UNITED STATES DISTRICT COURT

EASTERN DISTRICT OF CALIFORNIA - FRESNO

CENTRAL VALLEY CHRYSLER-JEEP, INC., *et al.*, Plaintiff, v. CATHERINE E. WITHERSPOON, Defendant.	)))))))))	Case No. 1:04-CV-06663 REC LJO **DECLARATION OF JAMES HANSEN**

The Case for Action by the State of California to Mitigate Climate Change*

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Automobile Manufacturers vs. California Air Resources Board

James Hansen submits this report as his personal opinion as a private citizen. For the sake of identification, Dr. Hansen is a senior scientist at the Columbia University Earth Institute, Adjunct Professor of Earth and Environmental Sciences at Columbia University, and Director of the NASA Goddard Institute for Space Studies. Dr. Hansen has degrees in Physics, Astronomy and Mathematics from the University of Iowa, where he was trained in Dr. James Van Allen's Department of Physics and Astronomy, receiving his Ph. D. in 1967. He has also studied at the University of Kyoto and University of Tokyo, and as a post-doctoral scientist at Leiden Observatory, Netherlands. Dr. Hansen has been an active researcher in planetary atmospheres and climate science for almost 40 years, with the last 30 years focused on climate research, publishing more than 100 scholarly articles on the latter topic. Dr. Hansen was elected to the National Academy of Sciences in 1995 and he is recipient of the American Geophysical Union's Roger Revelle Medal and the Heinz Environment Award. He has testified numerous times to committees of the United States Senate and House of Representatives, and has twice made presentations to the George W. Bush Administration's cabinet level Climate and Energy Task Force chaired by Vice President Richard Cheney.

The present report employs the charts that Dr. Hansen used for a presentation at the National Academy of Sciences on 23 April 2006. Those charts and the present discussion of them are freely available at www.Columbia.edu/~jeh1

Abstract

Global warming is almost surely the greatest threat to the environment and economic well-being of California that the state has ever faced. Tangible effects of global warming are beginning to emerge in California and around the world, including a tendency for increased drought in the American Southwest, decreased snow-pack in certain mountain ranges, increased strength of storms driven by latent heat of vaporization including tropical storms, increase in the number of extreme rain events and flooding, diminution of the Arctic ice pack, and worldwide melt-back of alpine glaciers. These climate trends already have significant practical implications.

Further, greater, climate change will occur because of climate and energy system inertias. Climate inertia, due to the ocean's heat capacity, implies that the Earth has not fully responded to human-made emissions already in the air. In addition, standing energy infrastructure will continue to emit more greenhouse gases, even if it is decided to slow future emissions.

As a result, the Earth is perilously close to passing a tipping point, beyond which devastating climate effects become inevitable. To assess this danger, I contrast two scenarios: Business-as-Usual, with continued growth of greenhouse gas emissions, and an Alternative scenario, with gradually slowing emissions. I present evidence that Business-as-Usual would lead to eventual sea level rise of 15-35 meters, possible extermination of as much as half or more of the animal and plant species on the planet, and regional climate disruptions. The causal chain from emissions to climate change to societal impacts has become clear. Consequences of climate change within California itself will be great, but some of the climate impacts, such as sea level rise, will be more destructive in other parts of the world. The United States is the greatest emitter of climate-warming greenhouse gases and it seems likely that continued high emissions will accrue future moral and legal obligations to citizens of the United States, falling mainly on today's young people, but that topic is beyond the scope of this expert report.

Actions to achieve the Alternative scenario and minimize climate change are feasible, if substantive steps are initiated this decade. The most effective near-term actions are improved energy efficiency and increased use of renewable energy sources, as needed to level out carbon dioxide (CO_2) emissions and obviate the need to build climate-damaging infrastructure during an interim period in which advanced low-emission technologies are developed and deployed. In addition, actions are needed to reduce non-CO_2 climate forcing agents, especially methane, tropospheric ozone, carbon monoxide, and black soot.

Attainment of these goals to reduce emissions of CO_2 and non-CO_2 climate forcings will minimize climate damage within California and stimulate development of technologies that will be needed throughout the United States and the world. Thus, in the long run, the actions to reduce climate change should be economically beneficial to California and the nation, while contributing to environmental stewardship and improvement of public health.

Vehicles and power plants are the most important emission sources. Emissions from these sources can be brought into conformity with a scenario that moderates climate change via two steps: (1) halting near-term growth of CO_2 emissions, principally via improved energy efficiency, and reducing emissions of non-CO_2 greenhouse gases and black soot, and (2) deployment of improved low-emission technologies over the next several decades. The near-term efficiency improvements are essential for success of the second phase, as well as for the first phase. Vehicle emission requirements proposed by the California Air Resources Board match closely the requirements for this scenario that minimizes future climate change.

Outline

1. Recent Global Warming

Global average surface temperature of the Earth increased about 0.7°C (1.26°F) between the late 1800s and 2000 (Figure 1). Most of this warming occurred in the past three decades, during which time the Earth has been warming at a rate of about 0.2°C/decade (0.36°F/decade).

The temperature measurements over land areas are made at meteorological stations, while ocean data are surface water temperatures measured by ships and buoys, as well as by satellites in the past 25 years. Figure 2 shows the surface temperature anomaly for the first half-decade of the 21st century, relative to the 1951-1980 climatology. Warming is nearly ubiquitous, larger over land than over ocean, and larger at high latitudes than at low latitudes, especially in the Northern Hemisphere. These characteristics of the climate change pattern are expected for the response to positive global climate forcings (discussed in the next section) such as increasing atmospheric greenhouse gases (GHGs), as shown in numerous global climate modeling studies.

Global warming, about 1°F over the past several decades, is seemingly small compared to weather fluctuations or monthly temperature anomalies (Figure 3). Day-to-day weather fluctuations are commonly 10°F or more and monthly mean anomalies are commonly a few degrees Fahrenheit. A rare case such as January 2006 (Figure 3) had an anomaly in North America of about +10°F, with a cold anomaly in Eurasia that was almost as strong. Note that the Eurasia cold snap was not caused by a slowed ocean "conveyor" circulation; indeed, the North Atlantic Ocean was unusually warm. Warmth in North America resulted from a predominance of southerly winds, while, not surprisingly, Eurasia winds were more northerly. It is important that the public recognize that such temporary cold snaps are normal climate fluctuations that will continue to occur. However, Figure 3 also reveals that the "climate dice" are now "loaded": the predominance of red areas over blue areas means that warmer-than-normal anomalies are more pervasive than cooler-than-normal anomalies, where "normal" is the 1951-1980 climatology.

Given that global warming is much smaller than day-to-day weather fluctuations, why should we be concerned? Part of the answer is that regional impacts of climate change can greatly exceed global average warming. Also, because of climate system and energy system inertias, more warming is "in the pipeline." And emissions of the most important greenhouse gas, CO_2, are still accelerating, as fossil fuel burning is continuing to increase year after year.

Continuation of this trend will yield global warming of at least 5°F, which, as we will show, would make the Earth "a different planet."

2. Climate Forcings and Climate Sensitivity

One way to estimate the expected climate effect of increasing greenhouse gases is with a global climate model, a computer program that uses fundamental equations to simulate atmosphere and ocean structure and motions. Given such a model, one can alter climate "forcing agents" (or simply "forcings") and calculate how much the simulated climate responds.

A climate forcing is an imposed change to the planet's energy balance that may alter the planet's temperature. For example, if the brightness of the sun increased by 2% that would increase the amount of solar energy absorbed by Earth by about 4 Watts per square meter (4 W/m^2) averaged over the Earth's surface. Doubling the amount of CO_2 in the air also yields a forcing of about +4 W/m^2, because that amount of the Earth's thermal (heat) radiation is trapped by the increased opacity of the atmosphere at infrared wavelengths.

How much will climate change in response to a given climate forcing? "Climate sensitivity" has been studied for decades with climate models. In the standard experiments the forcing is allowed to act long enough to achieve the "equilibrium" or long-term response. Climate models typically yield a response of about 3°C global warming for doubled CO_2, i.e., about ¾°C per each W/m^2 of forcing. This model-estimated climate sensitivity is uncertain by perhaps a factor of two, however, because many physical processes are included in the climate models, some of which are not well understood, and these processes may not be accurately simulated or "parameterized." Thus it is inherently difficult to estimate the uncertainty in model-derived climate sensitivity.

It should be noted that this "climate sensitivity" refers to a specific set of assumptions about which climate parameters are allowed to change and which parameters are kept as fixed "boundary conditions." The specific assumptions usually employed might be called the "Charney" definition of climate sensitivity, because these assumptions were used by a panel of the National Academy of Sciences chaired by Prof. Jule Charney in 1979. It is noteworthy that the Charney panel estimated climate sensitivity as 3°C for doubled CO_2, with estimated uncertainty 1.5°C.

In the Charney definition of climate sensitivity the area of ice sheets on the planet is kept fixed, but the area of sea ice is allowed to change as calculated by the climate model. Similarly, atmospheric water vapor and cloud cover are allowed to vary as calculated by the model. This choice was made because the Charney panel was primarily interested in estimating the climate change that might occur during the next few decades or century. On that time scale the great ice sheets covering Greenland and Antarctica would not be expected to change much. On the other hand, it is appropriate to allow sea ice, water vapor and clouds to be free variables, because these quantities can change rapidly as the Earth's temperature changes.

A climate sensitivity of 3°C for doubled CO_2, i.e., ¾°C per W/m^2 of forcing, implies the existence of some positive "feedbacks" in the climate system. If all quantities except temperature were kept fixed, doubling CO_2 would cause a temperature rise of only about 1.2°C, i.e., climate sensitivity would be about 1/3 °C per W/m^2. The greater sensitivity found in climate models is a result mainly of positive feedbacks from water vapor and sea ice. As the air becomes warmer it holds more water vapor, which is a powerful greenhouse gas that adds to direct warming by CO_2. Also some sea ice melts as the ocean surface warms, which is also a positive feedback, because dark ocean absorbs much more solar radiation than does sea ice.

All climate models find these positive feedbacks by water vapor and sea ice. Clouds provide another possibly important set of feedback possibilities. Cloud feedbacks are complex and vary from one climate model to another. Clouds affect both the amount of sunlight reflected or absorbed by the Earth and the amount of infrared energy radiated to space. The effect of increasing or decreasing cloud cover also depends on the temperature and thus altitude of the cloud. The difficulty in accurately modeling clouds is one reason that model-derived climate sensitivity remains rather uncertain and varies from model to model.

The Charney choice of which feedbacks to include in the definition of climate sensitivity is mainly for the sake of standardization in comparing models, and the choice can readily be changed as appropriate for ones purposes. On long time scales ice sheets would be expected to melt in response to warming, thus making the climate system more sensitive to forcings on millennial time scales. Even on the century time scale important additional forcings may come into play, e.g., as the planet warms forests may advance poleward and permafrost may melt releasing GHGs. These additional feedbacks can be added to the models, and indeed they are being investigated in many climate models at this time.

Large uncertainty would probably always accompany a purely model-based estimate of climate sensitivity. Fortunately, the Earth's history provides examples with rather accurate knowledge of global climate response to known climate forcings. This empirical information provides our best measure of climate sensitivity. The combination of empirical data from the Earth's history with climate modeling studies allows better understanding of historical climate changes and provides research tools that are needed to reliably project the effects of human-made climate forcings on future climate.

3. Earth's Longer Climate History: Ice Ages and Warm Periods

Over the past hundreds of thousands of years the Earth's climate has varied repeatedly between cold ice ages and warm interglacial periods. The lower curve in Figure 4 shows the temperature change at the Vostok station in Antarctica for the past 400,000 years, with time running from left to right. The temperature record, as well as the amount of atmospheric carbon dioxide (CO_2) and methane (CH_4) as a function of time (the upper curves), are inferred for this period from ice cores drilled in the Antarctic ice sheet. The ice sheet was formed by snowfall that piled up year after year and compressed under its own weight to form ice, thus trapping bubbles of air that provide a history of atmospheric composition. Temperature is inferred from the isotopic composition of the ice, as the proportion of ^{18}O and ^{16}O in the ice depends on the temperature where the snowflakes formed.

Note that at present (the farthest right point in Figure 4) Antarctica is relatively warm. The earth has been in this warm (interglacial) period, called the Holocene, for about 14,000 years. Prior interglacial periods, some of which were warmer than the Holocene, occurred several times in the past 400,000 years, at intervals of approximately 100,000 years. Figure 4 reveals a strong positive correlation between the CO_2, CH_4, and temperature records. When the curves are carefully compared, it is found that the temperature usually leads the gas changes. Thus a warming planet must tend to drive CO_2 and CH_4 out of the ocean or continental surface into the atmosphere. However, these gases then contribute to temperature change, because they are greenhouse gases (GHGs) that trap the Earth's infrared (heat) radiation. Indeed, as we will show, the GHGs cause about half of the temperature variation on these long time scales.

Empirical Climate Sensitivity. The sensitivity of the climate system to forcings such as changing GHGs can be inferred by comparing the changes between the last ice age, which peaked about 20,000 years ago, and the Holocene. From geologic records we know the changes that occurred on the Earth's surface. During the ice age an ice sheet more than a mile thick covered most of Canada and parts of northern United States, including Seattle, Minneapolis and New York City, and there were smaller ice sheets in Europe and Asia. So much ice was locked in these ice sheets that sea level was more than 100 meters lower than today, exposing large areas of the continental shelves.

Because both atmospheric composition and planetary surface conditions are known quite well for both the ice age and the Holocene, we can calculate the forcings that maintained the temperature difference between these periods. As summarized in Figure 5, the surface change (mainly the area of ice sheets) caused a forcing of 3.5 ± 1 W/m^2. The total forcing of about 6½ W/m^2, including the GHGs, maintained a global temperature change of 5 ± 1°C, thus implying a climate sensitivity of ¾ ± ¼ °C per W/m^2.

This empirical climate sensitivity has a smaller estimated uncertainty than pure model results. An advantage of the empirical measure is that we know all real-world climate processes and feedbacks were free to operate, a characteristic that pure models can never obtain. However, it is noteworthy that the empirical and modeled climate sensitivities are in agreement.

The 400,000 year records. We derived climate sensitivity by comparing a single time, the peak of the last ice age 20,000 years ago, with the current interglacial period. A useful check on this climate sensitivity and additional information can be obtained by examining the longer ice core records. The longer record is particularly informative now because of the availability of good sea level records for the entire 400,000 year period. Sea level change is caused primarily by growth and decay of ice sheets on the continents, whose volumes can thus be estimated from the sea level change.

Figure 6 shows a global sea level record obtained by Mark Siddall and colleagues from analysis of oxygen isotope records in the Red Sea, where changes of sea level have a magnified effect due to limited rate at which water can be exchanged between the Red Sea and open ocean via a narrow straight that connects them. The standard error in the sea level estimates in Figure 6 is 12 meters, which is about 10% of the amplitude of glacial to interglacial sea level changes.

We can estimate the change of ice sheet area from the change of sea level by assuming a simple shape for the ice sheets, which yields an ice sheet forcing proportional to the 2/3 power of sea level. The ice sheet climate forcing for every value of sea level is thus defined by the constraint that the forcing was 3.5 W/m^2 for the sea level change of ~110 meters between the last ice age and the current interglacial period.

The greenhouse gas climate forcing can also be calculated as a function of time for the entire 400,000 year period from knowledge of the greenhouse gas histories. We can include a reasonable estimate of the effect of the third important greenhouse gas, N_2O, in addition to CO_2 and CH_4, despite the fact that good data on N_2O changes is available only for limited periods during the 400,000 period. From measured glacial-interglacial N_2O change, and evidence that its time variation has general similarities to the variations of both CO_2 and CH_4, we take the N_2O forcing as 15 percent of the sum of CO_2 and CH_4 forcings.

The resulting ice sheet and greenhouse gas forcings for the past 400,000 years, shown in Figure 7, can then be multiplied by climate sensitivity ¾ °C per W/m^2 to obtain a "predicted" global temperature for the entire 400,000 period. The resulting calculated global temperature is shown by the blue curve in Figure 8.

Accurate records of temperature change at many points on the globe would be needed to define the true global mean temperature change. Given the absence of such comprehensive data, we instead make use of the approximation that global mean temperature changes on millennial time scales are about half of Central Antarctic temperature changes. The red "observations" curve in Figure 8 is thus the Vostok temperature change divided by two. This approximation for observed global temperature is consistent with our knowledge from detailed reconstruction of conditions during the last ice age, which indicate that the global glacial-interglacial temperature change involves a temperature change of 3-4°C at low latitudes, about 10°C at the pole, and 5°C on global average.

Figure 8 reveals remarkable agreement between observed and calculated temperatures during the 400,000 years. The error (uncertainty) in the dating of the two curves is a few thousand years.

The close agreement of observed and calculated temperatures makes it scientifically interesting to discuss two of the minor discrepancies, although these have only indirect relevance to the California automobile efficiency case. The failure of the calculated temperature to capture a clear minimum temperature at MIS (marine isotope stage) 5d (approx. 110 kybp, where kybp is kiloyears before present) may be due to inaccuracy or poor temporal resolution in the sea level record, as our global climate model calculations (not illustrated here) suggest a strong shift from ice sheet growth to ice sheet melting across this period, which is consistent with the observed temperature change. In other words, we expect that future improved sea level records are likely to find a clear minimum in sea level near 110 kybp.

The discrepancy between observed and calculated temperature in the most recent 8000 years is probably due to anthropogenic climate forcings. As Bill Ruddiman has argued, human effects via deforestation and agriculture probably became significant about 6-8 thousand years ago. We have included all human effects on GHGs in our calculations, because we use measured ice core values of GHG amounts. However, we have not included the effects of humans on surface albedo (cooling), aerosols (cooling), and the aerosol indirect effect on clouds (cooling), as we have no measurements of those quantities. The aerosol indirect effect is non-linear, so even moderate amounts of human-made aerosols may be important in an otherwise pristine atmosphere. It seems that positive and negative human-made forcings competed on comparable terms up until the past 30 years, after which time efforts to reduce particulate air pollution combined with rapidly increasing GHG emissions to throw the balance dramatically to the warming side.

One implication of Figure 8 is that the GHG and ice sheet changes account for most of the global temperature change. GHGs and ice sheets are feedbacks on these long time scales, implying that climate is exceedingly sensitive on these long time scales. The small instigating forcings that give rise to the regular climate variations are a result of perturbations of the Earth's orbit (tilt of axis, eccentricity of orbit, and season of nearest approach to sun) on time scales of tens of thousands of years. However, the high climate sensitivity means that any other small forcings and chaotic variations can also lead to large climate variations.

The past century. Another important implication from Figure 8 becomes obvious when we add on to the CO_2 and CH_4 records data from the past century, as we have done to the right side of Figure 9. Atmospheric CO_2 and CH_4 in the Earth's atmosphere are now far outside the range that has existed for hundreds of thousands of years. In addition, ice and snow areas are in rapid retreat on a global basis, with even the masses of the Greenland and West Antarctic ice sheets in decline, as discussed below. Although, absent humans, the Earth would have been expected to eventually cool off and head into a new ice age, that natural cycle, which relied on natural reductions in atmospheric GHG amounts, has been totally obliterated by human-made GHGs. A significant fraction of human-made CO_2 emissions will remain in the atmosphere for thousands of years. Thus the next ice age will not occur unless humans become extinct, and even then it would require thousands of years. As summarized in Figure 10, humans now control global climate, for better or worse.

A few more comments are needed about Figure 9. The time scale has been greatly expanded for the added portion of the figure after 1850. In the prior 400,000 years we could assume that the planet was nearly in energy balance with space, for the time resolution of the curves (1000 years or more). Thus calculated temperature change was simply a product of the forcing and equilibrium (long-term) climate sensitivity. This assumption is no longer valid in modern times, as climate forcings are changing so fast, especially in the past few decades, that the climate system has not come to equilibrium with today's climate forcing. Thus the observed temperature rise in the past century is only part of that expected for the current level of atmospheric composition. As discussed below, the additional amount of global warming "in the pipeline" is probably ~0.5°C or ~1°F.

Warming in the past century has also been reduced by the fact that there are several other climate forcings in addition to GHGs, especially human-made aerosols (fine particles in the air) that yield a negative (cooling) forcing. In the next section we estimate all of the known forcings and calculate the expected global temperature change.

