UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF VERMONT

GREEN MOUNTAIN CHRYSLER-PLYMOUTH-DODGE-JEEP, et al., Plaintiffs,	
ASSOCIATION OF INTERNATIONAL AUTOMOBILE MANUFACTURERS, Plaintiff, v.	Case Nos. 2:05-CV-302, and 2:05-CV-304 (Consolidated)
THOMAS W. TORTI, Secretary of the Vermont Agency of Natural Resources, et al., Defendants.	**DECLARATION OF JAMES E. HANSEN**

I James E. Hansen, state and declare as follows:

1. I am over 18 years of age and am competent to testify regarding the following.

2. I submit this report as my personal opinion as a private citizen. For the sake of identification, I am 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. I have degrees in Physics, Astronomy and Mathematics from the University of Iowa, where I was trained in Dr. James Van Allen's Department of Physics and Astronomy, receiving my Ph. D. in 1967. I have also studied at the University of Kyoto and University of Tokyo, and as a post-doctoral scientist at Leiden Observatory, Netherlands. I have 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. I was elected to the National Academy of Sciences in 1995 and am the recipient of the American Geophysical Union's Roger Revelle Medal and the Heinz Environment Award. I have testified numerous times to committees of the United States Senate and House of Representatives, and have twice made presentations to the George W. Bush Administration's cabinet level Climate and Energy Task Force chaired by Vice President Richard Cheney.

1. Recent Global Warming

3. The 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). By comparison, the global average temperature of the Earth during the last ice age was only about 5°C (9°F) cooler than today.

4. The temperature measurements over land areas are made at meteorological stations, while ocean surface water temperatures are measured by ships and buoys, as well as by satellites over 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 by numerous global climate modeling studies.

5. Global warming, which has amounted to about 1°F over the past several decades, is seemingly small compared to daily 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. However, the global average temperature has been quite stable over the last several thousand years. Although there have been recent cold snaps in some areas of the globe and although this will continue to happen in the future even with continued global warming, as shown in Figure 3, 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.

6. Regional 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 because fossil fuel burning is continuing to increase year after year. Continuation of this trend will yield global warming of at least 5°F by end-of-century, which, as I will explain further, would make the Earth “a different planet.”

2. Climate Forcings and Climate Sensitivity

7. 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.

8. 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.

9. In order to determine how much the climate will change, climatologists measure “climate sensitivity,” i.e., how much the planet will warm in response to a certain amount of forcing. The standard reference point for climate sensitivity to increased greenhouse gas concentrations is doubled-CO_2, i.e., how much the planet would warm in response to a doubling of atmospheric carbon dioxide concentration over the pre-industrial concentration. The pre-industrial concentration was 280 ppm (parts per million) and it is now about 380 ppm. At the current rate of CO_2 emissions, doubled-CO_2 will be reached late this century. However, CO_2 emissions are increasing 1.5-2% per year and other greenhouse gases are also increasing. In the absence of prompt action to reduce CO_2 emissions, doubled-CO_2 climate forcing will be reached in approximately the year 2050.

10. 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 (5.4°F) 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. As I shall explain, however, the Earth’s climate sensitivity can be verified with much greater accuracy by way of paleo climate studies.

11. 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 over the pre-industrial concentration of 280 ppm to 560 ppm 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.

12. All climate models find these positive feedbacks by water vapor and sea ice. Clouds provide another possibly important set of feedbacks. 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. Depending on their height and other physical properties, clouds could cause a net positive feedback or net negative feedback for anthropogenic climate change. However, there is no indication that they are likely to provide a net negative feedback of sufficient magnitude to offset the net warming due to GHGs. Indeed, the cloud feedback is fully incorporated in empirical evaluation of climate sensitivity, and, as discussed below, it is found on global average to be nearly neutral (i.e., the global average cloud feedback is small).

