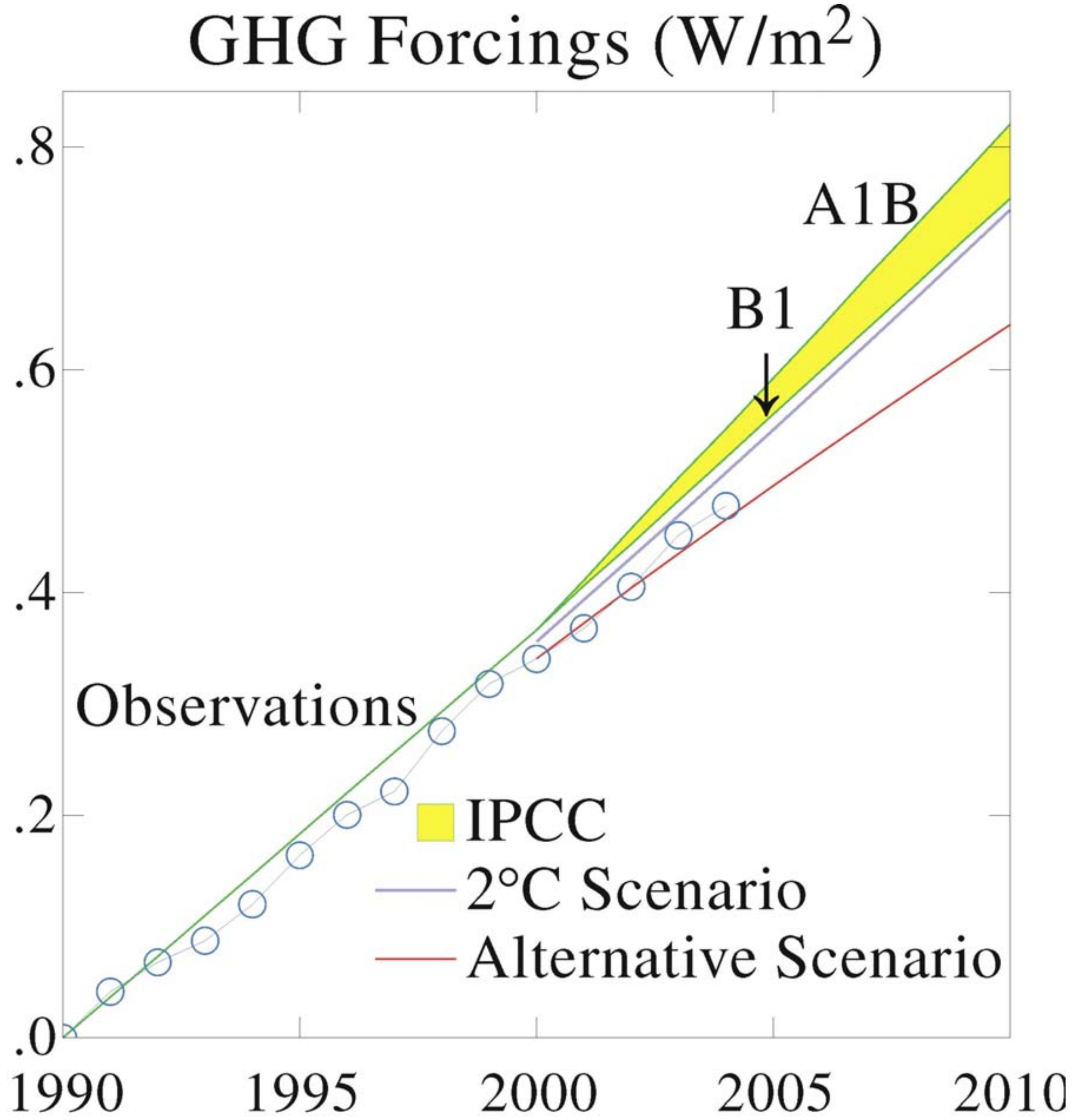


Increase of greenhouse gas climate forcings since 1990.