4. Climate Change in the Era of Human Influence

Analysis of climate change during the era in which humans have become a major factor must account for several forcing agents and their temporal changes. Figure 11 shows estimated changes of known climate forcings during the past century. Although it is possible that there are still more significant forcings, it is highly unlikely that there any others comparable in magnitude to the largest known forcings. GHG and aerosol (direct and indirect) forcings are the largest human-made global forcings, although land-use effects are large in limited regions. Volcanic aerosols and solar irradiance variations are substantial natural forcings.

Greenhouse gas forcing is known accurately (estimated error ~10-15%). Volcanic aerosol forcing is known within ~25% in recent decades and within ~50% for the earlier eruptions. Solar forcing is measured accurately since the late 1970s but is much more uncertain at earlier times. The greatest uncertainties are associated with tropospheric aerosols (fine particles). The history of aerosol amount is uncertain and the aerosol indirect effect on clouds is poorly understood. The aerosol forcings are estimated to be uncertain by about a factor of two.

When the forcings of Figure 11A are used to drive the Goddard Institute for Space Studies (GISS) global climate model, which has a sensitivity of 2.7°C for doubled CO_2, the simulated global temperature change is in good agreement with observations (Figure 11B). The close agreement must be in part fortuitious, given the forcing uncertainties. Equally good agreement could probably be obtained with a larger net forcing and smaller climate sensitivity or vice versa. However, the climate sensitivity of the GISS model is near the middle of the range that is consistent with paleoclimate data.

Projections of climate simulations through the 21st century avoid many uncertainties associated with the lesser climate forcings because of the growing dominance of GHG climate forcing. The primary uncertainty becomes the scenario for future increase of greenhouse gases. Figure 12 shows the simulated global warming for IPCC (Intergovernmental Panel on Climate Change) greenhouse gas scenarios as well as for the Alternative scenario.

The IPCC A2 and A1B scenarios can be described as Business-as-Usual scenarios. They have growth of CO_2 emissions at about 2%/year as well as some continued growth of non-CO_2 forcings (CH_4, N_2O, O_3, and black soot) during the first half of the 21st century.

The Alternative scenario has a moderate decline in CO_2 emissions before 2050 and a steeper decline thereafter, such that atmospheric CO_2 peaks at 475 ppm in 2100 and declines very slowly thereafter. The Alternative scenario is designed to keep growth of net forcing after 2000 at about 1.5 W/m^2, as required to keep additional global warming (beyond that in 2000) less than 1°C (assuming equilibrium climate sensitivity ~3°C for doubled CO_2). The Alternative scenario assumes reductions of CH_4, carbon monoxide, tropospheric O_3, and black soot, so as to achieve a zero net change in non-CO_2 forcings in the 21st century despite anticipated growth of N_2O and anticipated reduction of sulfate aerosols. If the assumed reductions of the positive non-CO_2 forcings are not achieved, the limit on CO_2 becomes less than 475 ppm to hold warming to less than 1°C.

The Business-as-Usual scenarios yield global warming (beyond that of 2000) of ~2°C or greater, with temperatures still rising rapidly in 2100. These results were calculated with a model having climate sensitivity 2.7°C for doubled CO_2, but they would not be substantially altered by another sensitivity within the range (2-4°C) that is consistent with paleoclimate data.

The Alternative scenario yields global warming less than 1°C in the 21st century. Limitation of the future growth of climate forcings to that in the Alternative scenario requires, over time, a substantial reduction in future climate forcings relative to growth that is projected under Business-as-Usual. In the first half-decade of the 21st century CO_2 emissions have continued to increase at about 2% per year. If this growth continues another decade, the 35% increase of CO_2 emissions (between 2000 and 2015) will make it implausible to achieve the Alternative scenario.

In summary, although several climate forcings are poorly defined over the past century, uncertainty about past forcings has little effect on the distinction between Alternative and Business-as-Usual scenarios for the 21st century. Warming of at least 2°C seems assured if GHG emissions continue to follow Business-as-Usual growth; indeed, warming in the past three decades has been at a rate of 2°C per century. Reduction of global warming to less than 1°C in the 21st century requires a substantial reduction of GHG emissions below recent levels.

Plausible future changes of human-made aerosols do not substantially alter these conclusions. Aerosols may decrease in response to clean-air requirements, which are presently focused on sulfate aerosols, thus increasing global warming as much as several tenths of a degree Celsius in the IPCC scenarios. In the Alternative scenario this warming tendency is balanced via reduction of black soot aerosols and other positive non-CO_2 forcings.

5. Dangerous Human-Made Climate Change

All countries, including the United States, agreed upon the Framework Convention on Climate Change. The problem is that the Framework's objective (Figure 13), to stabilize GHG emissions at a level that avoids dangerous human-made climate change, does not include definition of what climate change would constitute danger.

Burning embers. IPCC addresses definition of "dangerous" with a "burning embers" diagram (Figure 14). It is appropriate to consider a broad range of "reasons for concern" about climate change, and use of probability distribution functions is a good way to incorporate uncertainties such as the true value of climate sensitivity. However, choice of the magnitude of global warming that raises concern to a high level remains arbitrary, leaving the impression that the mean warming at which "danger" is encountered may be almost 3°C.

Such a conclusion is patently absurd. The last time the Earth was 3°C warmer than in 2000 was at least three million years ago, in the Middle Pliocene, when the Earth was, for practical purposes "a different planet." The Arctic was apparently ice-free in the warm season and sea level was at least 25 meters higher. It is inconceivable that citizens would want to wait until we were approaching such a state before being warned with bright danger flags.

"Dangerous" metrics. A more realistic estimate for the global warming that constitutes "danger" can be found by identifying key threats to the physical and biological components of the planet. My nomination for key metrics is shown in Figure 15: (1) magnitude of sea level rise, (2) degree of extermination of animal and plant species (sometimes, euphemistically, described as decrease of biological diversity), and (3) devastating regional climate change, e.g., increased storm strength, more frequent and intense droughts and heat waves, heavier rainfall events and more frequent floods, and loss of fresh water supply.

Sea level rise and extermination of species deserve high priority because of their finality. If an ice sheet is softened to the point that its disintegration is guaranteed and unstoppable, there is little merit in arguing over whether its final demise will take 50 years or 150 years. And the ice sheet will not be resurrected during the lifetime of any of our foreseeable descendents. Similarly, once a plant or animal species is extinct, it is gone. It can be argued that even destruction of the habitat of an animal constitutes "extinction" in the eyes of most people. No doubt an iconic species such as the polar bear would be "saved" in zoos and perhaps in the "wild" with human assistance. But in such case should the bears be considered "saved" and should the public be warned of the likelihood of that fate?

Impending human-made forcing of climate is so unusual, especially the magnitude and rapidity of climate forcing changes, that it is difficult to quantify the expected "climate impacts." There are no similar paleoclimate examples to study. Present models are of little value for key issues such as ice sheet stability and species survival. However, if the discussion is broken into specific subtopics such as expected equilibrium sea level change, ice sheet response time, and species migration rates, progress can be made in estimating "dangerous" levels of change.

Earth's historical precedents. It is easy to be misled by the magnitude of some local paleoclimate temperature changes, especially changes toward colder climates. As a result, it is not universally recognized that global warming of 1°C above year 2000 temperature would be a large climate change and 3°C would yield "a different planet."

Until recently, the best indication of the Earth's temperature change over hundreds of thousands of years was provided by Antarctic and Greenland ice cores. The Greenland temperature depends strongly on regional sea ice cover and small changes of wind direction, so it is not a representative measure of global change. Central Antarctica provides a somewhat better indication of global change, at least in the case of large global climate changes. A canonical 5°C global mean temperature between glacial and interglacial periods typically has a Central Antarctic temperature change of ~10°C and tropical change ~3-4°C. However, Antarctic temperature is also subject to local variable factors such as changes in the height of the ice sheet surface and regional changes of insolation due to Earth orbital changes.

Tropical ocean temperatures are especially important because the ocean integrates the effect of most climate forcings and transmits the impact to the rest of the world. It is for this reason that the world has a fairly congruent response to most climate forcings [JGR, 110, D18104, 2005]. Highly localized forcings can produce a localized climate response, but reasonably broad-scale forcings, including large ice sheets and human-made aerosols, both of which are concentrated more in the Northern Hemisphere, affect the low latitude ocean temperature and thus in turn affect the temperature in both hemispheres, albeit with a smaller temperature change in the opposite hemisphere.

In recent years improved paleoclimate "thermometers" have been developed for extracting the record of sea surface temperature, for example, by using the ratio of magnesium to calcium in the shells of foraminifera. The latter tiny organisms live near the sea surface, and their shells accumulated in sea floor sediments over millennia. Ocean cores, analogous to the Antarctic ice cores, thus allow investigation of how the sea surface temperature changed over great time intervals.

Figure 16 shows a record, for more than one million years, of sea surface temperature in the Pacific Ocean "Warm Pool" region. The Warm Pool, in the Western Pacific, may be the single most important place on the planet to know the temperature because it has a strong influence on moisture and heat fluxes to the atmosphere and, in turn, on the transport of moisture and heat to higher latitudes in both hemispheres. Variations of temperature in this region that occur during El Nino Southern Oscillation phenomena are transmitted on a global scale.

The temporal resolution in Figure 16 changes at the points with vertical lines, the objective being to provide higher resolution for more recent times. As expected, there is a high correlation of Warm Pool glacial to interglacial temperature changes of the past 400,000 years with temperature change in Antarctica (Figure 4).

Measured sea surface temperatures in the Warm Pool region since 1870 (right side of Figure 16) show that recent warming has raised temperature to the highest level in the current interglacial period. Although it might be argued that the different methods of measuring recent and paleoclimate temperatures could introduce an offset between the two records, we know that the modern thermometer measurements must begin somewhere within the Holocene temperature range recorded by foraminifera. It follows that the temperature in the Warm Pool today is at its highest level in the Holocene and it is within less than one degree Celsius of the warmest temperature of the past 1.3 million years.

The range of the Earth's temperature in the past million years, and especially the upper limit of that range, is critical for estimating when global warming will become "dangerous." The rationale for the Alternative scenario is that, if global temperatures can be kept within the range that has existed in the past several hundred thousand years, then it is unlikely that the most extreme climate impacts will occur. For example, although the paleoclimate record (Figure 4) reveals a positive correlation between temperature and GHGs, which suggests that a warming climate has a positive feedback that releases GHGs to the atmosphere, the feedback is small compared with the magnitude of human-made GHG emissions. This conclusion implies that the potential release of huge amounts of CH_4 and CO_2 that is presently frozen in clathrates in the tundra or in ocean sediments on the continental shelf would be unlikely, provided that the temperature stays within the range that has existed on Earth for several hundred thousand years.

This does not mean that climate impacts will be negligible if global warming is kept under 1°C (relative to year 2000), but the planetary conditions will be within a range in which we know that the climate did not go seriously haywire in the past. In contrast, if warming approaches the range 2-3°C, it is virtually certain that there will be large-scale disastrous climate impacts, for humans as well as for other inhabitants of the planet, as discussed below.

An important point to note is that the tripwire between keeping global warming <1°C, as opposed to having a warming that approaches the range 2-3°C, may depend upon a relatively small difference in human-made direct forcings. The reason for that conclusion is that keeping global warming <1°C depends upon having both a moderate limit on CO_2 and a reduction of non-CO_2 forcings. However, if the warming becomes >1°C, it may become impractical to achieve and maintain the presumed reductions of the non-CO_2 forcings, in part because positive GHG feedbacks from tundra or other terrestrial sources may become significant in the warmer climate.

5.A. Sea Level Rise

Sea level rise is underway now at a moderate rate. In the past decade sea level increased about 3 cm, i.e., at a rate of 30 cm (one foot) per century. This is about double the average rate of sea level rise during the preceding century. In turn, the rate of sea level rise over the 20th century was probably greater than the rate of rise in the prior millennium, as most analyses suggest that the sea level increase following the last ice age had essentially run its course and sea level had become almost stable prior to the global warming of the past 125 years.

The recent observed sea level rise is at least in part anthropogenic. About half of the increase is accounted for by thermal expansion of ocean water due to global warming. In addition, melting alpine glaciers worldwide are responsible for at least several centimeters of the observed sea level increase. Possible contributions from Greenland and Antarctica have been very difficult to determine until the advent of high technology measurements of the past few years. Perhaps most notable is the precise gravity field measurements by the GRACE satellite, which determined that Greenland and West Antarctica each were losing mass at a rate of about 200 cubic kilometers (about 50 cubic miles) of ice in 2005. Spread over the world ocean, this amounts to 1 mm of sea level, or a rate of 10 cm per century.

The existing moderate rate of sea level change is not without practical consequences, as will be discussed by different experts. Sea level change is larger if the GHG growth rate is larger, as, for example, thermal expansion certainly will be larger for a Business-as-Usual 2-3°C global warming than for <1°C warming of the Alternative scenario.

However, the primary issue about sea level concerns the likelihood that global warming will reach a level such that ice sheet disintegration begins to proceed in a rapid non-linear fashion on either Greenland, West Antarctica, or both. Once well underway, such ice sheet collapse may be impossible to stop, because of multiple positive feedbacks including the effect of sea level rise itself on ice sheets grounded in marine areas. In that event, sea level rise of at least several meters would be expected. In the opinion of the writer, if Business-as-Usual global warming of 2-3°C occurs, such massive sea level rise is inevitable and a substantial fraction of the rise would occur within a century. Although some ice sheet experts believe that the ice sheets are more stable, I believe that their interpretation is based in part on the faulty assumption that the Earth has been as much as 2°C warmer in prior interglacial periods. As discussed elsewhere in this document, there is strong evidence that the Earth is within 1°C of its highest temperature in the past million years, and, as a consequence Business-as-Usual global warming would almost surely send the planet beyond a tipping point, thus guaranteeing a disastrous level of sea level rise.

Ice sheet stability. The great ice sheets on Greenland and Antarctica require millennia to grow, because their rate of growth depends on the snowfall rate in a cold, relatively dry, place. Ice sheet disintegration, on the other hand, is a wet process that can proceed rapidly.

Figure 17 shows summer melt-water descending into a moulin on Greenland. A moulin is a vertical shaft in the ice sheet formed by summer melt-water that runs into a crevasse and melts its way to the base of the ice sheet.

Although summer melting is normal on parts of Greenland, the area with melting has been increasing in recent years, as shown in Figure 18. In 2005 summer melting increased further (Figure 19) to the greatest area in the period of data (since the late 1970s).

A principal effect of the increased melt-water is to lubricate the base of the ice sheet, causing the ice streams to move faster as they carry icebergs to the ocean. Figure 20 shows the largest ice stream on Greenland, which has doubled its speed over the past few years. The other large ice streams on Greenland have similarly accelerated and increased their flux of icebergs to the ocean.

The net impact of these ice stream accelerations has recently been measured by the satellite GRACE, which measures the Earth's gravity field to very high precision. GRACE finds that the mass of the Greenland ice sheet decreased markedly over the period of satellite data, which began in 2002 (Figure 21). In 2005 the mass of Greenland decreased by 200 cubic km of ice, which is approximately 50 cubic miles of ice. In the same way, GRACE measured the change of mass of West Antarctica, finding a mass loss similar to that of Greenland.

When the 2005 ice losses from Greenland and West Antarctica are spread over the world ocean they raise sea level by 1 mm, which is a rate of sea level change of 10 cm per century. This rate of change is moderate, but it calls into question the IPCC assumption that mass loss from the ice sheets would not contribute significantly to sea level rise in the 21st century.

The primary question, however, is whether the rate of melt has the potential to accelerate in a rapid, nonlinear fashion. Some hint of that possibility is contained in recent earthquake data for Greenland. Seismometers around the world have detected an increasing number of earthquakes on Greenland between 1993 and 2005, as shown by the green bargraph in Figure 22. The location of these earthquakes is near the outlets of major ice streams on Greenland, as shown by the red circles in Figure 22. The earthquakes, which have magnitudes between 4.6 and 5.1, are an indication that large pieces of the ice sheet lurch forward and then grind to a halt from friction with the ground.

The number of these Greenland earthquakes, or ice quakes, doubled between 1993 and the late 1990s, and it has since doubled again. The GRACE record of Greenland mass loss is too short to determine whether mass loss is proportional to Earthquake number. However, the rapid increase of quake number is cause for concern about the long-term stability of the ice sheet.

Figure 23 shows estimates of decadal mean surface temperature anomalies on Greenland (top half of figure) and yearly anomalies since 1994 (bottom half of figure). The estimated mean temperature anomaly for the first several years of the present century is ~1°C, relative to the 1951-1980 climatology.

In contrast, additional global warming of 2-3°C under a Business-as-Usual scenario would be expected to yield ~5°C additional warming over Greenland. Such a level of additional warming would spread summer melt over practically the entire ice sheet and considerably lengthen the melt season. It is inconceivable that the ice sheet could long withstand such increased melt-water before entering a period of rapid disintegration, but it is very difficult to predict when such a period of large rapid change would begin.

Paleoclimate ice sheet lessons and summary. Ice sheet models have been constructed to help analyze global climate change on 100,000 year time scales. These models, by their nature, respond on millennial time scales. These models do not incorporate all the processes that introduce the possibility of rapid ice sheet change, such as realistic ice streams, the effect of a warming ocean on melting ice shelves that buttress land-bound ice, and penetration far inland of the effect of ice shelf removal.

Given the absence of adequate ice sheet models, it is important to examine paleoclimate data to reveal how ice sheets have responded to climate change in the past (Figure 24). During the Earth's history there have been numerous occasions in which sea level rose at a rate of several meters per century. For example, during meltwater pulse 1A, about 14,000 years ago, sea level rose approximately 20 meters in 400 years, or about one meter every 20 years. Sea level rise at a rate of several meters per century has occurred on at least several occasions.

The primary forcing that drives long-term paleoclimate changes, changes of the seasonal and geographical distribution of sunlight, which in turn are caused by changes of the Earth's orbital elements, varies slowly over thousands of years. Climate changes, however, are commonly more rapid, because once significant change is initiated, multiple positive feedbacks can come into play. On a planetary scale, these feedbacks include change of atmospheric GHG amount and the area of ice sheets. However, within the ice sheets themselves, there are multiple feedbacks including change of ice sheet albedo as it becomes wet, change of altitude of the ice sheet surface, and the nonlinear dynamical processes involved in the wet disintegration of ice.

A system with such positive feedbacks exhibits the potential for rapid disintegration of ice sheets, because ice sheet changes provide a source of further energy imbalance that drives further ice sheet change. In the natural system, the initiating energy imbalance is small and changes slowly over millennia. In the present system, however, the human-made GHG forcing dwarfs the paleo forcing (Figures 9 and 25) and the rapidity with which human-made GHGs are being added yields a planetary energy imbalance that can drive ice sheet change.

The upshot is that, if human-made global warming is large enough to cause the expectation of a large long-term sea level rise, there is the potential, indeed the likelihood, of creating a system in which ice sheet change begins and then continues out of our control.

If additional human-made global warming (above that in 2000) is so large, say 2-3°C, that the expected equilibrium (long-term) sea level rise is of the order of 25 meters, there would be the potential for a continually unfolding planetary disaster of monstrous proportions. If additional warming is kept less than 1°C there may still be the possibility of initiating ice sheet response that begins to run out of our control. However, the long term change that the system would be aiming for would be "only" several meters, at most, and, because the energy imbalance would be much less, the time required to reach a given sea level change would be longer, thus yielding a situation with better opportunities for both adaptation and mitigation.

Illustrative sea level rise. If humanity follows a Business-as-Usual course with global warming of at least 2-3°C, we should anticipate the likelihood of an eventual sea level rise of 25 ± 10 m. It is not possible to say just how long it would take for sea level to change, as ice sheet disintegration begins slowly until feedbacks are strong enough to evoke a highly non-linear cataclysmic response. Global warming of 2-3°C would cause larger polar warmings, with likely polar amplification of at least a factor of two, thus leaving both Greenland and West Antarctica dripping in summer melt-water. It is exceedingly difficult to estimate the effect of such extreme conditions. Given the evidence of rapid ice stream acceleration and rapid increase in "ice quake" frequency, neither of which is included in ice sheet models, I believe it is probable that such strong global warming would begin to elicit a strong nonlinear ice sheet response this century.