13. Large uncertainty would probably always accompany a purely model-based estimate of climate sensitivity. Fortunately, the Earth's history provides more accurate knowledge of global climate response to known climate forcings. This empirical information is 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

14. Over the past hundreds of thousands of years the Earth's climate has varied repeatedly between cold ice ages and warm interglacial periods due to variations in the Earth's orbit (tilt of axis, eccentricity of orbit, and season of nearest approach to sun). These periodic changes in Earth's orbit cause small changes in the seasonal and geographical distribution of sunlight and thus alter the amount of "solar forcing," which in turn has affected the temperature of the Earth over time scales on the order of thousands of years. This is illustrated by the lower curve in Figure 4, which 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 accurately deduced from the isotopic composition of the ice, as the proportion of various isotopes of oxygen in

the ice depends on the temperature where the snowflakes formed. As discussed later, the effects of orbital variations on climate are not able to account for the warming seen in recent decades. Indeed, absent human influence, the natural trend would be toward a cooler climate, as peak warmth of the current interglacial period occurred 8-10 thousand years ago. However, as shown below, the mechanisms that would cause natural cooling are now overwhelmingly controlled by humans and these mechanisms are being driven rapidly in the sense that causes global warming, not cooling.

15. 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, in the past, the temperature changes (dictated by the changes in Earth's tilt and orbit) usually preceded 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 I will show, the GHGs cause about half of the temperature variation on these long time scales. Now, human emissions of greenhouse gases are overwhelming and have reversed the order so that greenhouse gases are driving temperature increases. And given that in the past the Earth has responded to increasing temperature with increases in greenhouse gases liberated from oceans and land, we can expect a positive feedback in response to anthropogenic climate change.

16. The sensitivity of the climate system to forcings such as changing GHGs can be determined 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.

17. 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 is the same sensitivity of Earth's climate given to us by the models.

18. 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 with a high degree of confidence. However, it is noteworthy that the empirical and modeled climate sensitivities are in agreement.

19. We also have derived climate sensitivity by examining longer ice core records extending back 400,000 years. The longer record is particularly informative now because of the availability of good sea level records for the entire 400,000 year period (Figure 6). Figure 8 reveals remarkable agreement over 400,000 years between observed temperatures and expected temperatures calculated using a climate sensitivity ¾ °C per W/m^2. The error (uncertainty) in the dating of the two curves is only a few thousand years.

20. 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 gave rise to the regular climate variations in the past are a result of perturbations of the Earth's orbit on time scales of tens of thousands of years. However, the high climate sensitivity means that any other small forcings, including human emissions of greenhouse gases, can also lead to large climate variations.

21. **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, as summarized in Figure 10, humans now control global climate, for better or worse.

22. 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, on time scales on the order of 1000 years or more, we could assume that the planet was nearly in energy balance with space. Thus, calculated temperature change was simply a product of the forcing and equilibrium (i.e., 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.

23. 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 such as sulfur oxides from power plants) that yield a negative (cooling) forcing. In the next section I estimate all of the known forcings and calculate the expected global temperature change.

4. Climate Change in the Era of Human Influence

24. 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. 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.

25. 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.

26. 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 2.7-2.9°C (variation occurs with use of alternative ocean models) for doubled CO_2 (near the middle of the range of the sensitivities consistent with empirical data and the range given by other models), the simulated global temperature change is in good agreement with observations (Figure 11B).

27. 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.

28. The IPCC A2 and A1B scenarios can be described as Business-as-Usual scenarios. They have growth of CO_2 emissions at about 2% per year (as occurred in the past decade) and 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.

29. 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.

30. 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 2.7-2.9°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.

31. 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.

32. 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 by end-of-century 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.

33. Plausible future changes of human-made aerosols do not substantially alter these conclusions. Aerosols may decrease in response to clean-air requirements, 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

34. 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 (1.8^{o}F) above year 2000 temperature would be a large climate change and 3°C (5.4^{o}F) would yield "a different planet."

35. 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 for us 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.

36. 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.

37. 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 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 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.

38. 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.

39. An important point to note is that the tripwire between keeping global warming less than 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 less than 1°C requires having both a moderate limit on CO_2 and a reduction of non-CO_2 forcings. However, if the warming becomes greater than 1°C, it may be come 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

40. 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.

41. 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.

42. 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 less than 1°C warming of the Alternative scenario.

43. 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 my opinion, 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 set forth above, 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.

44. **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.

45. 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).

46. 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.

47. 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.

48. When the 2005 ice losses from Greenland and West Antarctica are spread over the world ocean they raise sea level at a rate 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. IPCC's baseline projection of about 45 cm of sea level rise by 2100 (with range 10-90 cm) relative to 1990 assumed no contribution from Greenland or Antarctica.