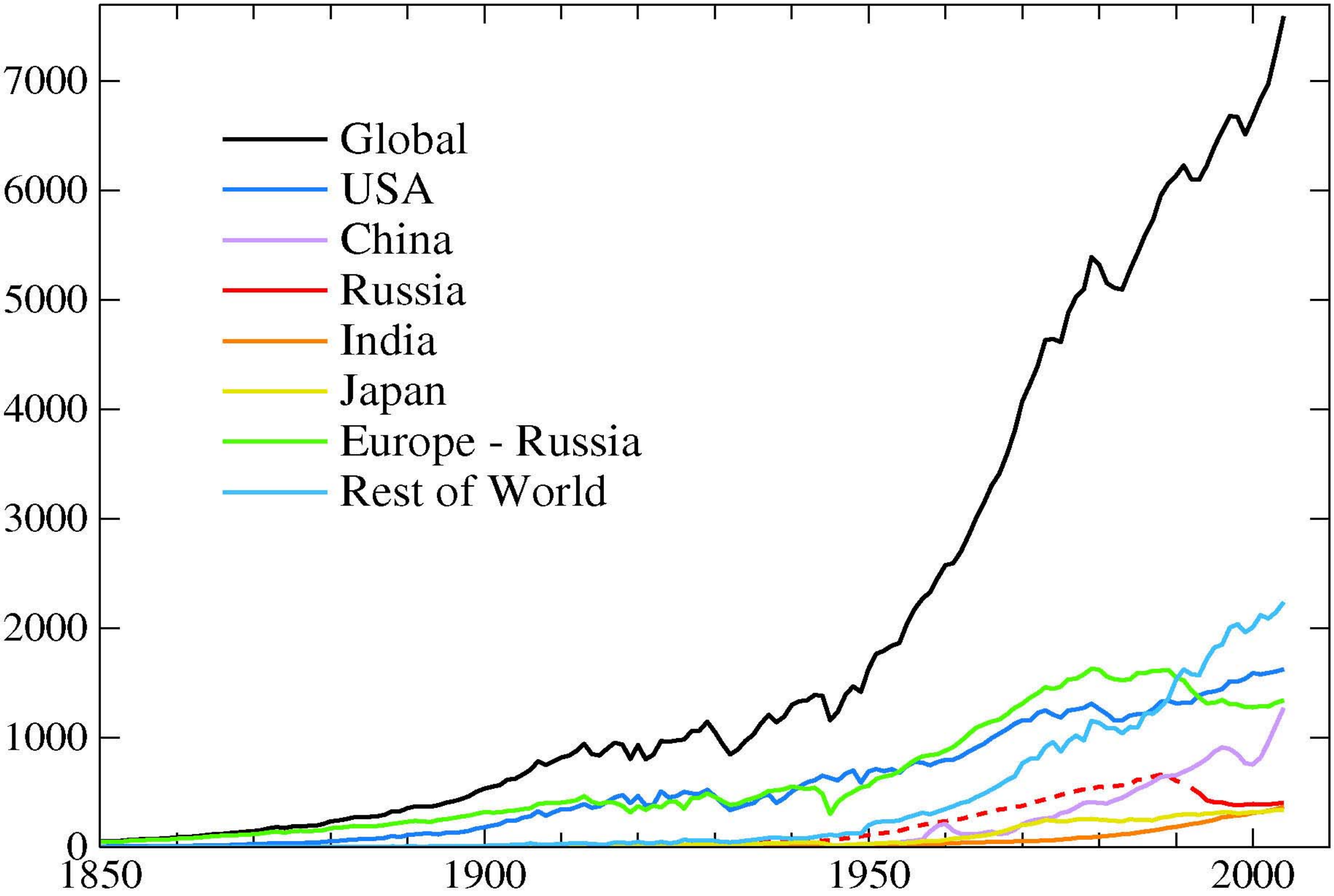
Greenhouse Gas Mixing Ratios

Greenhouse gas amounts (a), growth rates (b), and resulting forcings (c) for IPCC, “alternative” and “2°C” scenarios compared with observational data.

Growth rate of atmospheric CO_2 (ppm/year).