Positive feedbacks of decreasing ice albedo, ice sheet basal lubrication, and loss of buttressing ice shelves are already beginning to come into play. As the ice loss and sea level rise become significant additional positive feedbacks from lowering (and thus warming) of the ice sheet surface and sea level rise (thus raising of ice shelves off hinge points) come into play. The climate forcing is larger than in the case of orbital forcing and year round. In my opinion it is likely that, by the time global warming of 2-3°C is reached, sea level rise at a rate of 1 meter every 20 years is possible, indeed, I would be surprised if it did not occur. Thus if, as seems likely under Business-as-Usual warming, rapid nonlinear disintegration begins this century, sea level rise of a few meters by 2100 is possible, with much more sea level rise on the way and practically unstoppable.

Ice sheet inertia may prohibit large changes for a few decades, but in my opinion rapid change probably would begin this century under the Business-as-Usual climate forcing scenario. The Earth's history reveals numerous cases in which sea level increased several meters per century. Although the paleoclimate cases may have involved disintegration of ice sheets at slightly lower latitudes, the driving forces were far weaker than Business-as-Usual anthropogenic forcings later this century. With global warming of 2-3°C the Greenland and West Antarctic ice sheets would be at least as vulnerable as the paleoclimate ice sheets.

The expected long-term sea level change due to Business-as-Usual global warming, 25 ± 10 m, may require a few hundred years or more, but it is difficult to assess the response time because of the absence of such a rapid large sustained forcing in the Earth's history. The blue regions in Figure 26 would be under water with a 25 m rise of sea level. In New York, for example, almost all of Manhattan would be under water. The White House is at an altitude of ~17 m, so it would be under about 8 m of water.

Figure 27 shows areas that would be under water for given sea level changes in several regions of the globe. The East Coast of the United States, including many major cities, is particularly vulnerable, and most of Florida would be under water with a 25 meter sea level rise. Most of Bangladesh and large areas in China and India would be under water.

Figure 28 shows the population density for the same regions. As summarized in the table of Figure 29, the population displaced by a 25 meter sea level rise, for the population distribution in 2000, would be about 40 million people on the East Coast of the United States and 6 million on the West Coast. More than 200 million people in China occupy the area that would be under water with a sea level rise of 25 m. In India it would be about 150 million and in Bangladesh more than 100 million.

The effects of a rising sea level would not occur gradually, but rather they would be felt mainly at the time of storms. Thus for practical purposes sea level rise being spread over one or two centuries would be difficult to deal with. It would imply the likelihood of a need to continually rebuild above a transient coastline.

5.B. Extermination of Species

Extermination of plant and animal species can be described euphemistically as a decrease of biological diversity (Figure 30). The distribution of plants and animals on Earth is a reflection of climate patterns. In the past, species have migrated and adapted as natural climate variations occurred. Today many species are under stress for a variety of reasons, many human-made, and as climate changes their ability to migrate often will be blocked by natural and human-made barriers, such as coastlines and urban sprawl.

Armadillos provide an example of a species that is apparently on the move (Figures 31 and 32). Although they appear to be a hardened case, it remains to be seen whether they will find appropriate habitat and be welcomed at points north.

A useful metric, for the sake of consideration of stress on plant and animal species, is the rate of migration of isotherms. In other words, as the Earth becomes warmer, how fast is the climate that a given species is adapted moving away from its current location, how fast will it move in the future, and is the movement either so fast or so far that it causes extinction of species? Figures 33 and 34 show, respectively, the poleward and vertical isotherm migration rates, for observations as well as for Business-as-Usual and Alternative scenarios.

The observed isotherm migration rates for the period 1950-1995 averaged 12 km/decade and 12 m/decade in the poleward and vertical directions, respectively. That period was chosen as typical of the period over which observations of species movement have been reported. Parmesan and Yohe (Nature 421, 37, 2003), from study of ~1700 species, find average migration rates of ~6 km/decade and ~6m/decade, about half as large as the mean movement of isotherms during 1950-1995.

IPCC scenario A2 yields a 21st century isotherm migration rate of averaging about 60 km/decade, which compares with about 10 km/decade in the Alternative scenario (Figure 34). The A2 scenario, combined with warming that has already occurred in recent decades, implies a total migration distance approaching 1000 km.

Business-as-Usual migration rates and distances imply difficulties for many species. Some species are more mobile than others, but in many cases there are interdependencies among different species. The migration distances are larger than the size of most nature preserves and parks, and large enough to push the range of some species beyond barriers such as coast lines.

In effect, the large climate change associated with Business-as-Usual climate forcing would push many polar species off the planet (Figure 35), as there are no colder places for them to migrate. To be sure, iconic species such as polar bears would be "rescued" to live in zoos, but the loss of their natural habitat would make such survival a hollow consolation.

Overall, it is impossible to specify what the casualty rate of species would be for a Business-as-Usual scenario. It is clear that a common perception, that warming of a few degrees Celsius is something that could be readily adapted to, is a gross misperception. A 3°C global warming, together with the 0.7°C warming up to 2000, would approach the magnitude of estimated global warmings (~5°C) that were associated with several mass extinctions in the Earth's history. These mass extinctions led to species loss of 50-90%.

New species developed and flourished following the mass extinctions, but it required millions of years. Clearly global warming of a degree that leads to mass extinctions would leave a desolate planet for any time scale of interest to humanity.

5.C. Regional Climate Change

A sense of the magnitude of expected climate change in the 21st century is provided in Figure 36 for IPCC Business-as-Usual GHG scenarios (A2 and A1B) and for the Alternative scenario. The left side of the figure is the change of seasonal mean (June-July-August) temperature over the 21st century, and the right side is the ratio of this temperature change to the observed standard deviation of seasonal mean temperature in the 20th century. The warming in the Business-as-Usual scenarios is 5-10 standard deviations, while in the Alternative scenario it averages a bit less than two standard deviations.

Rise of the seasonal mean temperature by 5-10 standard deviations implies that even the average temperature at the end of the century would be in a range that was never experienced in the prior century. Such a huge change in environmental conditions, I argue, is prima facie evidence of dangerous change.

Regional climate variations and change commonly can have large practical impacts. There is widespread scientific agreement about some regional climate effects that will accompany global warming, as summarized in the upcoming (2007) IPCC report. For the purposes of the present expert report it is assumed that expected regional climate effects in California will be covered by others. Therefore I make note here only of a few regional effects that are beginning to be noticed already in climate observations.

Global warming is expected to cause an increase in the extremes of the hydrological cycle, thus in the intensity of droughts, on the one hand, and on the intensity of heavy rainfall events and floods, on the other hand. Specifically, a tendency for increased drought in subtropical regions including the American Southwest is expected because of a slowdown in the tropospheric overturning circulation. An increase in the strength of storms driven by latent heat of vaporization, which includes tropical storms, is expected. Melt-back of mountain glaciers is expected and, overall, a decrease of the snow-pack in most mountain ranges.

Given that some of these regional effects are already becoming apparent, we cannot expect to avoid entirely such climate impacts by reducing the rate of GHG emissions. However, in all of these cases the effects are understood to be monotonic, i.e., the effects get larger as the forcing gets larger. Thus the largest most harmful consequences can be avoided by reducing the climate forcing. In some cases this reduction is likely to make a very large difference. For example, the climate change so far has a mixed effect on mountain snow-pack in California, because warming increases atmospheric moisture content and thus it can increase snowfall in some cases. On the other hand, if the warming is so large as to greatly shorten the snow season, the impact on snow-pack will become unambiguous and strongly negative. The conclusion is that there can be large benefits from limiting the climate forcing and climate change, even though it is impossible to avoid anthropogenic effects entirely.

6. Real World Trends: Business-as-Usual or Alternative Scenario?

The Alternative scenario was proposed in 2000 (PNAS, 97, 9875, 2000) at a time when most developed countries were in the process of achieving agreement to moderately reduce their emissions of CO_2 and other GHGs. Thus the Alternative scenario was designed by analogy to the successful management of the ozone depletion problem that occurred two decades earlier. In that case developed countries agreed to level out production and emissions of the relevant chemicals while working on alternative technologies. Developing countries were allowed to increase their use of the chemicals for a decade, but they would eventually also phase them out with technological assistance from developed countries. The decade lag for developing countries did not make a huge difference in emissions, because the emissions problem was addressed promptly, before developing countries built up a large old-technology infrastructure.

The Alternative scenario for GHGs had a chance of working analogously. Most developed countries favored the Kyoto Protocol, and although the United States appeared unlikely to adopt the Kyoto Protocol, there was widespread agreement that CO_2 would be treated as a pollutant whose emissions would be reduced. However, this path was not followed, so CO_2 emissions have continued to increase in much of the developed world, and in the mean time the developing world has been rapidly increasing its emissions, mostly using old inefficient technology. Thus the question is: has the delay in fully addressing the global warming problem ruled out the possibility of achieving a scenario resembling the Alternative scenario? How do real-world emissions compare with the Alternative and Business-as-Usual scenarios?

CO_2. The annual increase of CO_2 in the atmosphere increased from less than 1 ppm/year (parts per million per year) in 1958 when precise measurements were initiated to about 2 ppm/year in recent years (Figure 37). In Business-as-Usual scenarios the annual growth continues to increase at typically 2%/year, achieving annual growth of about 4 ppm/year by mid century. The Alternative scenario, in contrast, requires a moderate reduction of CO_2 annual growth by mid-century, and a sharper reduction in the second half of the century such that annual growth goes to zero at 2100, i.e., atmospheric CO_2 peaks at ~475 ppm in 2100.

CO_2 fossil fuel emissions must decline to achieve the Alternative scenario. The growth rate of fossil fuel annual CO_2 emissions was ~4.5%/year after World War II until the oil embargo and price increase that occurred in 1973. Since then there has been a greater emphasis on energy efficiency, which has resulted in partial decoupling of fossil fuel and economic growth rates, such that the growth rate of CO_2 annual emissions has averaged ~1.5%/year (Figures 38 and 39). The sectors contributing most to continued growth since 1973 are transport and power plants, with growth rates of 2.6% and 2.2%, respectively.

Achievement of the Alternative scenario would require another fundamental change in fossil fuel emissions. Specifically it would be necessary to level out emissions in the near-term and significantly reduce emissions before mid-century. The feasibility and technical requirements for achieving this scenario are discussed below.

Non-CO_2 forcings. The non-CO_2 portion of the Alternative scenario is essential for success in climate management. A CO_2 amount as large as 475 ppm can result in global warming less than 1°C only if some non-CO_2 forcings decrease in absolute magnitude. Actual non-CO_2 forcings during 2000-2005 have come close to matching the Alternative scenario, and their growth has been notably slower than in IPCC Business-as-Usual scenarios. The most important of these forcing agents, methane (CH_4), has been almost stable in abundance for several years, for reasons that are not well understood. One candidate reason for the slowdown is reduction of methane loss (release to the atmosphere) during the mining of fossil fuels. Capture of methane at landfills and waste management facilities also may have contributed to the slowdown in methane growth, although the number of landfills continues to increase.

Continued success in matching the non-CO_2 portion of the Alternative scenario will be more difficult and is unlikely to happen without concerted efforts, because the scenario assumes a significant long-term absolute reduction of CH_4 abundance. The present status of other non-CO_2 forcing agents is uncertain, because there are not sufficiently accurate global measurements of O_3, black soot, and other aerosols.

7. Relevance of the Stratospheric Ozone Story to Global Warming

There are close analogies between the ozone depletion and global warming stories. Because a potential global catastrophe was averted successfully in the ozone case, it is worth summarizing the steps taken to solve that problem. Indeed, the Alternative scenario was partly designed based on analogy to the approach that was followed in addressing the ozone problem.

Review of the ozone problem is relevant to the global warming problem. It is specifically relevant to considerations of the merits of proposed automobile efficiency standards, as discussed in the Summary (Section 9). However, some topics, e.g., regarding liabilities, may be irrelevant and can be neglected. Although it is impossible to separate completely the relevant from the less relevant, a small font is used for material that has less relevance.

Of course solution of the ozone problem, requiring phase-out of certain chemicals, was far easier than solution of global warming. On the other hand, there are huge additional benefits that come with solutions of global warming. However, our main objective is to examine the role of the different players in addressing the solution, and to contrast the behavior of the players in the two cases, as a guide to the source of difficulties and ways to overcome them.

Ozone. In 1974 Rowland and Molina reported that it was likely that chlorofluorocarbons (CFCs) would destroy stratospheric ozone. This was the first chapter in what turned out to be a remarkably successful environment preservation story, a story in which all of the significant players, scientists, media, special interests, the public, and governments played positive critical roles. Less well known is how close the world was to a tipping point that could have caused irreparable damage, and the close analogy to the current situation with global warming.

CFCs had been increasing at about 10%/year for decades up to 1974 (Figure 40). If that growth had continued for another decade the greenhouse effect of CFCs would now greatly exceed that of CO_2 and there would have been catastrophic global ozone loss.

In reality, the scientists issued a clear warning. The media did a good job of reporting the message to the public. After initial skepticism, the chemical manufacturers spent their energy on quickly developing alternative technologies. The public, encouraged by environmental groups, boycotted CFC spray cans, leading to a plateau in CFC production (Figure 40) and thus a halt in construction of CFC production infrastructure. Governments, with leadership from the United States and Europe, took action. For example, after the Antarctic ozone hole was discovered in 1980s and CFC production began to climb because of rapid growth of refrigeration, the non-binding Vienna Convention was adopted.

The non-binding Vienna Convention did not stem increasing CFC production (Figure 40), but shortly thereafter the binding Montreal Protocol was adopted and CFC production began to decline. Developing countries were a party to the Protocol, but they were allowed a 10-year lag in phasing out CFC production and they were provided financial assistance via the World Bank to acquire alternative technologies for refrigeration.

The public (Figure 41) deserves special mention among the players in the ozone story, because it was the public's actions that quickly terminated the need for construction of more CFC-producing infrastructure after it was realized that CFCs were dangerous.

Global warming. An analogous situation exists today in the global warming story (Figure 42), with the world dangerously close to a tipping point. I believe that the public will need to again play the key role in solving the problem. Given the influence of special interests, actions needed to solve the problem are unlikely to be taken until the public becomes sufficiently energized and applies pressure through the democratic process.

Costs of future climate change, especially if Business-as-Usual is followed, will be great. If sea level rise reaches several meters, with hundreds of millions of displaced persons, social and economic costs will be staggering. Costs of extermination of species are difficult to quantify on economic grounds, but they are potentially great. Regional climate effects in some cases, such as loss of fresh water supply due to glacier disappearance, will be directly attributable to global warming.

The question of who will bear legal liability in the future as climate changes and its impacts unfold (Figure 43) is beyond the scope of this expert report. However, the United States is, by far, the greatest contributor to accumulated fossil fuel CO_2 emissions (Figure 44), and it continues to be the largest source of emissions, even though China's emissions are now growing more rapidly.

8. A Brighter Future: Emissions Requirements

Quantitative examination of emissions trends of the different energy sectors reveals that the two largest and fastest growing sources of emissions are vehicle emissions and power plants. These emission sources must be addressed to move emission trends off the Business-as-Usual path and onto something approximating the Alternative scenario.

Vehicle emissions. Vehicle emissions are the single most rapidly growing source of CO_2 emissions. Achievement of a leveling off of vehicle emissions, given continuing growth in the number of vehicles on the road, requires both: (1) a substantial increase of vehicle fuel efficiency during the next several years, and (2) technology advances on the longer-term that fundamentally reduce CO_2 emissions, e.g., hydrogen-powered vehicles using hydrogen from an energy source that produces little or no CO_2, or plug-in hybrids with improved capacity batteries.

The improvement of vehicle fuel efficiency is needed not only to move the near-term emissions growth curve off the Business-as-Usual track onto the Alternative scenario track. It is also important in the long-term, because even with advanced technologies energy will be at a premium. For example, with plug-in hybrids the portion of a trip that can be handled by the battery alone is proportional to the efficiency, and hydrogen production is energy intensive.

The CO_2 emissions reductions from automobiles and light trucks in the "moderate action" case illustrated in Figure 45 are slightly less ambitious than the standards being proposed by the California Air Resources Board, yet they are sufficient to yield a continuing decrease in vehicle CO_2 emissions for more than two decades as the new vehicle standards are phased in and the infrastructure is gradually replaced, despite a continuously increasing vehicle population. In reality, even better results could be achieved as there would likely be further improvements in standards at later times as technology innovations occur. The assumed efficiency improvements in the illustrated example are based on recommendation of the National Resource Council using technologies that are available.

Given the plans of several other states to follow California's lead in vehicle efficiency requirements, it is likely that similar improvements would eventually carry over to the remainder of the United States. The resulting national annual savings of oil, at $50 per barrel, would be $108B (Figure 46). At recent substantially higher oil prices the savings would be proportionately greater.

Power plant emissions. Electricity use is continuing to increase, which is good for the environment because it is a clean energy carrier. However, as in the case of vehicles, CO_2 emissions from power plants will need to be reduced to minimize climate change. The power plant issue is outside the scope of the present discussion, except it should be noted that long-term reductions of power plant emissions are feasible and thus power plants do not prevent attainment of emissions consistent with the Alternative scenario.

Indeed, reduction of power plant emissions in some ways is more straightforward to address than vehicular emissions, because of the localization of the source. In the long-term, power plant emission of CO_2 can be practically eliminated via either capture and geologic sequestration of the CO_2 or replacement of fossil fuels with alternatives such as renewable energies or next generation nuclear power. As in the case of vehicles, there is a need for near-term improvements of energy efficiency to avoid the construction of new fossil fuel power plants that do not sequester CO_2 while alternative technologies are being developed.

9. Avoiding the Climate Tipping Point

The Earth's climate contains several tipping points for specific processes and one overall tipping point that is critical to the fate of the planet. In general, a tipping point exists for a system that has strong positive feedbacks that, once initiated, can carry the system to large changes even with relatively small added forcing.

Sea ice. An example of a tipping point is the sea ice covering the Arctic Ocean. If the planet warms a bit, the sea ice retreats a bit, other things being equal, and, because the ocean is much darker than the ice, the ocean absorbs more sunlight and melts a bit more ice. This is not a runaway feedback (even a very strong, say 50%, feedback only doubles the response: 1 + ½ + ¼ … = 2), but it does make the polar sea ice cover much more sensitive to global warming than it would be otherwise. Global warming has now reached a level, with already about a 25% loss of late summer sea ice, such that the Arctic is near a tipping point. It will not take much more global warming to cause loss of all the summer sea ice. Indeed, given the additional global warming that is "in the pipeline" it appears that the only practical way to avoid loss of all the Arctic summer sea ice is reduction of those climate forcings that are particularly effective in the Arctic (methane, ozone, black carbon), with the negative forcing from this reduction being sufficient to balance a substantial fraction of the positive forcing from some inevitable additional increase of CO_2. However, if the amount of additional CO_2 is too great, the question of non-CO_2 forcings becomes moot, and the Arctic sea ice is doomed.

Ice sheets/sea level. Ice sheet disintegration, with resulting sea level rise, is probably the most important tipping point process in the climate system. The saw-tooth shape of the global temperature curve on glacial to interglacial time scales owes its shape to the ice sheet tipping point. The multiple positive feedback processes (surface albedo, basal lubrication, removal of buttressing ice shelves, lowering of ice sheet surface, lifting from rising sea level) that cause the ice sheet tipping point together are so powerful that, with the help of the greenhouse gas feedback (see section 3 above), they can drive the climate all the way from the depth of a glacial period to peak interglacial warmth. The ice sheet tipping point process is more ponderous than the sea ice process, because of massive ice sheet inertia, but it is also more lethal.

Although paleoclimate data show that ice sheets disintegrate much more rapidly than they warm, their demise can still require millennia. However, the paleo response time is at least in part a reflection of the slow change and small magnitude of the paleo forcings that drive ice sheet change. The anthropogenic forcing is changing much more rapidly and it is stronger. With Business-as-Usual global warming of 2-3°C, thus local warming on the ice sheets of perhaps 4-6°C, the Greenland and West Antarctic ice sheets would be bathed in summer melt. As a result, it is unlikely that the response time, for disintegration of a substantial fraction of these ice sheets, could be more than of the order of a century.