49. 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.

50. The annual number of these Greenland earthquakes, or ice quakes, doubled from 7 to 14 between 1993 and 1999, 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, and the most recent GRACE data show that Greenland mass loss is accelerating.

51. 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.

52. 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.

53. **Paleoclimate ice sheet lessons and summary.** Paleoclimate data reveals 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. This rapid rate of sea level rise indicates that, once the process is set in motion, ice sheet disintegration can accelerate rapidly due to positive feedbacks. Such positive feedbacks include reduction of ice sheet albedo as it becomes wet, decrease of altitude of the ice sheet surface as it melts, and the nonlinear dynamical processes involved in the wet disintegration of ice.

54. 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 (Figure 9) and the rapidity with which human-made GHGs are being added yields a planetary energy imbalance that can drive ice sheet change.

55. 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.

56. 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.

57. **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 meters ± 10 meters. 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, leaving both Greenland and West Antarctica dripping in summer melt-water. It is my opinion that 2-3°C global warming would likely cause a sea level rise of at least ~6 m within a century. Although ice sheet inertia may prohibit large change for a few decades, it is plausible that rapid change 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 the presumed 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.

58. 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.

59. 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 also would be under water.

60. 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.

61. 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. Regional Climate Change

62. A sense of the magnitude of expected climate change in the 21^{st} century is provided in Figure 33 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 21^{st} century, and the right side is the ratio of this temperature change to the observed standard deviation of seasonal mean temperature in the 20^{th} 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.

63. 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.

64. 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.

65. Global warming is expected to cause an increase in the extremes of the hydrological cycle, thus in the intensity of droughts and forest fires, 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.

66. 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 in 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.

67. 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 reduce moderately 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 emission of the relevant chemicals while working on alternative technologies. Developing countries (where residents were just in the process of acquiring refrigeration) 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.

68. 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, and without United States participation in its Clean Development Mechanism the Kyoto Protocol has been relatively ineffective in slowing the growth of developing country emissions. 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 and 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?

69. **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% per 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, causing atmospheric CO_2 to peak at ~475 ppm in 2100.

70. CO_2 fossil fuel emissions must decline to achieve the Alternative scenario. The growth rate of annual fossil fuel 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 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).

71. 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.

72. **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.

73. 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 parts of the non-CO_2 forcing agents is uncertain, because there are not sufficiently

accurate global measurements of O_3, black soot, and other aerosols.

8. A Brighter Future: Emissions Requirements

74. Quantitative examination of emission 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.

75. **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 reduction in vehicle emissions during the next several years, and (2) technology advances on the longer-term that fundamentally reduce CO_2 emissions.

76. The reduction in vehicle emissions 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.

77. The CO_2 emissions reductions from automobiles and light trucks in the “moderate action” case illustrated in Figure 45 is slightly less ambitious than the standards being proposed by the California Air Resources Board, yet it is 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 allowed. The assumed efficiency improvements in the illustrated example are based on recommendation of the National Resource Council using technologies that are available.

78. 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.

9. Avoiding the Climate Tipping Point

79. The "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.

80. 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).

81. 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.

82. 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. At minimum, the emission reductions required if these standards were to be implemented in either the states that have adopted them or on a national basis, would delay onset of future impacts including reaching a tipping point such as that described above, as well as lessening or mitigating these impacts.

10. Abrupt Climate Change

83. The climate system is capable of abrupt changes and surprises, as demonstrated by a variety of rapid changes in the Earth's history. These abrupt climate changes are surprises not so much in the sense of being unexpected from a scientific perspective, but rather by the fact that their occurrences are infrequent and their exact timing is unpredictable. Abrupt climate change occurs when gradual change pushes the earth system across a threshold, suddenly switching the climate into a new system. Abrupt climate change is closely related to "tipping points" discussed above, because once an abrupt climate change occurs it can be difficult or impossible to reverse the climate change on a time scale relevant to civilization.

84. The occurrence of abrupt climate changes this century is practically certain, if we continue with Business-as-Usual greenhouse gas emissions. This assertion is based on the magnitude and speed of the human-induced changes of atmospheric composition (which dwarf natural changes) and the rate of global warming that will result from such atmospheric changes (which exceeds any documented natural global warming event). The magnitude of the expected total climate change under Business-as-Usual is so large that it almost surely passes a number of thresholds. Although, it is impossible to say when these thresholds will be passed, we give examples here of abrupt changes that seem highly likely under Business-as-Usual and we discuss additional more speculative possibilities.