*Source: Hansen and Sato, PNAS, **101**, 16109, 2004.*

Country/Region Fossil Fuel CO_2 Annual Emissions

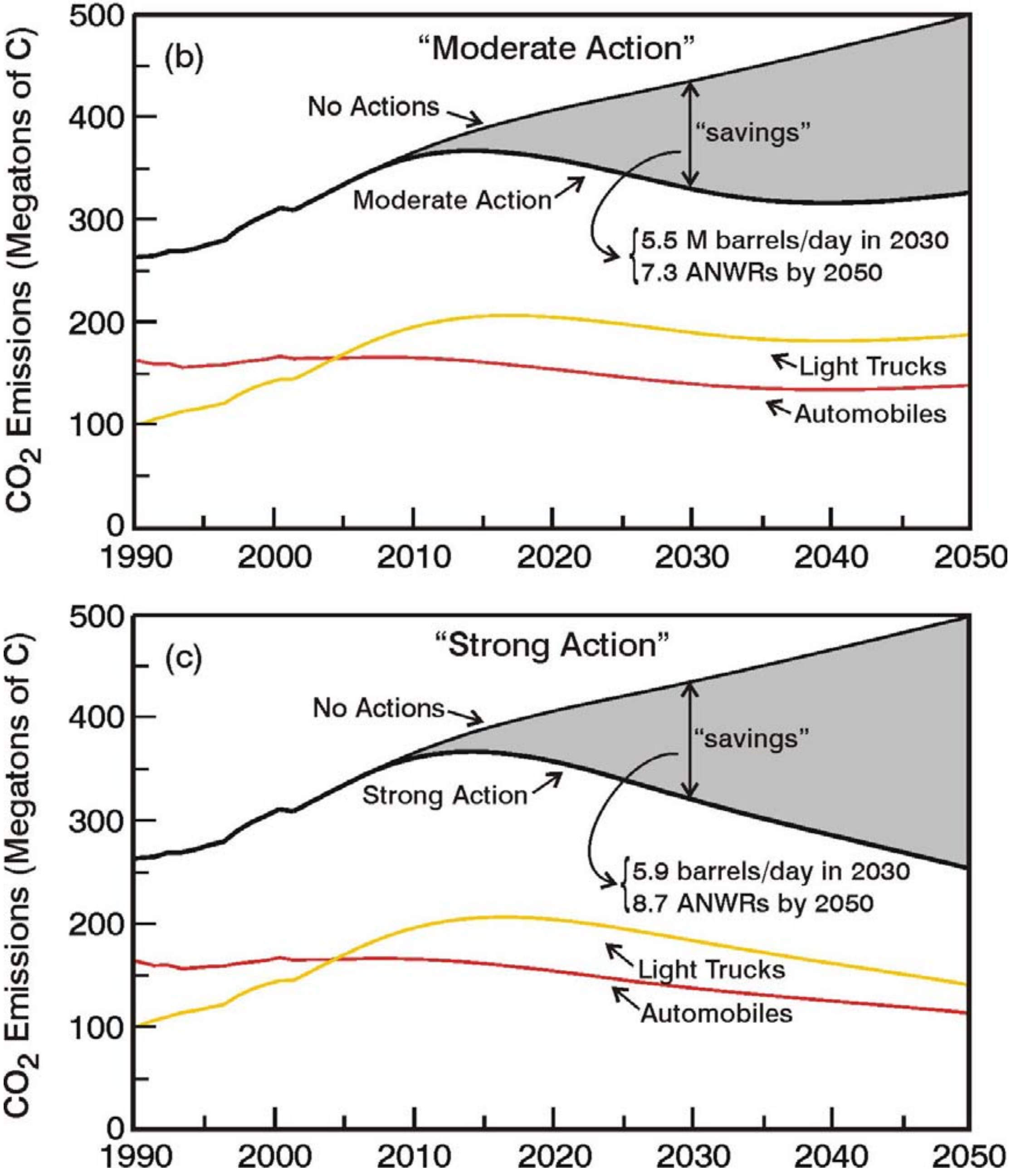


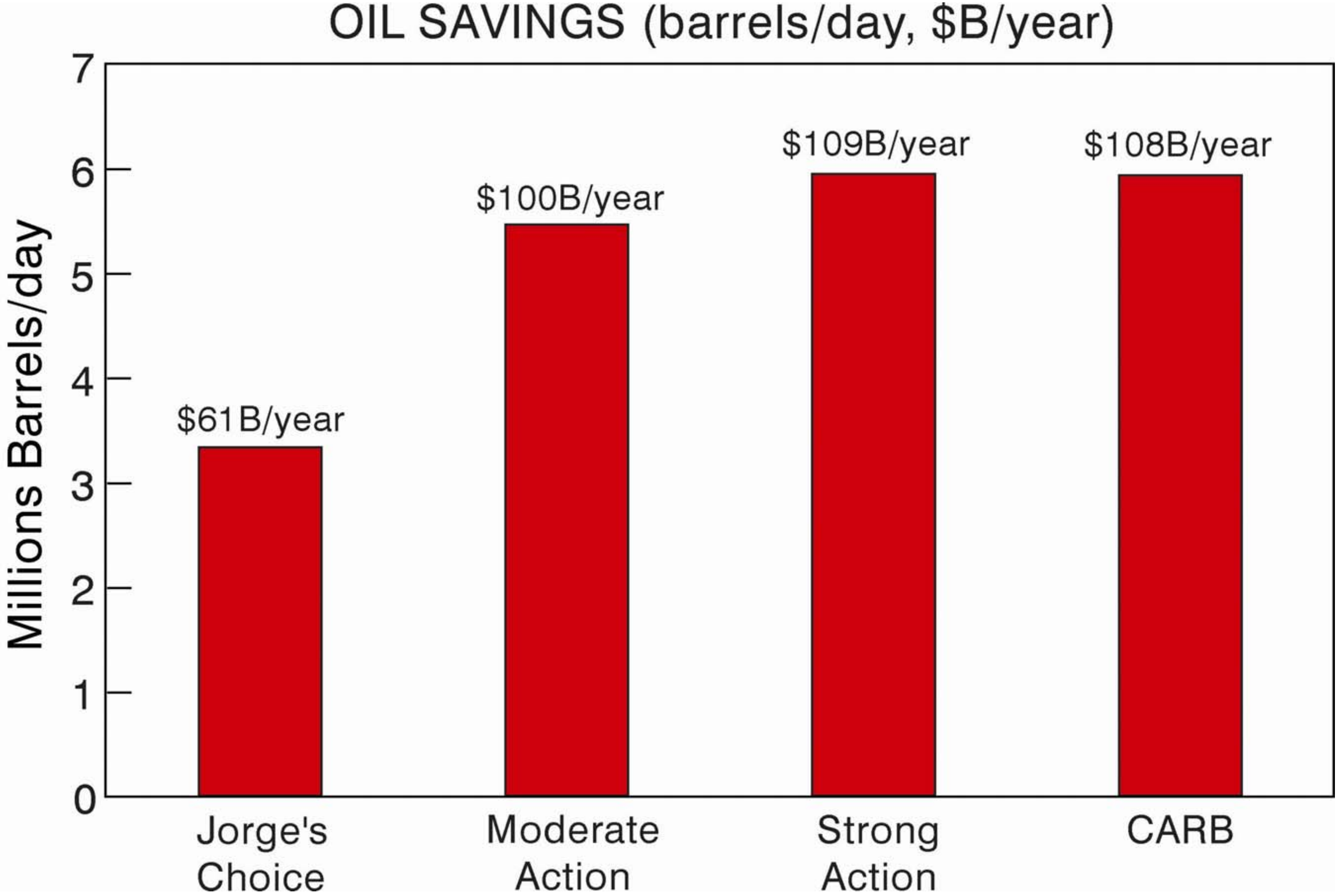
U.S. Auto & Light Truck CO_2 Emissions

“Moderate Action” is NRC “Path 1.5” by 2015 and “Path 2.5” by 2030.

“Strong Action” adds hydrogen-powered vehicles in 2030 (30% of 2050 fleet). Hydrogen produced from non-CO_2 sources only.

Source: On the Road to Climate Stability, Hansen, J., D. Cain and R. Schmunk., *to be submitted*.





United States annual savings (at $50/barrel, today’s dollars) in 2030 for alternative automotive efficiency improvements.

Source: On the Road to Climate Stability, Hansen, J., D. Cain and R. Schmunk., to be submitted.

Fossil Fuel CO_2 emissions by source country in 2004.

Source: Hansen et al, J. Geophys. Res., to be submitted

Workshop at East-West Center, Honolulu

April 4-6, 2005; Local Host: Intn'l. Center for Climate & Society, Univ. Hawaii

“Air Pollution as Climate Forcing: A Second Workshop”

► **Multiple Benefits by Controlling CH_4 and CO**
(benefits climate, human health, agriculture)

► **Multiple Benefits from Near-Term Efficiency Emphasis**
(climate & health benefits, avoid undesirable infrastructure)

► **Targeted Soot Reduction to Minimize Warming from Planned Reductions of Reflective Aerosols**
(improved diesel controls, biofuels, small scale coal use)

► **Targeted Improvements in Household Solid Fuel Use**
(reduces CH_4, CO, BC; benefits climate, human health, agriculture)

Conclusion: Technical Cooperation Offers Large Mutual Benefits to Developed & Developing Nations.

References:

►**Air Pollution as Climate Forcing: 2002 Workshop; 2005 Workshop** http://www.giss.nasa.gov/meetings/pollution02/ and 2005/

Summary: Is There Still Time?

Yes, But:

- **Alternative Scenario is Feasible, But It Is Not Being Pursued**
- **Action needed now; a decade of BAU eliminates Alter. Scen.**
- **We Are All in This Together**
- **Role of the Public & Scientists**