The planet's tipping point. The overall tipping point question is: will human-made climate forcings reach a point such that dramatic climate change with disastrous global impacts becomes inevitable? Specific tipping point processes mentioned above, especially ice sheets and their effect on global sea level, are key ingredients in defining the global tipping point, but there are other ingredients. Additional feedbacks must be considered in the planetary case. For example, a warming planet has significant effects on the vegetation and soils in high latitude land areas, indeed, with the global warming of 0.6°C of the past 30 years poleward expansion of vegetation is already underway and extensive areas of permafrost are melting and expected to become sources of greenhouse gases.

These high-latitude vegetation-tundra feedbacks are relevant to the question of when an overall planetary tipping point might be reached. Regardless of what level of global warming is estimated as defining a "dangerous" level for ice sheet stability, the effect of positive feedbacks from high-latitude changes of vegetation-tundra needs to be considered. The rationale for the 1°C maximum warming in the Alternative scenario is that paleoclimate data indicate that these terrestrial feedbacks are of only moderate size if global warming is kept within that range. On the other hand, if warming becomes larger, concerns about positive feedbacks become acute. Indeed, the concept for the Alternative scenario, which depends upon reduction of non-CO_2 forcing, especially CH_4, may become invalid, i.e., it may be impractical or impossible to achieve the assumed reduction of CH_4.

The implication is that if climate forcings, especially CO_2, are not capped so as to keep additional warming (beyond 2000) less than 1°C, there is a high likelihood that the warming will run well above 1°C because of these feedbacks. The presumption in the Alternative scenario is that CH_4 will decrease substantially, but with global warming exceeding 1°C it becomes unlikely that this reduction will be achieved. Once global warming is allowed to go beyond 1°C, it may not take a great deal of additional human-made forcing for global warming to approach 2°C.

The upshot is that if global warming passes the +1°C level (relative to 2000), it may not take much additional human-made forcing for global warming to reach the 2°C level. In other words, success in constraining growth of CO_2 makes is easier to reduce CH_4, but failure to limit CO_2 means that it will probably be impractical to achieve the planned reductions of non-CO_2 forcings, and thus global warming is likely to be at least +2°C (relative to 2000).

Discussion. This "tipping point" issue is a fundamental aspect of the global warming issue and it is the reason why I believe that, in analyzing the global warming problem, we must compare and contrast two distinct scenarios: one (dubbed Alternative scenario) in which human-forcings are constrained so as to keep global warming approximately within the range that has existed in the past million years, and a second (Business-as-Usual) in which human-made climate forcings push the planet's temperature above that range.

In this second (Business-as-Usual) case, human-made greenhouse gas emissions will be pushing the planet into a climate regime where we do not know how large climate feedback effects will be and we do not have detailed relevant evidence from the Earth's history sufficient for empirical assessment. Even without high-latitude vegetation-tundra feedbacks that may occur in that climate regime, Business-as-Usual emissions for several more decades would be expected to yield global warming approaching +2°C (relative to 2000).

In my opinion there is no significant doubt (probability > 99%) that such additional global warming of 2°C would push the Earth beyond the tipping point and cause dramatic climate impacts including eventual sea level rise of at least several meters, extermination of a substantial fraction of the animal and plant species on the planet, and major regional climate disruptions. Much remains to be learned before we can define these effects in detail, but these consequences are no longer speculative climate model results. Our best estimates for expected climate impacts are based on evidence from prior climate changes in the Earth's history and on recent observed climate trends.

Given existing evidence, in my opinion the minimum steps needed to avoid passing the climate tipping points, with their likely disastrous climate impacts, are those required to achieve a climate scenario corresponding approximately to the Alternative scenario. As I have shown above, the emission standards proposed by the California Air Resources Board are consistent with attainment of the vehicles portion of the Alternative scenario.

10. Summary: Climate Merits of Proposed Efficiency Standards

CO_2 molecules omitted at any place in the world are equally effective at causing global warming. Thus reduction of California emissions will reduce global warming only in the proportion of California's emissions to global emissions. Nevertheless, given perceived nearness of global warming to climate system tipping points that could have devastating impact on global sea level, extermination of species, and regional climate, even the direct effects of proposed emission reductions are useful for minimizing undesirable impacts of climate change.

However, the primary value of the proposed California emission standards is (1) probable magnification of the California reduction via likely adoption of the same or similar standards elsewhere, and (2) demonstration that it is practical to achieve the most difficult part of the Alternative scenario for climate forcings. The Alternative scenario, as discussed in preceding sections, defines a level of emission reductions estimated as necessary to avoid passing climate tipping points that lead to disastrous climate change.

The proposed reduction of vehicle emissions is only a first step, if large climate change is to be avoided. Vehicle emissions must decline even further within a few decades. However, it is realistic to anticipate development of appropriate technologies for further reductions on such time scales. As discussed in Section 8, the proposed near-term improvements in vehicle efficiency requirements are essential prerequisites for success in meeting more stringent long-term requirements.

It will also be necessary to reduce power plant emissions to achieve a greenhouse gas scenario that avoids large climate change, and it will be necessary to involve other key countries in emissions limitations. Although the magnitude of these tasks should not be understated, I note that it is technically more straightforward to address emissions from a point source such as a power plant, and that involvement of other countries in emissions limitations becomes more realistic if the United States is taking steps to reduce its emissions.

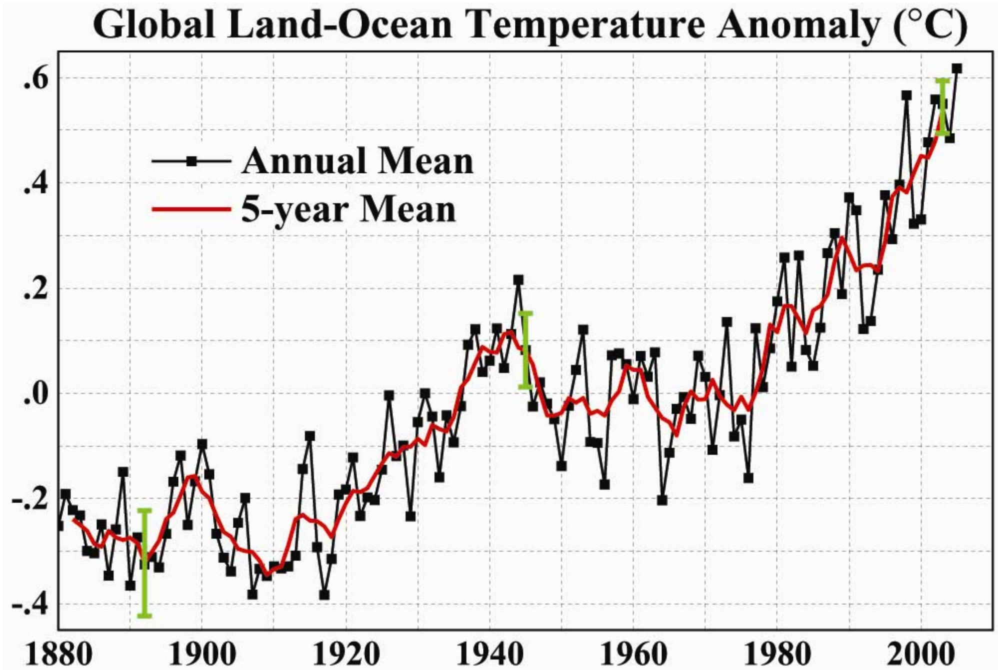


Fig. 1. Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. Source: update of Hansen et al., JGR, 106, 23947, 2001; Reynolds and Smith, J. Climate, 7, 1994; Rayner et al., JGR, 108, 2003.

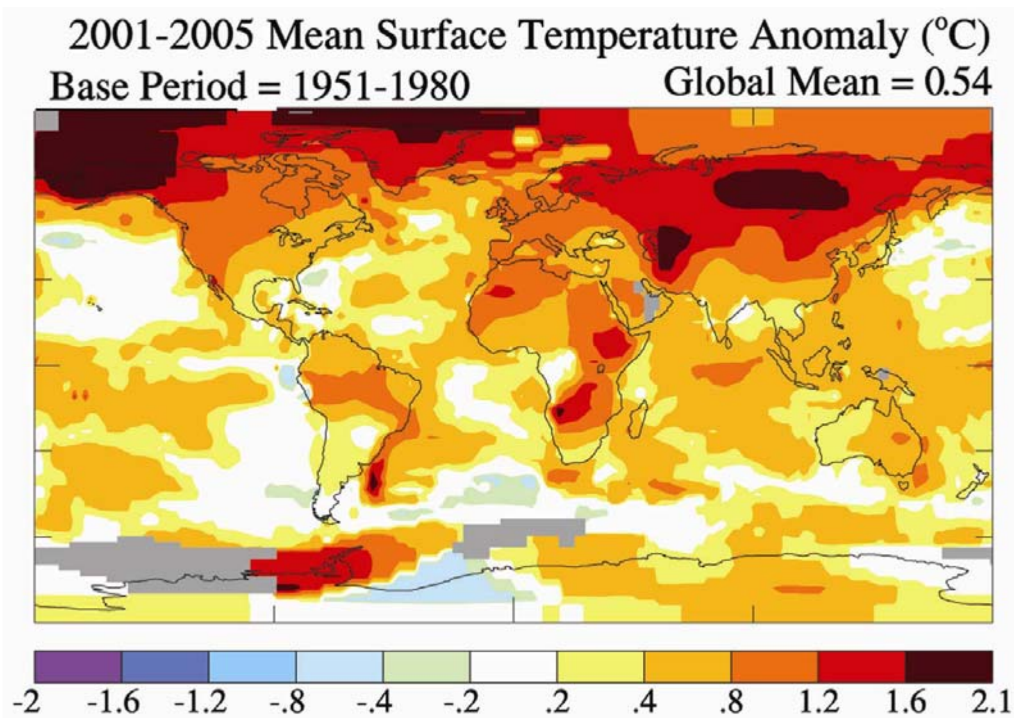


Fig. 2. Global surface temperature anomaly for the first five years of the 21st century relative to 1951-1980. Source: Hansen et al., submitted to Proc. Natl. Acad. Sci., 2006.

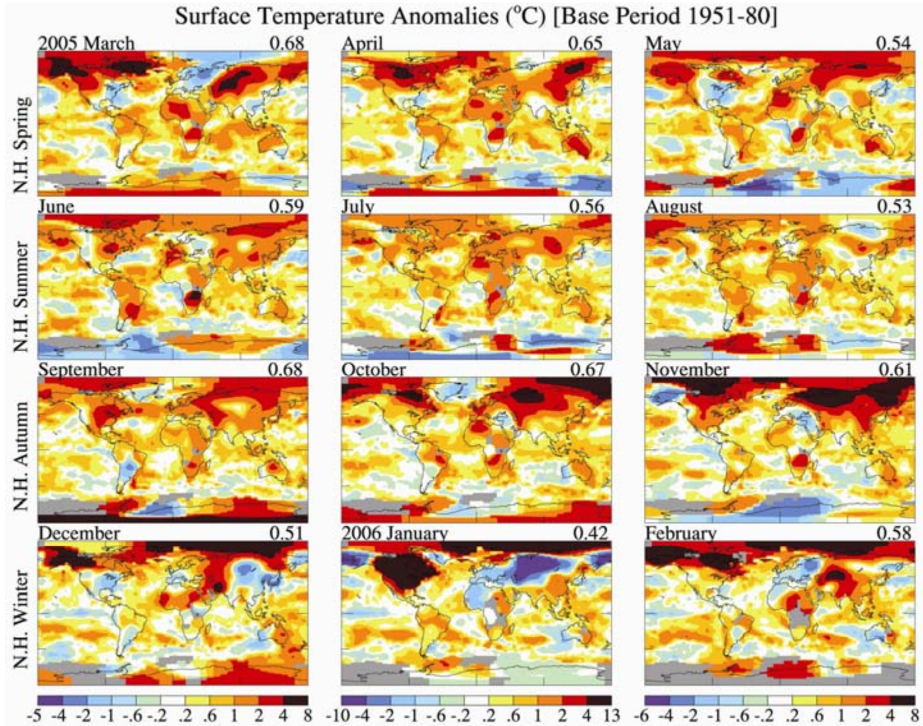


Fig. 3. Monthly surface temperature anomalies for 12 recent months, based on the data sets described in Fig. 1.

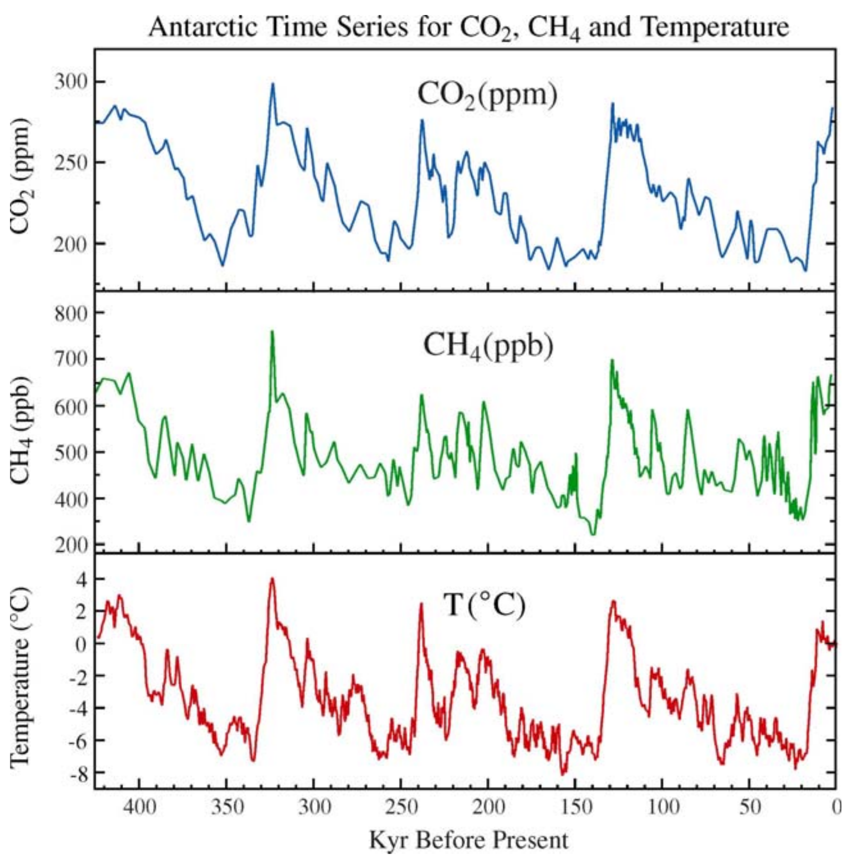


Fig. 4. CO_2, CH_4 and temperature records from Antarctic ice core data. Source: Vimeux et al., Earth Plan. Sci. Lett., 203, 829, 2002.

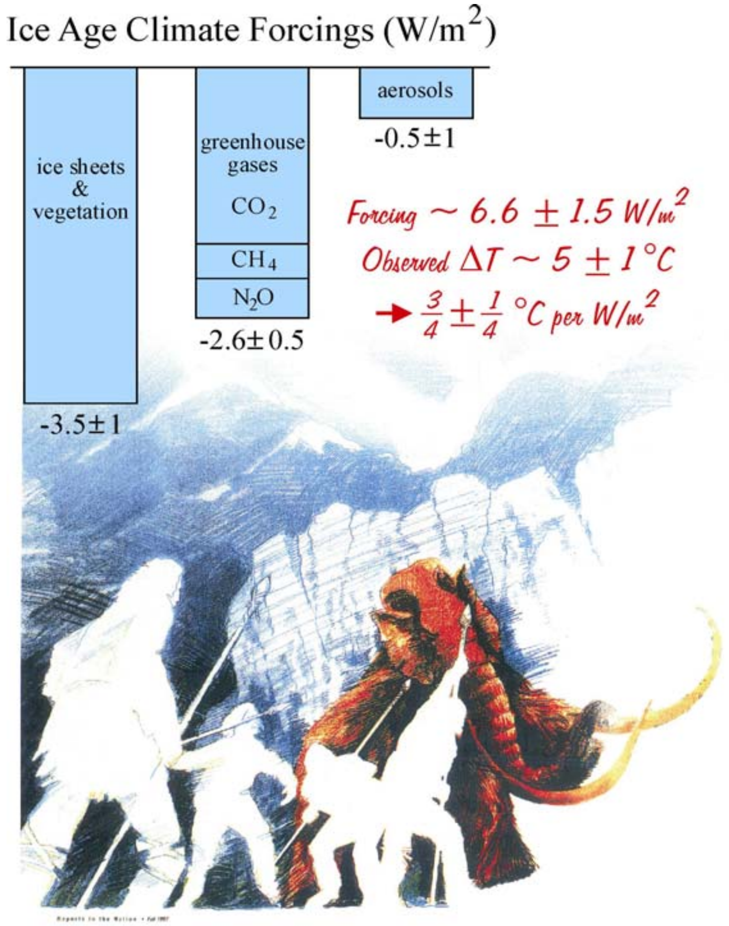


Fig. 5. Ice age climate forcings imply global climate sensitivity ~¾°C per W/m^2.
Source: Hansen et al., Natl. Geogr. Res. & Explor., 9, 141, 1993.

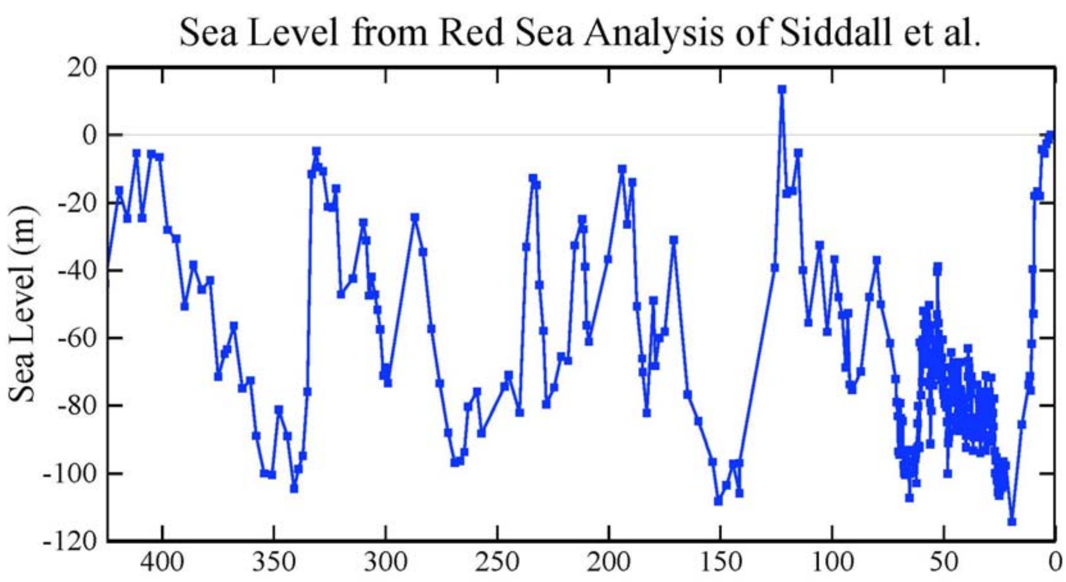


Fig. 6. Global sea level extracted, via a hydraulic model, from an ozygen isotope record for the Red Sea over the past 470 kyr (concatenates Siddall's MD921017, Byrd, & Glacial Recovery data sets; AMS radiocarbon dating). Source: Siddall et al., Nature, 423, 853, 2003.