85. An example of an abrupt regional climate change relevant to the United States is a switch to a long-term mega-drought encompassing most of the Western United States and portions of the Midwest. Such mega-droughts have occurred in the Earth's history, generally in conjunction with warmer climate. Global warming causes a relaxation of the tropospheric overturning circulation (Soden and Held, J. Clim. 19, 3354, 2006) with resulting intensification of hot, dry conditions in subtropical regions such as the Southwest United

States and the Mediterranean. There is already evidence for an increased tendency toward warmer drier conditions in those regions in conjunction with global warming of 0.6°C during the past three decades. If global warming continues to increase there is the danger that decreasing winter snowpack, intensifying summer dry conditions, and increasing forest fires may reduce vegetation cover and regional soil-biosphere water-holding capacity. If these conditions reach sufficient intensity and geographical scale they may become self-perpetuating, and we will have suddenly entered a long-term megadrought in the western United States. Weather would continue to fluctuate from year to year, but water supplies would be much more limited than in prior decades and dust storms may become frequent. We cannot say what level of global warming is needed to cause such a mega-drought, but the likelihood increases with increase of greenhouse gases and global warming.

86. An example of an abrupt change with global consequences is the cataclysmic collapse of the West Antarctic ice sheet. The Earth's history reveals cases when ice sheet collapse caused sea level to rise at an average rate of about 1 meter every 20 years for centuries. Within such periods there must have been times when the rate of sea level change was even faster. Because hundreds of large cities are located on coast lines around the world, such abrupt ice sheet collapse would have devastating consequences. It is impossible to specify the exact level of global warming necessary to cause such an ice sheet collapse, but, as argued above, it is nearly certain that West Antarctica and/or Greenland would disintegrate at some point if global warming approaches 3°C, as it would with a Business-as-Usual greenhouse gas scenario.

87. Another regional climate change that may proceed rapidly as we pass a tipping point is loss of all Arctic sea ice in the summer. The complete loss may occur rapidly, on the time scale of a decade, once ice loss has reached a degree that the albedo feedback becomes a dominant process. The albedo feedback refers to the fact that loss of some sea ice increases the solar energy absorbed by the Arctic, the ocean being darker than the ice, thus increasing ice melt. We do not know the exact level of added CO_2 necessary to cause complete ice loss, but once such a state were reached it would be difficult to return to a climate with summer sea ice, because of the long lifetime of atmospheric CO_2.

88. The above examples are, in the opinion of this expert witness, not only possible with Business-as-Usual global warming, but highly likely to occur. Other abrupt climate changes are likely with global climate change of such unprecedented magnitude, but their nature can only be speculated upon. For example, storms driven by latent heat of vaporization can achieve increased intensity as sea surfaces warm and evaporation increases. Thus as warm ocean waters encompass broader areas regions that previously had few if any hurricane-force storms may become vulnerable. Last year, for the first time in recorded meteorological history, an Atlantic hurricane occurred in the southern Hemisphere. Of concern for the Eastern United States is the possibility that warmer coastal areas may allow hurricanes to survive longer and strengthen, thus making this region vulnerable to storms that have long been associated more with the Southeast United States.

89. Abrupt climate change, and the thresholds or tipping points whence abrupt change initiates, are relevant to the question of whether actions to reduce greenhouse gas emissions by a limited region such as the Eastern states is meaningful, given their small fraction of total

global emissions. The existence of multiple climate thresholds means that there is a reasonable chance that reduced emissions from such a region could prevent the climate system from crossing one or more thresholds. Furthermore, if such reductions are matched by other states, they may have a snowballing feedback effect leading to similar technologies and reduced emissions being adopted by other states, and in turn such actions in the United States are likely to affect technologies and emissions of other countries. If, on the contrary, such reduced emissions are not initiated in the United States, other countries will be less disposed to initiate their own greenhouse emission reductions. Because of the long lifetime of a substantial fraction of CO_2 emissions, accumulated emissions are a relevant measure of existing responsibilities. Figure 44 shows that the United States is responsible for almost four times the CO_2 emissions of any other country.