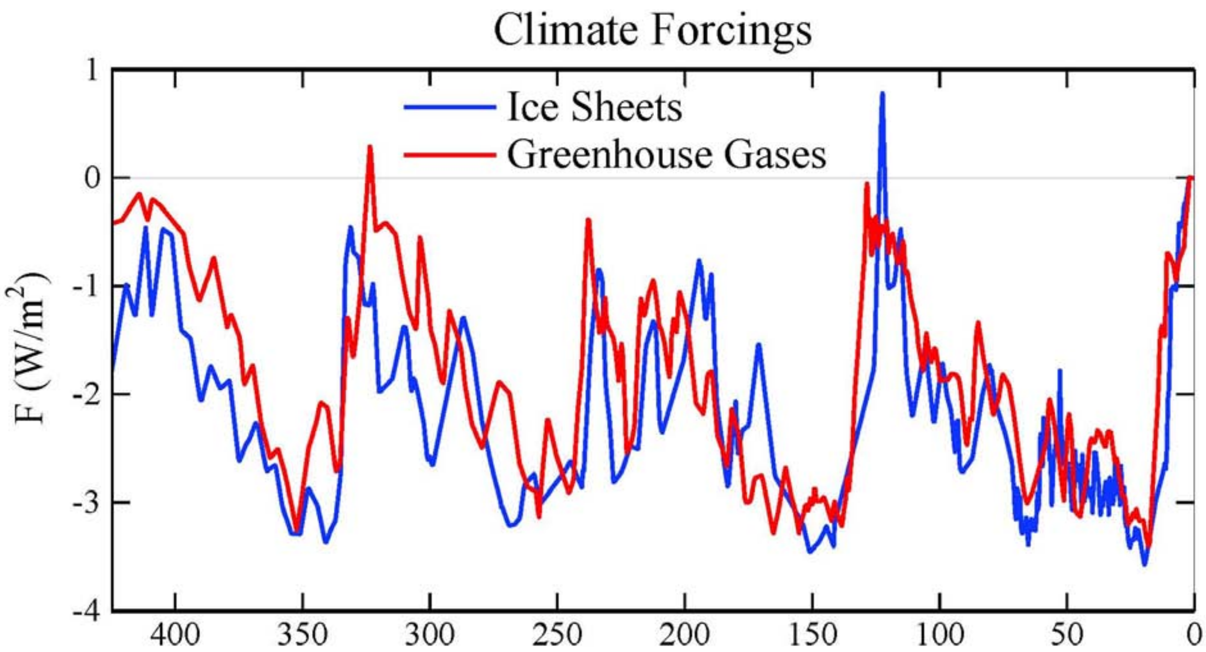


Fig. 7. Calculated climate forcings. Ice sheet forcing is proportional to (sea level)$^{2/3}$ and equal to 3.5 W/m^2 20,000 ybp. GHG forcing is based on Vostok CO_2 and CH_4, with the N_2O forcing 15% of the combined CO_2 and CH_4 forcings. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

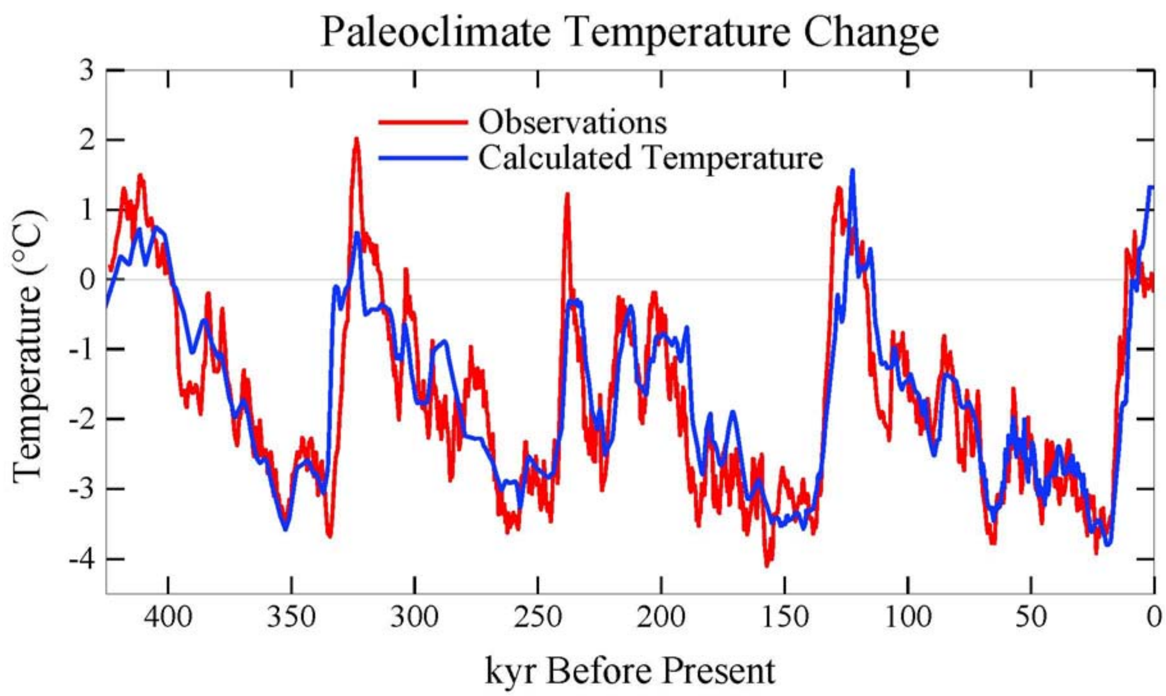


Fig. 8. Calculated and observed temperature for past 400,000 years. Calculated temperature is the forcing from the preceding figure multiplied by climate sensitivity ¾°C per W/m^2. Observation is the measured Vostok Antarctica temperature divided by two. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

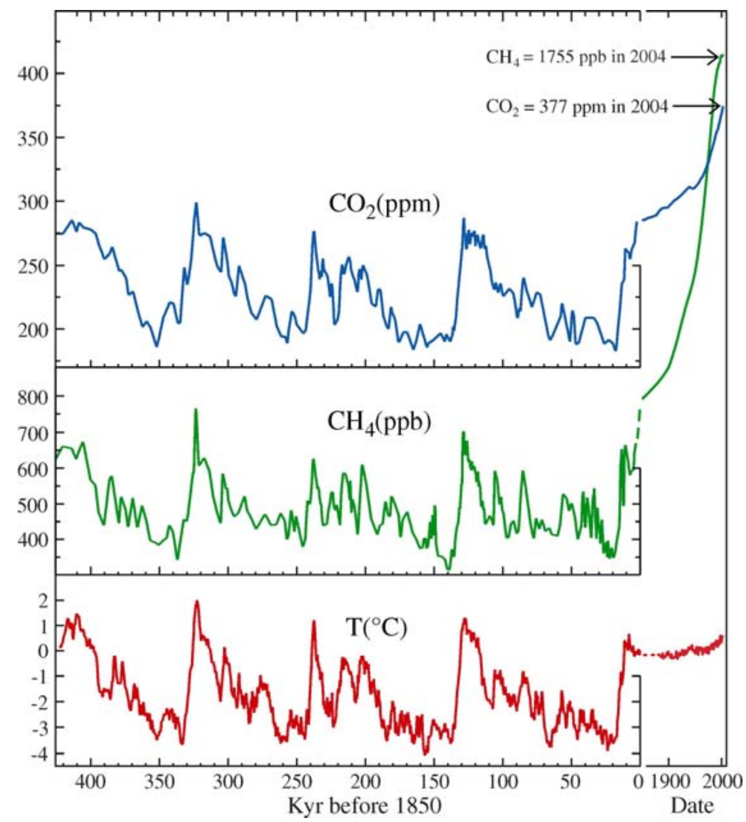


Fig. 9. Extension of CO_2, CH_4 and temperature records of Fig. 4 to 2004. Temperature change since 1880 is the land-ocean temperature index (Fig. 1), with the 1880-1899 mean defined as zero, while the earlier temperature is the Vostok Antarctica temperature change divided by two. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

Implications of Paleo Forcings and Response

1. **“Feedbacks” (GHGs and ice area) 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.**

Fig. 10. Several implications that follow from comparison of paleoclimate forcings, and the simulated and observed paleoclimate changes, as discussed in the text. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

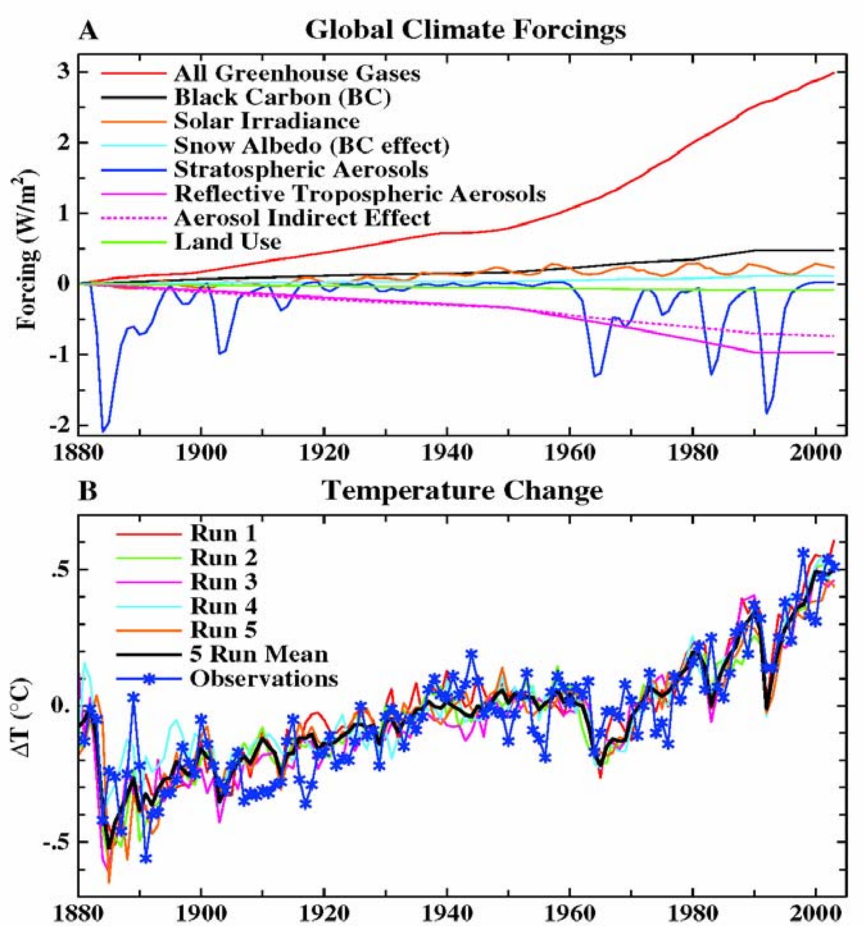


Fig. 11. (A) Climate forcings used to drive the GISS global climate model, and (B) the global temperature change simulated by the model compared with observations. Source: Hansen et al., Science, 308, 1431, 2005.

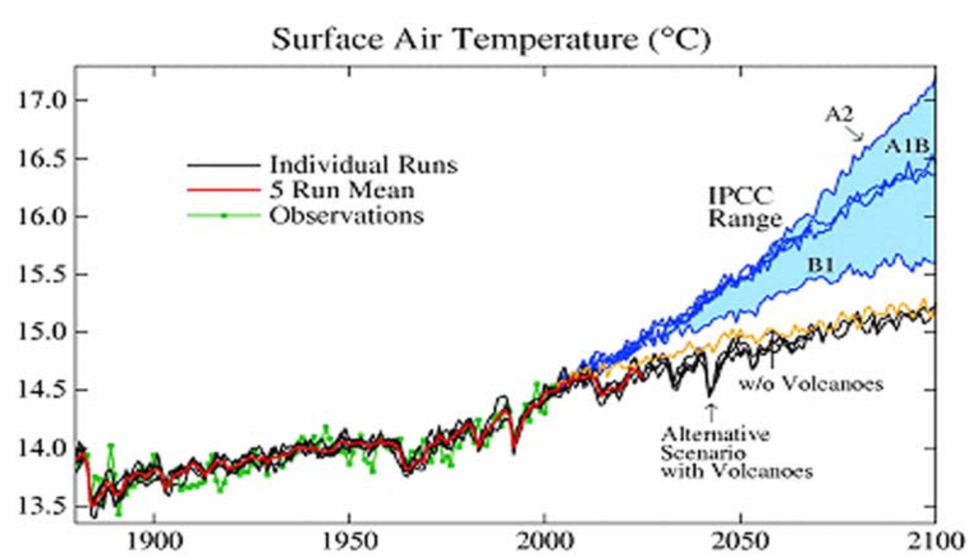


Fig. 12. Extension of the climate simulations in the prior figure through the 21st century for IPCC scenarios (A2 and A1B are "business as usual" scenarios) and the "alternative scenario." Source: Hansen et al., J. Geophys. Res., in review, 2006.

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."

Fig. 13. The Framework Convention on Climate Change was agreed to by all countries, including the United States, in the early 1990s. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

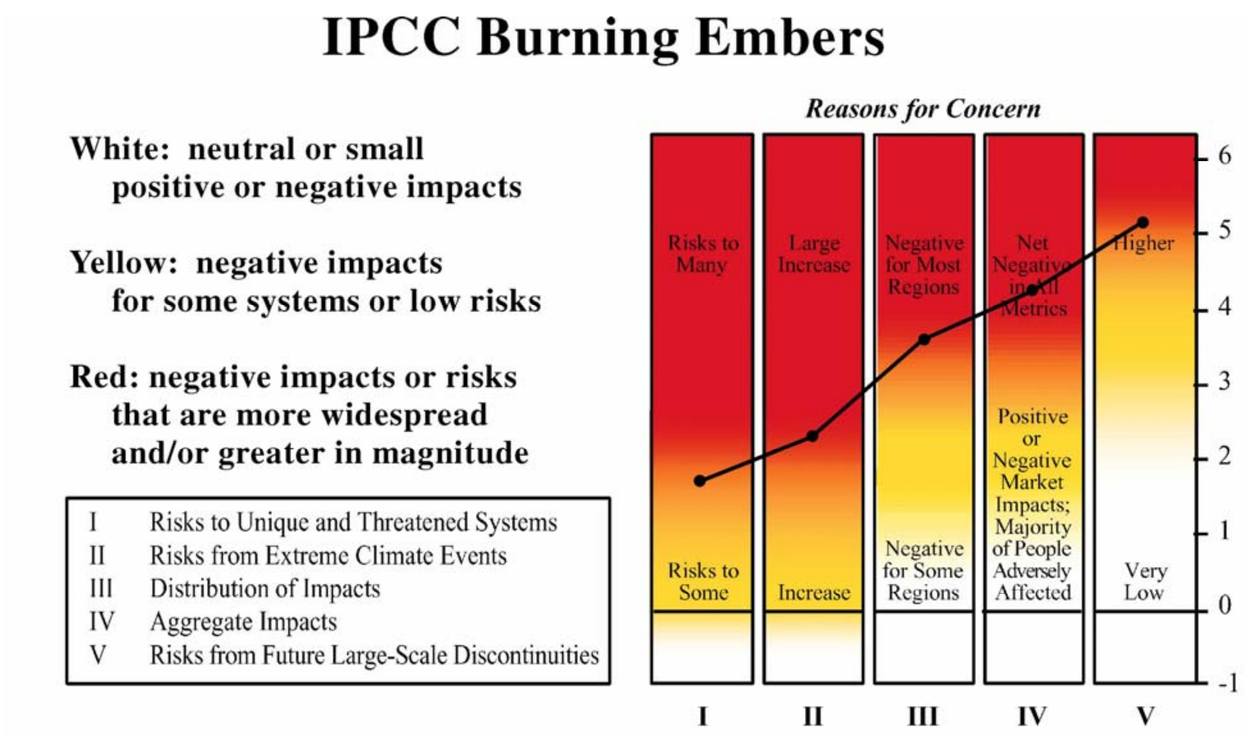


Fig. 14. Reasons for concern about projected climate impact changes. Source: IPCC Climate change 2001; S. Schneider & M. Mastrandrea, PNAS, 102, 15728, 2005.

Metrics for "Dangerous" Change

Global Sea Level

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

Loss of Animal + Plant Species

1. Extinction of Polar and Alpine Species
2. Unsustainable Migration Rates

Regional Climate Change

1. General Statement
2. Arctic, Tropical Storms, Droughts/Floods

Fig. 15. Principal criteria determining the level of climate change constituting "dangerous" change. Source: Hansen, Apr. 23, Natl. Acad. Sci., www.columbia.edu/~jeh1, 2006.

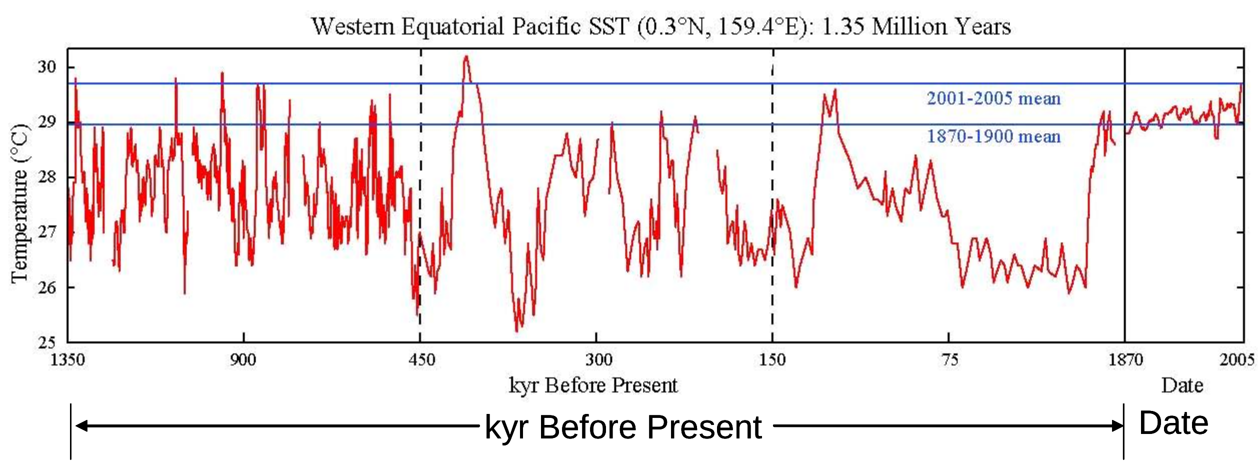


Fig. 16. SST in Pacific Ocean Warm Pool in past millennium, with recent time scale expanded. Data after 1880 is 5-year mean. Source: Medina-Elizade and Lea, ScienceExpress, Oct. 13, 2005; data for 1880-1981 based on Rayner et al., JGR, 108, 2003, after 1981 on Reynolds and Smith, J. Climate, 7, 1994.

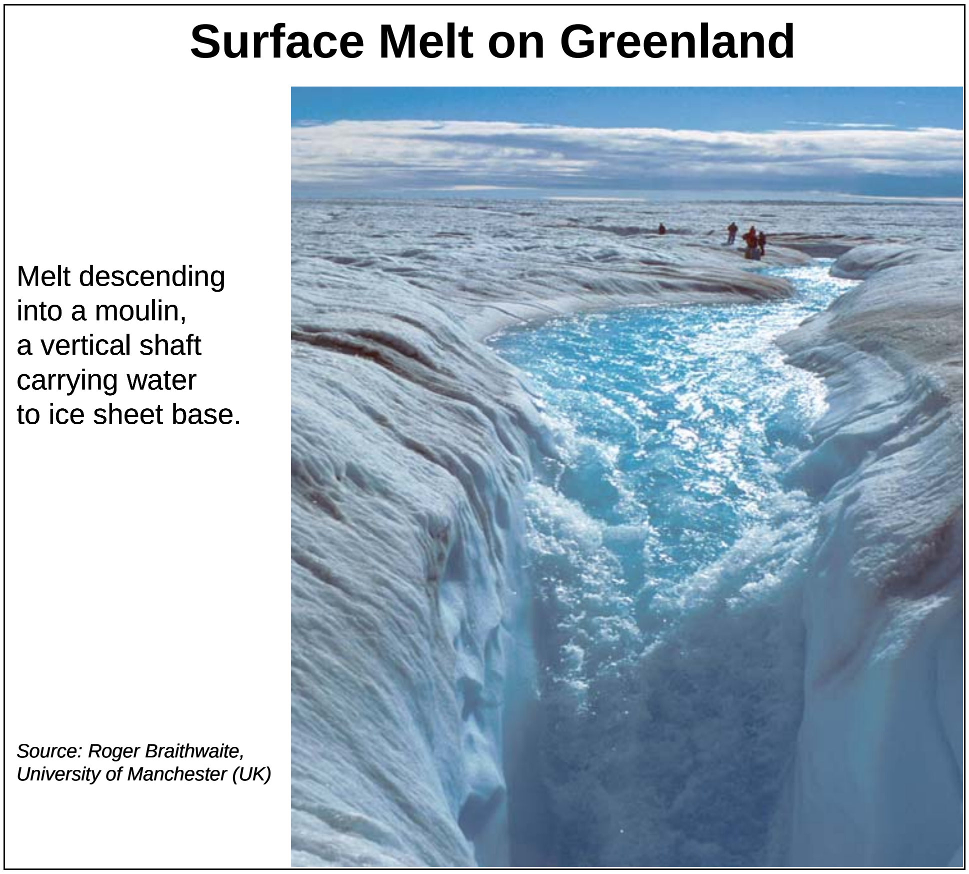


Fig. 17. Melt-water on Greenland descending into a Moulin, a vertical shaft carrying water to the base of the ice sheet. Source: Roger Braithwaite, Univ. Manchester (U.K.).

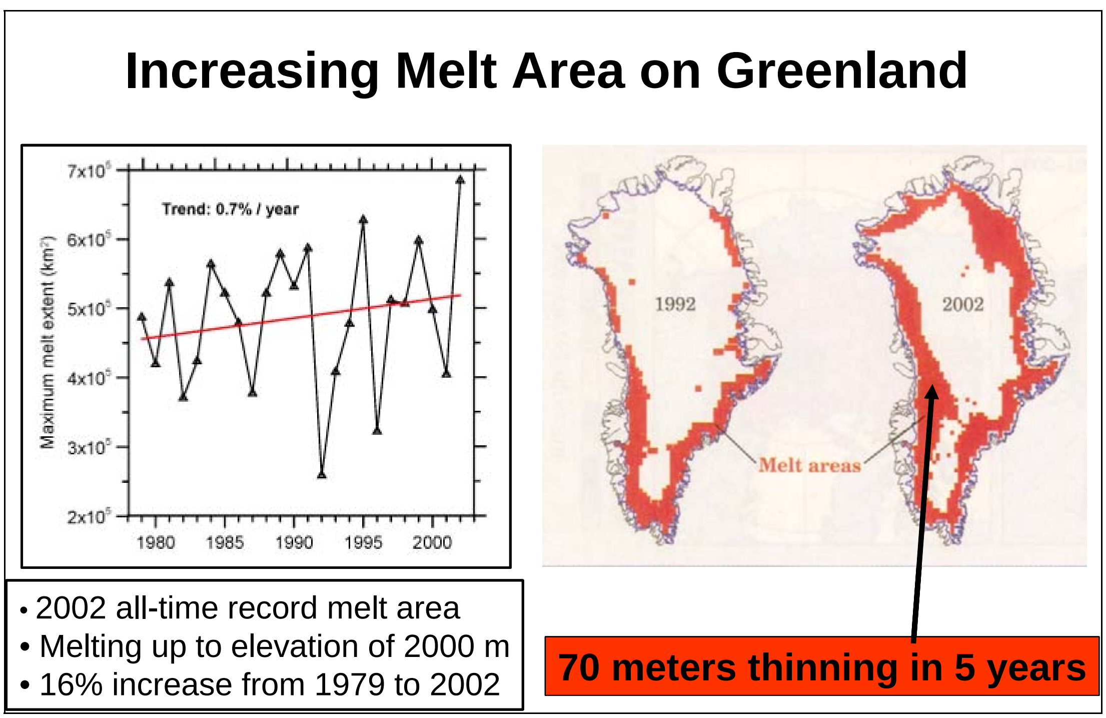


Fig. 18. Increasing area with summer melt on Greenland. The satellite-era record melt area of 2002 was exceeded in 2005. Source: Waleed Abdalati, Goddard Space Flight Center.

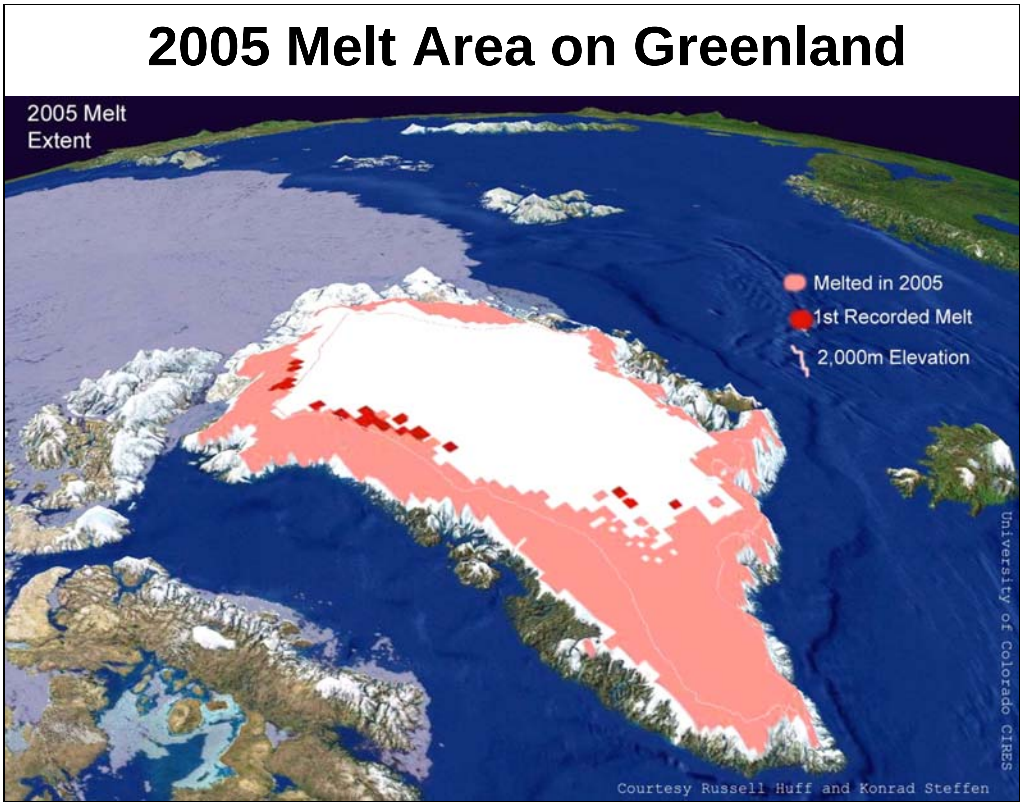


Fig. 19. Area on Greenland with summer melt in 2005, the dark red areas having their first recorded melt in the satellite era. Source: Russell Huff and Konrad Steffen, Univ. Colorado.

Fig. 20. Iceberg discharge via the largest ice stream in Greenland. The flux of ice from Greenland ice streams has at least doubled in the past decade. Source: Konrad Steffen, Univ. Colorado.

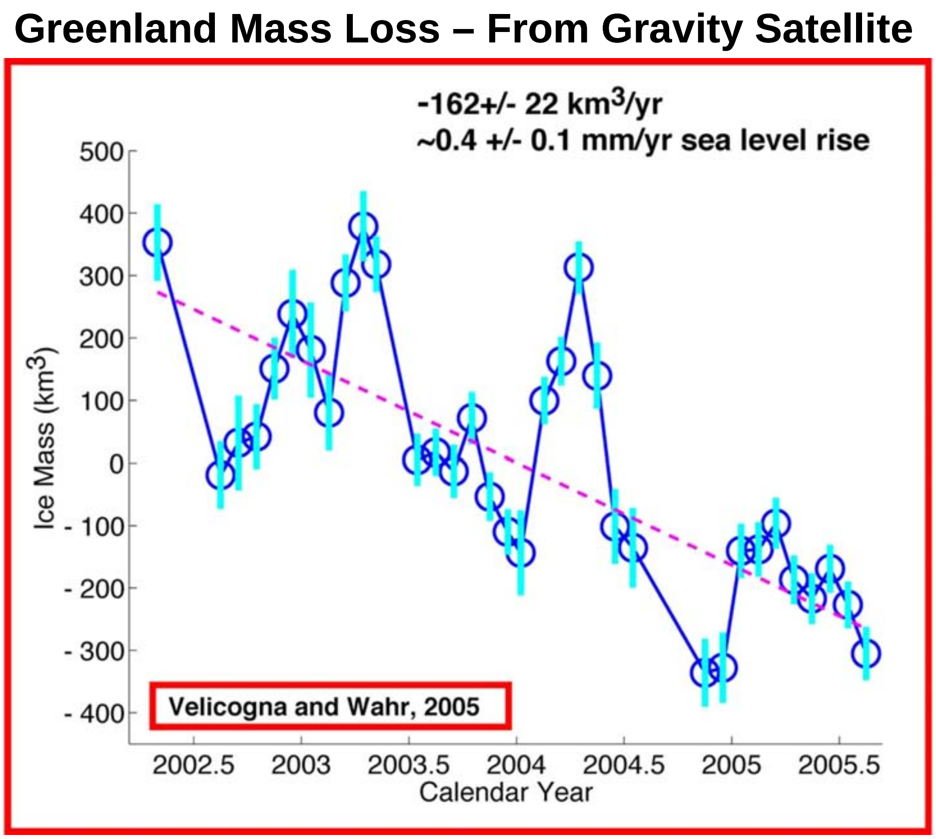


Fig. 21. Mass loss by Greenland as determined from gravity field changes measured by the GRACE satellite. Source: Velicogna and Wahr, Geophys. Res. Lett., 2005.

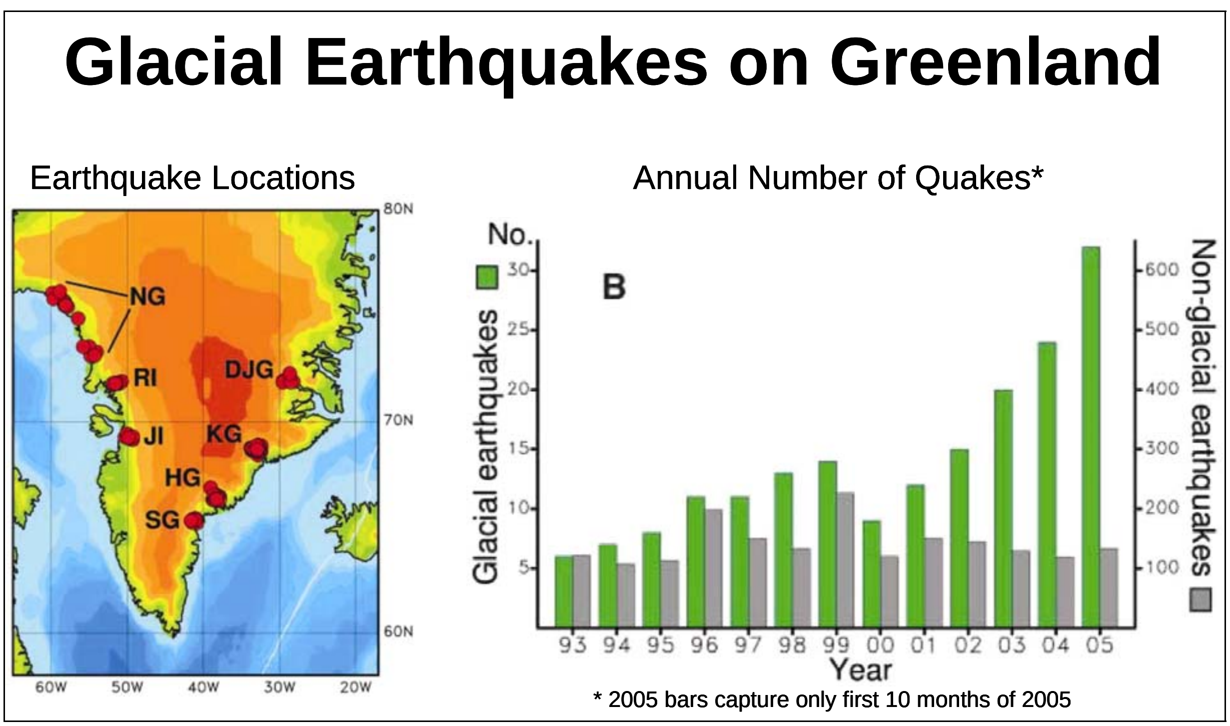


Fig. 22. Location and frequency of earthquakes on Greenland. Magnitudes of the earthquakes are in the range 4.6 to 5.1. Source: Ekstrom, Nettles and Tsai, Science, 311, 1756, 2006.

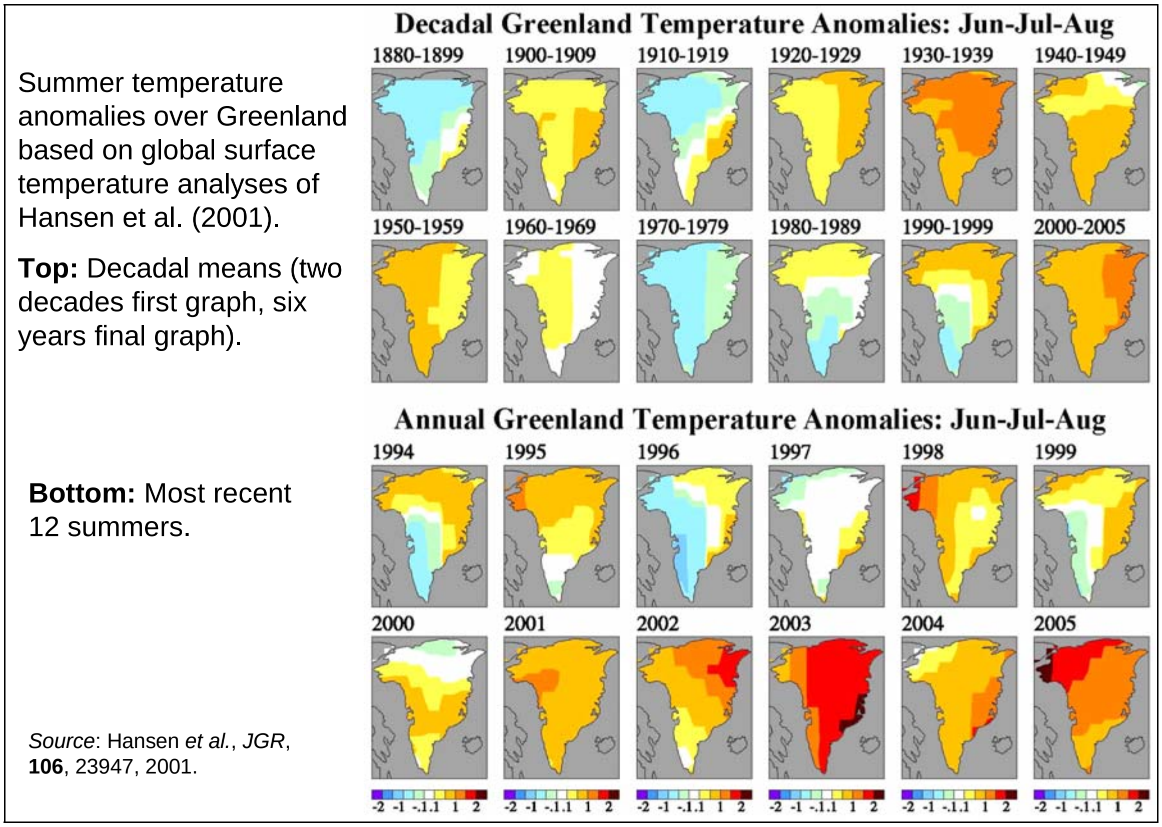


Fig. 23. Decadal (top) and annual summer temperature anomalies over Greenland as estimated from limited station measurements. Source: Hansen et al., JGR, 106, 23947, 2001.

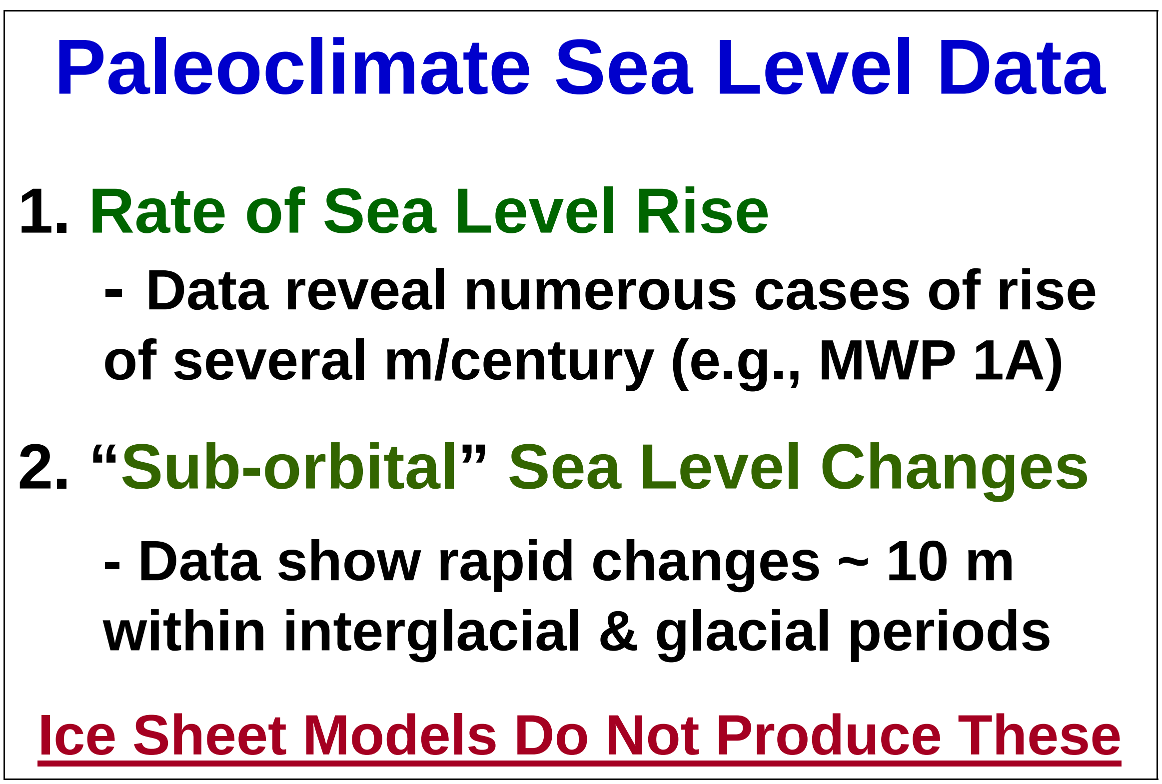


Fig. 24. Comments re: paleoclimate sea level data. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

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

Fig. 25. Summary comments re: ice sheets and sea level. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

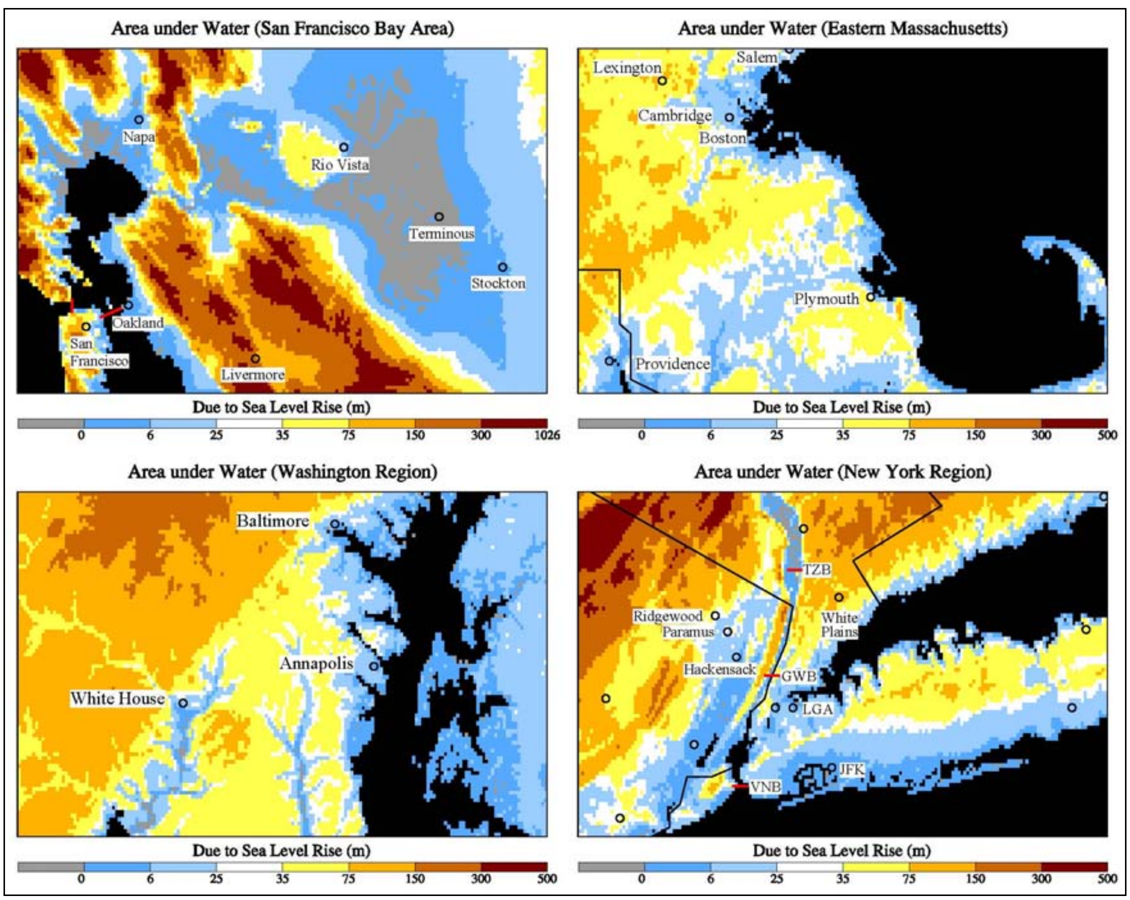


Fig. 26. Additional area under water for sea level rise of 6 m (dark blue), 25 m (light blue), 35 m (white), and 75 m (yellow) for San Francisco, Boston, Washington and New York City regions.

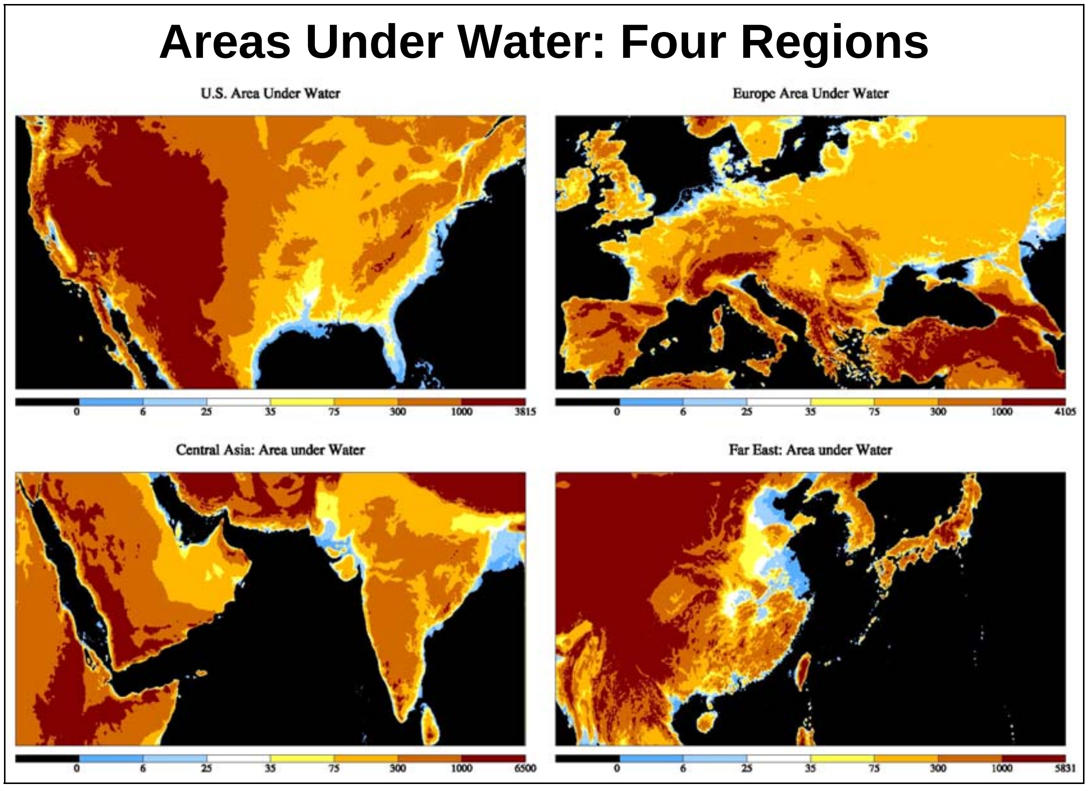


Fig. 27. Additional area under water for sea level rise of 6 m (dark blue), 25 m (light blue), 35 m (white), and 75 m (yellow) in regions focused on the United States, Europe, India and China.

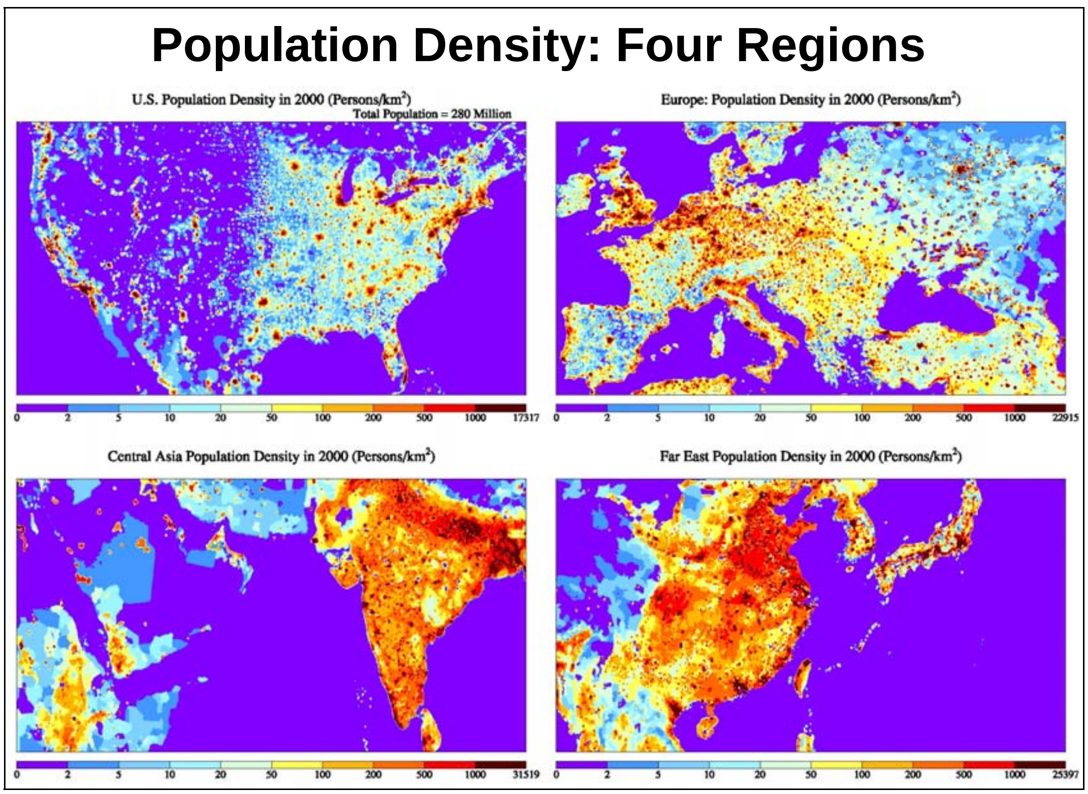


Fig. 28. Population density of the four regions shown in the preceding sea level maps.

Population (millions) in 2000

Region (total population)	Population Under Water (for given sea level rise)			
	6m	***25 m***	***35m***	***75m***
United States (283)				
East Coast	9	41	51	70
West Coast	2	6	9	19
China + Taiwan (1275+23)	93	224	298	484
India + Sri Lanka (1009+19)	46	146	183	340
Bangladesh (137)	24	109	117	130
Indonesia + Malaysia (212+22)	23	72	85	117
Japan (127)	12	39	50	73
Western Europe (454)	26	66	88	161

Fig. 29. Population under water in specified regions for specific sea level rises, based on population data for 2000.

Extermination of Species

(a.k.a. decrease of biological diversity)

1. **Distributions of plants and animals reflect climate**
2. **Extinctions are occurring due to variety of stresses**
3. **Added stress of climate change forces migrations**
4. **Some paths blocked by natural and human barriers**
5. **Observed rates (~6 km & 6 m/decade) < isotherms**
6. **Non-linear because of species interdependencies**

→large difference between BAU/alternative scenario

Fig. 30. Discussion points relating to the effect of climate change on extinction of species.

Armadillos in Arkansas

19 March 2006 E-Mail

Dear Sir:

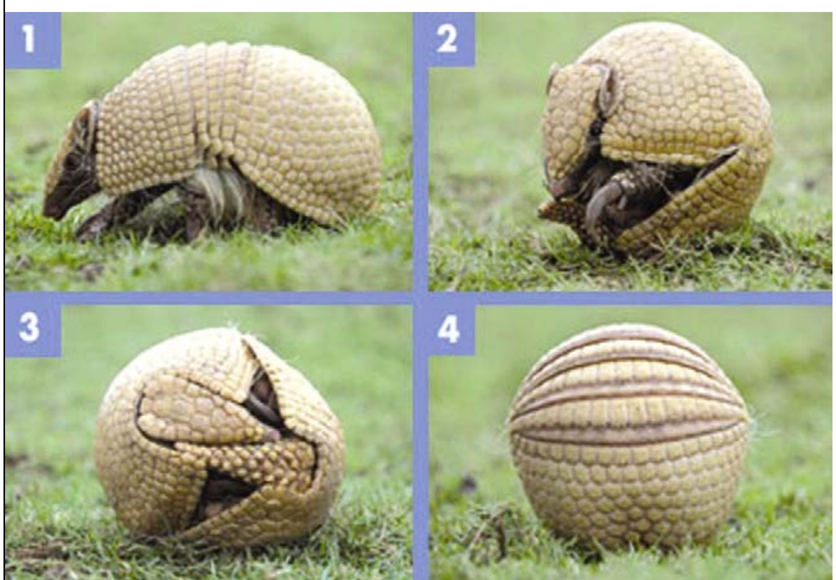
I wish to tell you how much I enjoyed your 60 Minutes Report…

If you have the time, I would like to tell you of an observation I have had over the last 10 years. I live in the Northeastern part of Arkansas, and except for a few years have been in this area for 53 years of my life.

The observation is the armadillo. I had not seen one of these animals my entire life, until the last 10 years. I drive the same 40 mile trip on the same road every day and have slowly watched these critters advance further north every year for the last 10 years and they are not stopping. Every year they will move 10 to 20 miles. Call it what you may, but I know these critters are not too happy with cold weather.

Fig. 31. "Armadillo" e-mail received by J. Hansen on 19 March 2006.

Armadillos: One of the Surviving Species?



Photos © Mark Payne-Gill, naturepl.com
source:http://seabed.nationalgeographic.com/splat_ngx_pathfinder/templates/output/articles/gallery.tmpl?DB_NUM_PARAMS=2&DB_PARAM_0=0503&DB_PARAM_1=2

Fig. 32. Armadillo photographs and map of region of armadillo migration.

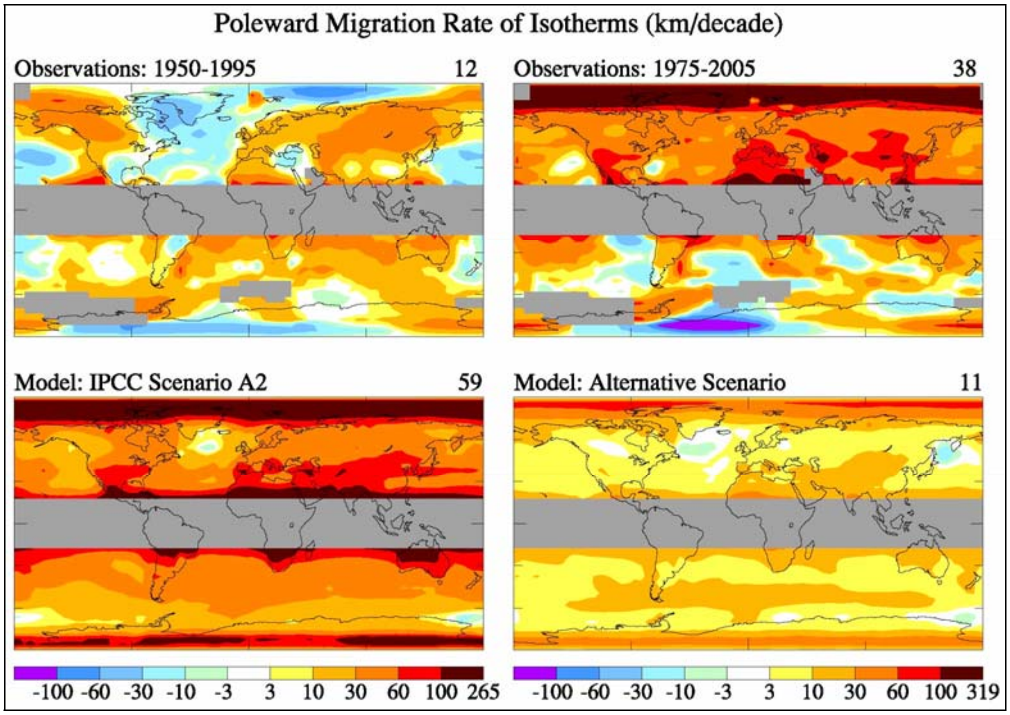


Fig. 33. Poleward migration rate of isotherms based on observed surface temperatures for two periods and in 21st century simulations for IPCC scenario A2 and the Alternative scenario.

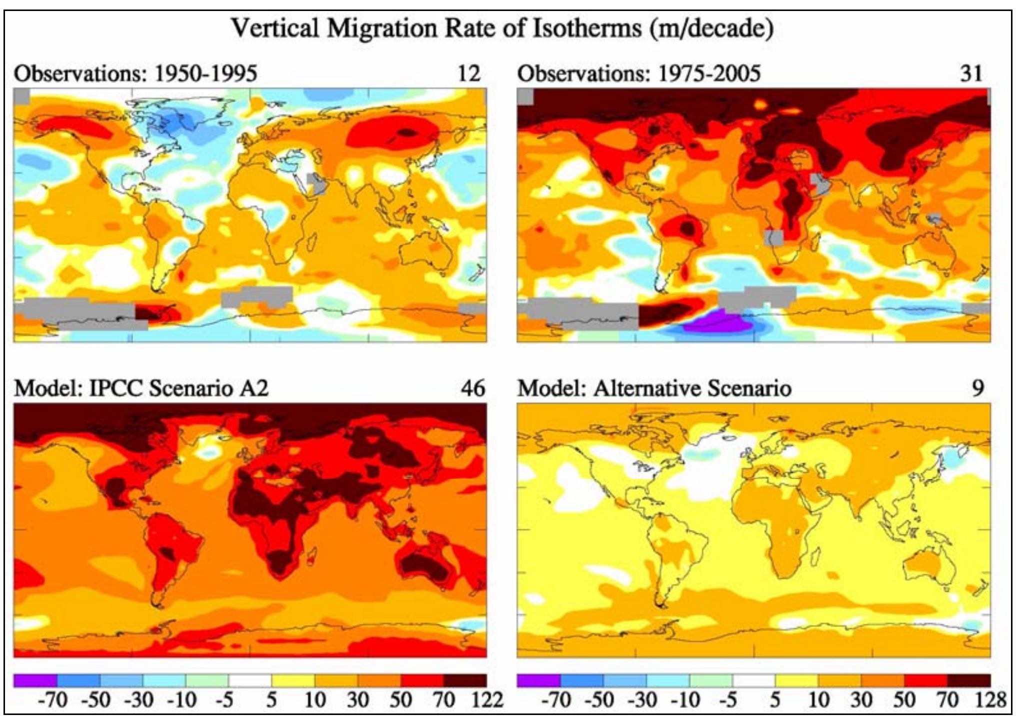


Fig. 34. Vertical migration rate of isotherms based on observations for two periods and in 21st century simulations for IPCC scenario A2 and the Alternative scenario.

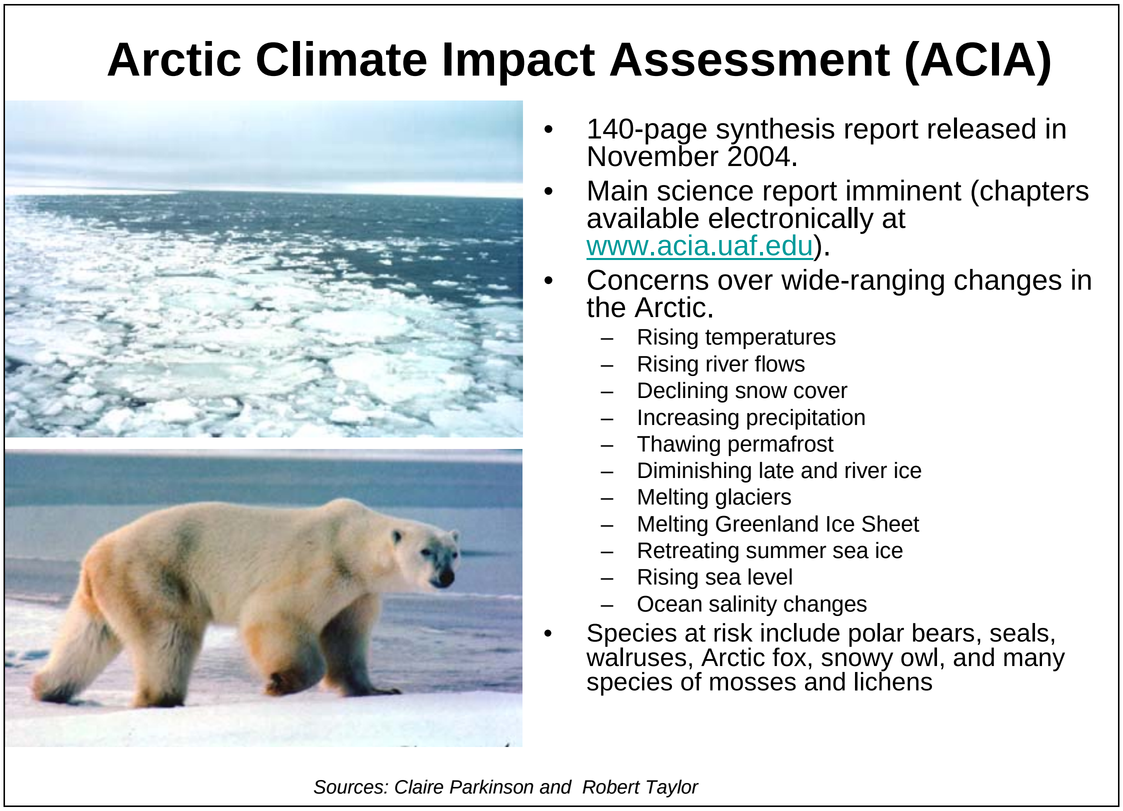


Fig. 35. Arctic climate impact assessment (www.acia.uaf.edu).

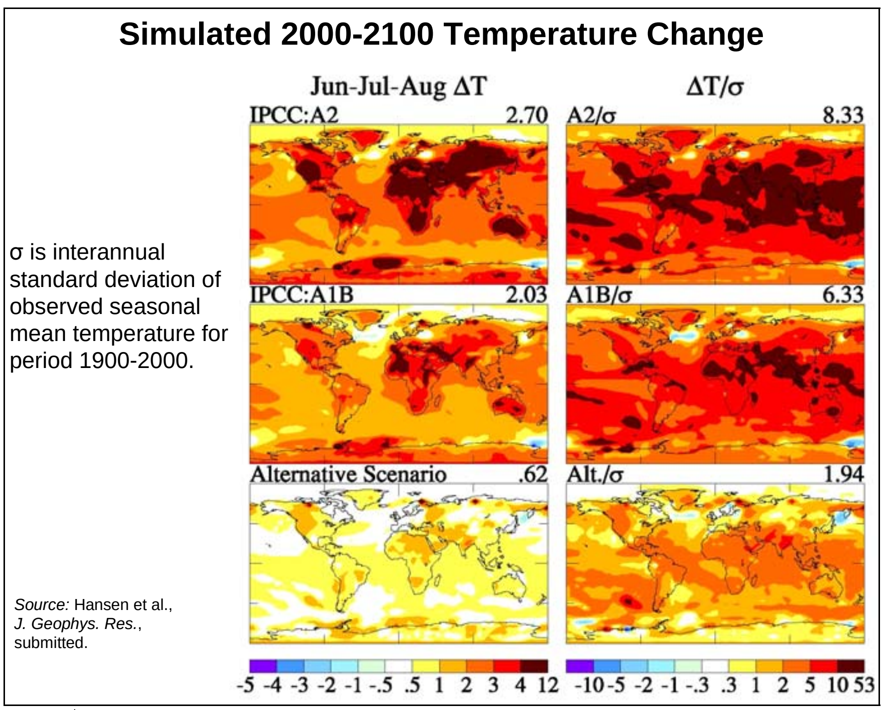


Fig. 36. Simulated 21st century seasonal (Jun-Jul-Aug) temperature change for Business-as-Usual and Alternative GHG scenarios, and the ratio of temperature change to the observed standard deviation of temperature in the prior century. Source: Hansen et al., J. Geophys. Res., in review, 2006.

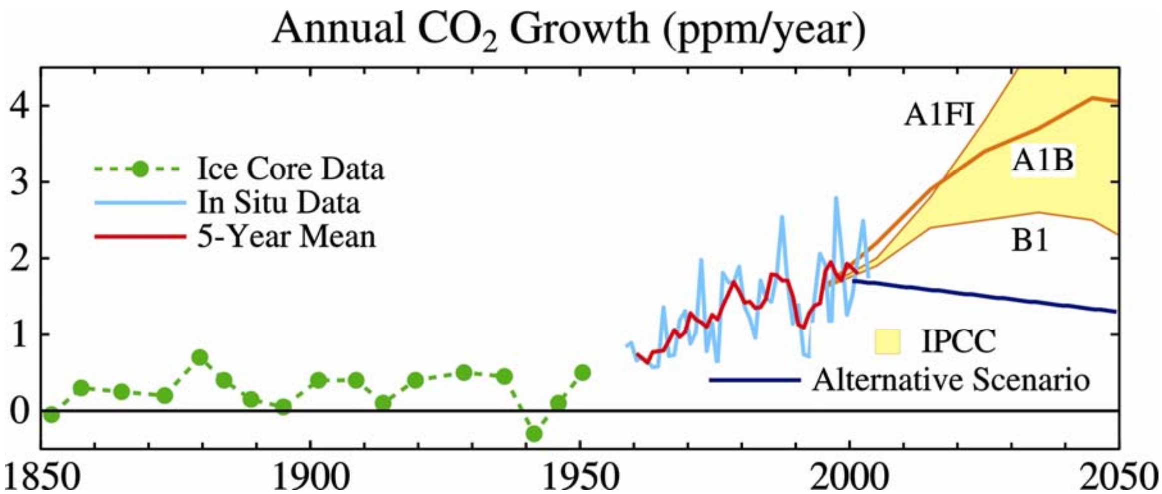


Fig. 37. Annual growth of atmospheric CO_2 (ppm/year) in observations and scenarios. Source: Hansen and Sato, PNAS, 101, 16109, 2004.

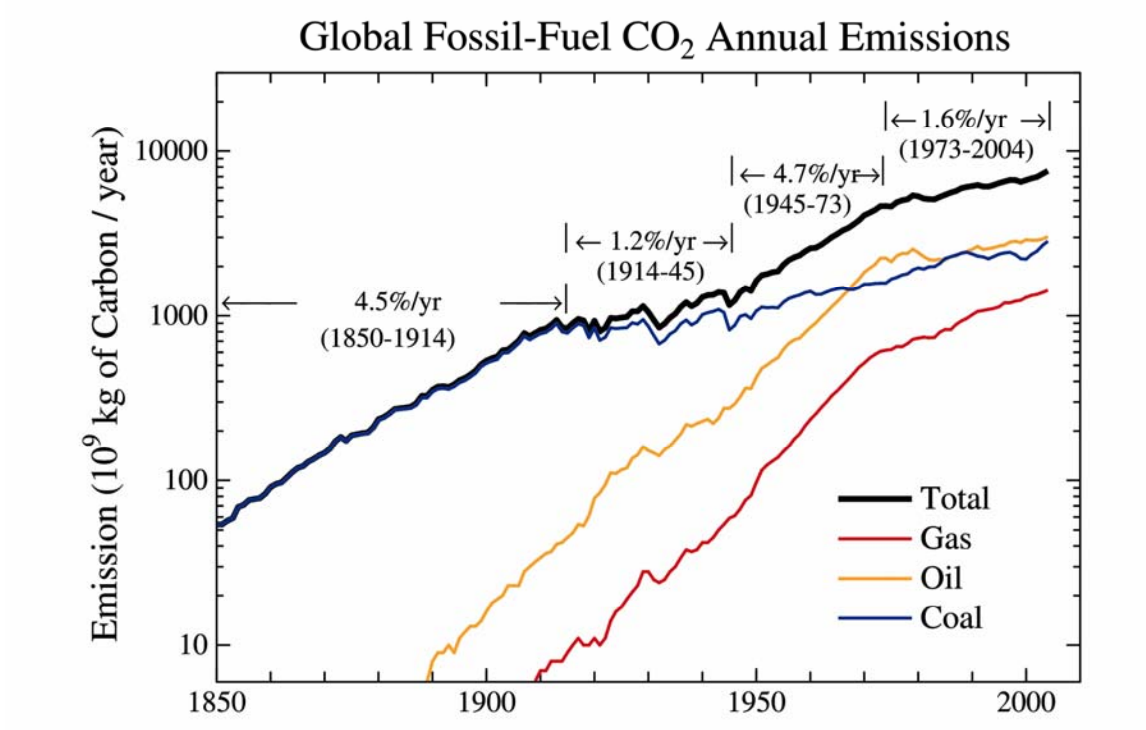


Fig. 38. Global fossil fuel annual CO_2 emissions based on data of Marland and Boden (DOE, Oak Ridge) and recent data from British Petroleum that is normalized in year of overlap with Marland and Boden data. Source: Hansen and Sato, PNAS, 98, 14778, 2001.

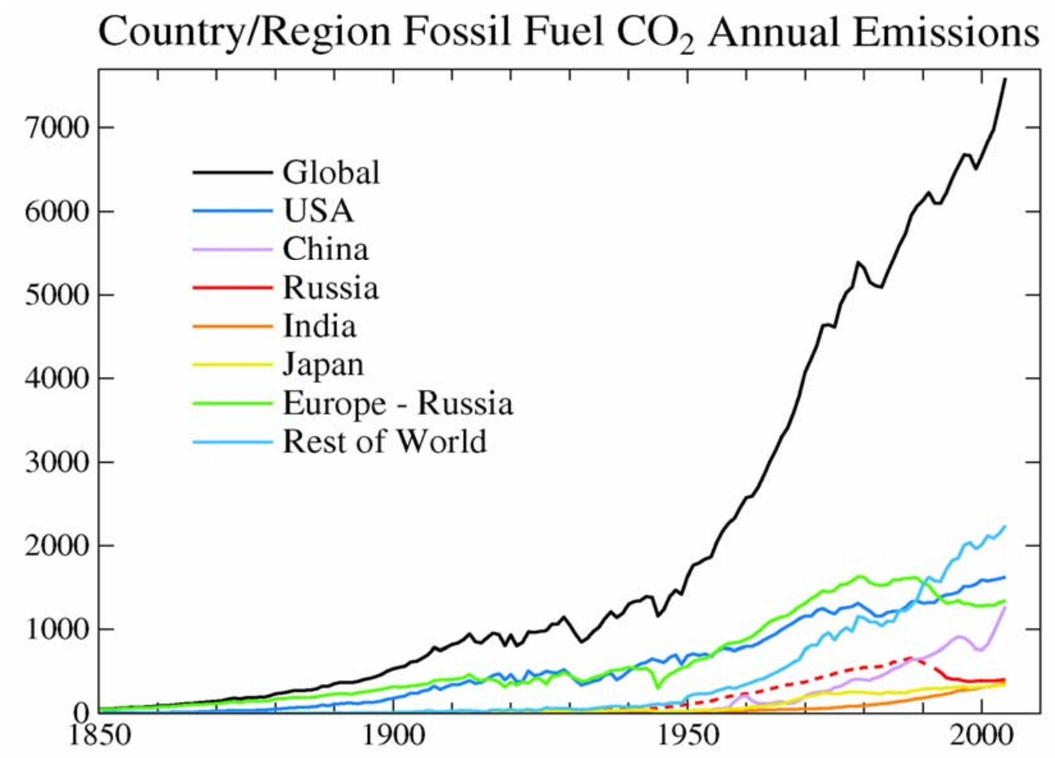


Fig. 39. CO_2 fossil fuel emissions data as in previous figure, but on a linear scale and divided into source regions. Source: Hansen et al., J. Geophys. Res., in review, 2006.

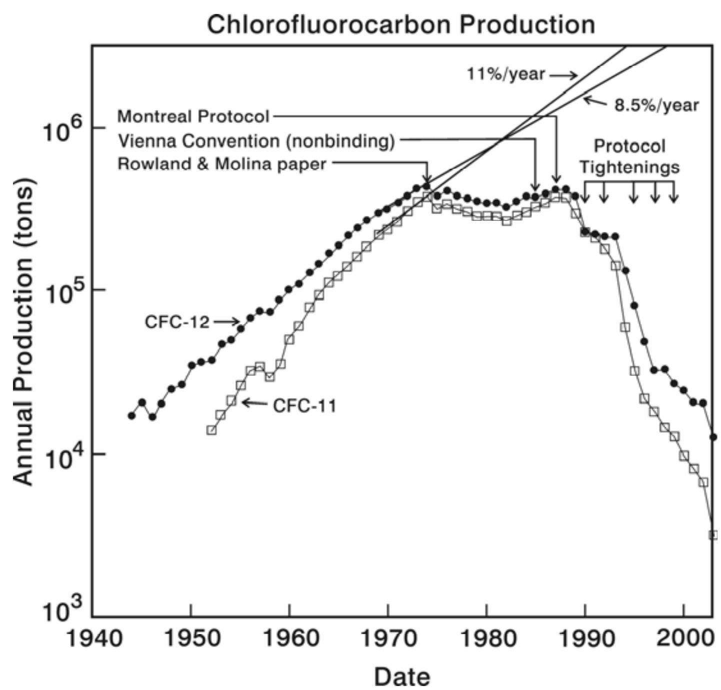


Fig. 40. Chlorofluorocarbon production (CFC-11 and CFC-12) versus time. Source: update of Hansen et al., JGR, 94, 16417, 1989.

Ozone Success Story

↑1. **Scientists**: Clear warning

↑2. **Media**: Transmitted the message well

↑3. **Special Interests**: Initial skepticism, but forsook disinformation, pursued advanced technologies

↑↑4. **Public**: quick response; spray cans replaced; no additional CFC infrastructure built

↑5. **Government**: U.S./Europe leadership; allow delay & technical assistance for developing countries

Fig. 41. Discussion points relating to "ozone success story."

Global Warming Story

↓1. **Scientists**: Fail to make clear distinction between climate change & BAU = A Different Planet

↓2. **Media**: False "balance", and leap to hopelessness

↓3. **Special Interests**: Disinformation campaigns, emphasis on short-term profits

↓4. **Public**: understandably confused, disinterested

↓5. **Government**: Seems affected by special interests; fails to lead – no Winston Churchill today

Fig. 42. Discussion points relating to "global warming story."

As it appears that the world may pass a tipping point soon, beyond which it will be impossible to avert massive future impacts on humans and other life on the planet:

Who Bears (Legal/Moral) Responsibility?

1. Scientists?

2. Media?

3. Special Interests?

4. U.S. Politicians?

5a. Today's U.S. Public?

5b. U.S. Children/Grandchildren?

Who Will Pay?

Fig. 43. Discussion points relating to responsibilities for climate impacts.

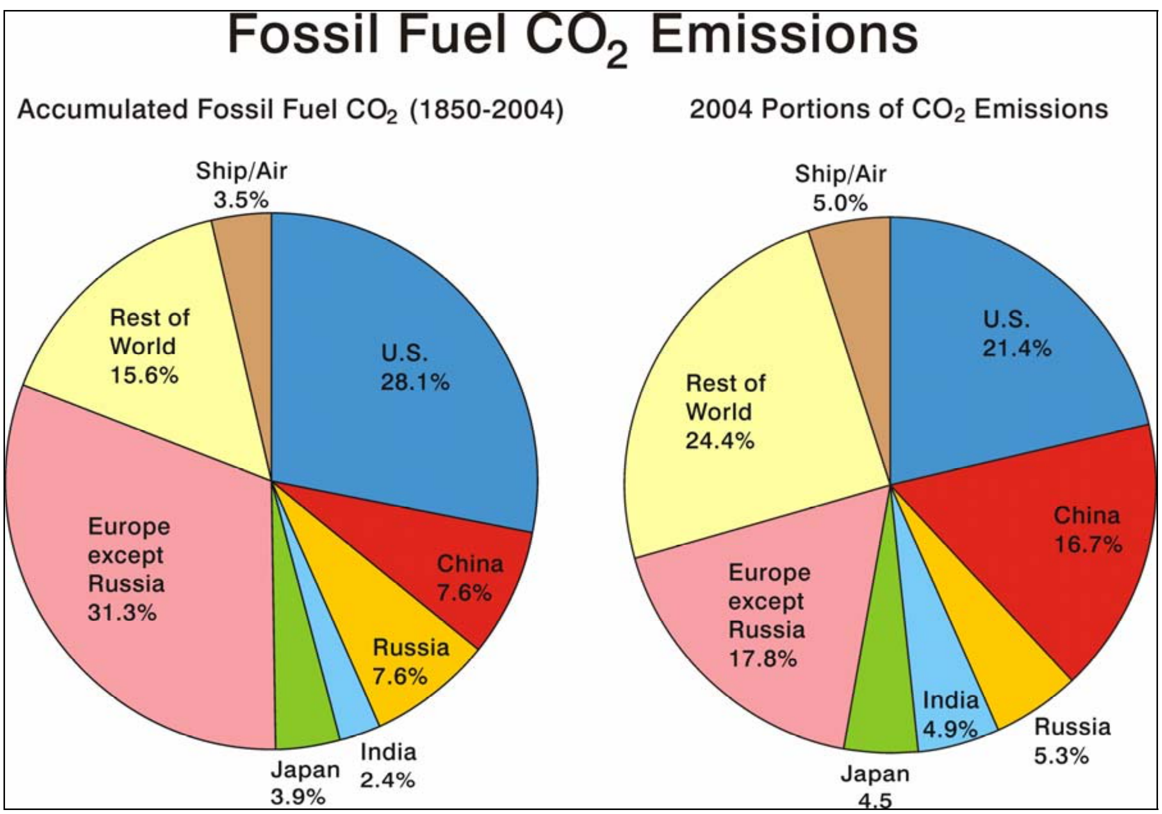


Fig. 44. Apportionment of accumulated (1850-2004) and recent (2004) fossil fuel CO_2 emissions.

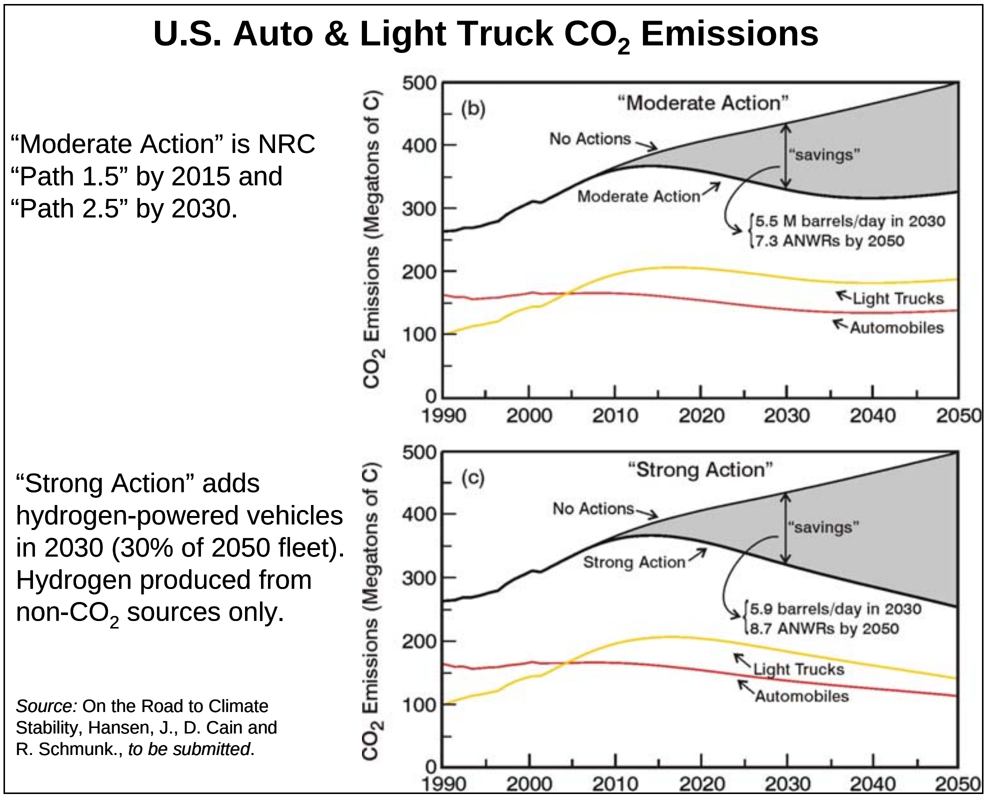


Fig. 45. CO_2 emissions by automobiles and light trucks in the United States based on past real-world data and alternative scenarios. ANWR refers to the amount of oil estimated by the United States USGS to exist in the Arctic National Wildlife Refuge. Source: Hansen et al., unpublished manuscript, 2005.

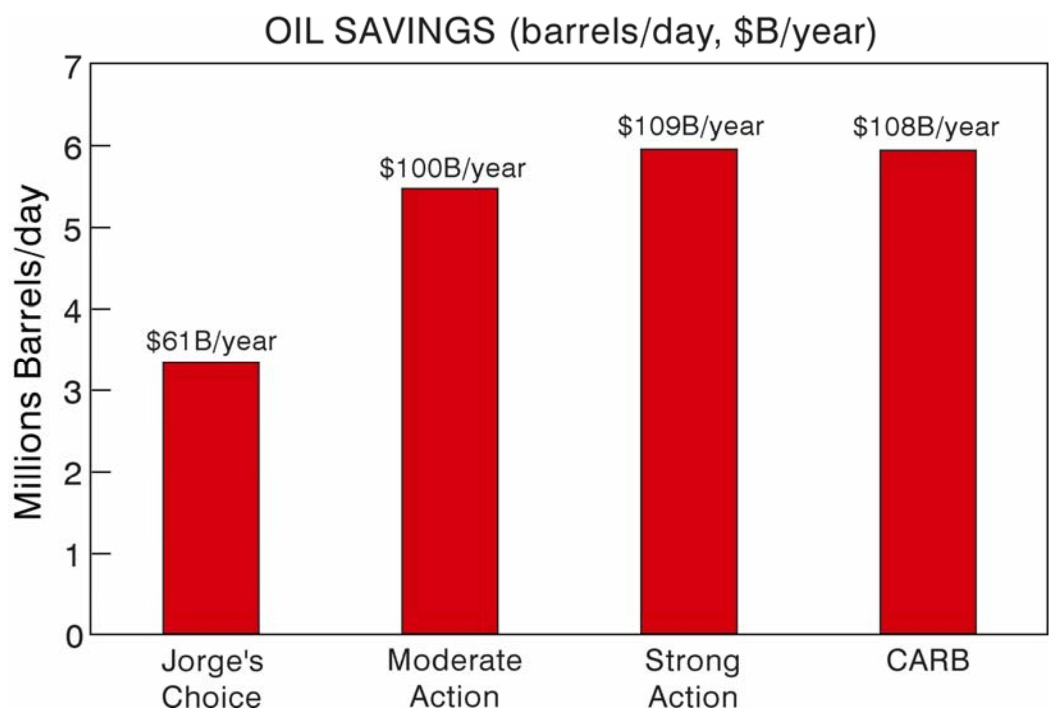


Fig. 46. Oil savings (barrels/day and $B/year) that would be saved in 2004 dollars at a price of $50 per barrel. Source: Source: Hansen et al., unpublished manuscript, 2005.

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/

Fig. 47. Workshop at East-West Center, Honolulu. Source: Air Pollution as Climate Forcing: 2002 and 2005 Workshops, 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.**
- **Best Hope: Public Must Become Informed and Get Angry**

Fig. 48. Discussions points relating to the question: Is there still time to avoid disastrous human-made climate change?