11. Summary: Climate Merits of Proposed Efficiency

90. 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.

91. Although the magnitude of these tasks should not be understated, I note that that involvement of other countries in emissions limitations becomes more realistic if the United States is taking steps to reduce its emissions.

Executed on this day the 14th of August 2006.

/S/
James E. Hansen Ph.D.

Figures

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 21^{st} 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.

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 21^{st} 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.

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.

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.

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.

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

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

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

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.

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

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

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

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

Fig. 44. Apportionment of recent (2004) and accumulated (1850-2004) 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

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/.

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

Appendix A

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Education:

Ph.D. (Physics), University of Iowa, 1967
Visiting student, Inst. of Astrophysics, University of Kyoto & Dept. of Astronomy, Tokyo University, Japan, 1965-1966
MS (Astronomy), University of Iowa, 1965
NASA Graduate Traineeship, 1963-1966
BA with highest distinction (Physics and Mathematics), University of Iowa, 1963

Research Interests:

Radiative transfer in planetary atmospheres and interpretation of remote sounding of atmospheres. Development of global climate models. Analysis of climate change, current climate trends, and projections of man's impact on climate.

Professional Employment:

1967-1969	NAS-NRC Resident Research Associate: Goddard Institute for Space Studies (GISS), NY
1969	NSF Postdoctoral Fellow: Leiden Observatory, Netherlands
1969-1972	Research Associate: Columbia University, NY
1972-1981	Staff Member/Space Scientist: Goddard Institute for Space Studies (GISS), Manager of GISS Planetary and Climate Programs
1978-1985	Adjunct Associate Professor: Department of Geological Sciences, Columbia University
1981-present	Director: NASA Goddard Institute for Space Studies
1985-present	Adjunct Professor: Earth and Environmental Sciences, Columbia University

Project Experience:

1971-1974	Co-Principal Investigator AEROPOL Project (airborne terrestrial infrared polarimeter)
1972-1985	Co-Investigator, Voyager Photopolarimeter Experiment
1974-1994	Principal Investigator (1974-8) and subsequently Co-Investigator, Pioneer Venus Orbiter Cloud-Photopolarimeter Experiment
1977-2000	Principal Investigator, Galileo (Jupiter Orbiter) Photopolarimeter Radiometer Experiment
1989-2000	Principal Investigator, Earth Observing System Interdisciplinary Investigation: Interannual Variability of Earth's Carbon, Energy and Water Cycles

Teaching Experience:

Atmospheric Radiation (graduate level): New York Univ., Dept. of Meteorology & Oceanography
Intro. to Planetary Atmospheres & Climate Change: Columbia Univ., Dept. of Geological Sciences

Awards:

1977	Goddard Special Achievement Award (Pioneer Venus)
1978	NASA Group Achievement Award (Voyager, Photopolarimeter)
1984	NASA Exceptional Service Medal (Radiative Transfer)
1989	National Wildlife Federation Conservation Achievement Award
1990	NASA Presidential Rank Award of Meritorious Executive
1991	University of Iowa Alumni Achievement Award
1992	American Geophysical Union Fellow
1993	NASA Group Achievement Award (Galileo, Polarimeter/Radiometer)
1996	Elected to National Academy of Sciences
1996	GSFC William Nordberg Achievement Medal
1996	Editor' Citation for Excellence in Refereeing for Geophysical Research Letters
1997	NASA Presidential Rank Award of Meritorious Executive
2000	University of Iowa Alumni Fellow
2000	GISS Best Scientific Publication (peer vote)
2001	John Heinz Environment Award
2002	Roger Revelle Medal, American Geophysical Union
2004	GISS Best Scientific Publication (peer vote)
2005	GISS Best Scientific Publication (peer vote)

Selected Publications:

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Appendix B

Documents and Data Used in Forming Opinions

1. Thousands of scientific papers. These are referenced at the end of my scientific papers, which are delineated as part of my curriculum vita (Appendix A).

2. A vast array of scientific data are employed, as specified in my scientific papers (Appendix A). These data include paleoclimate data, on the history of the Earth's climate, as well as modern data for climate of the past century. Data sources for the specific charts appearing in the present statement are specified in the figure captions.

Appendix C

I am not being compensated for my time on this case.

I have not testified under oath in deposition or trial in any legal case in the last four years.

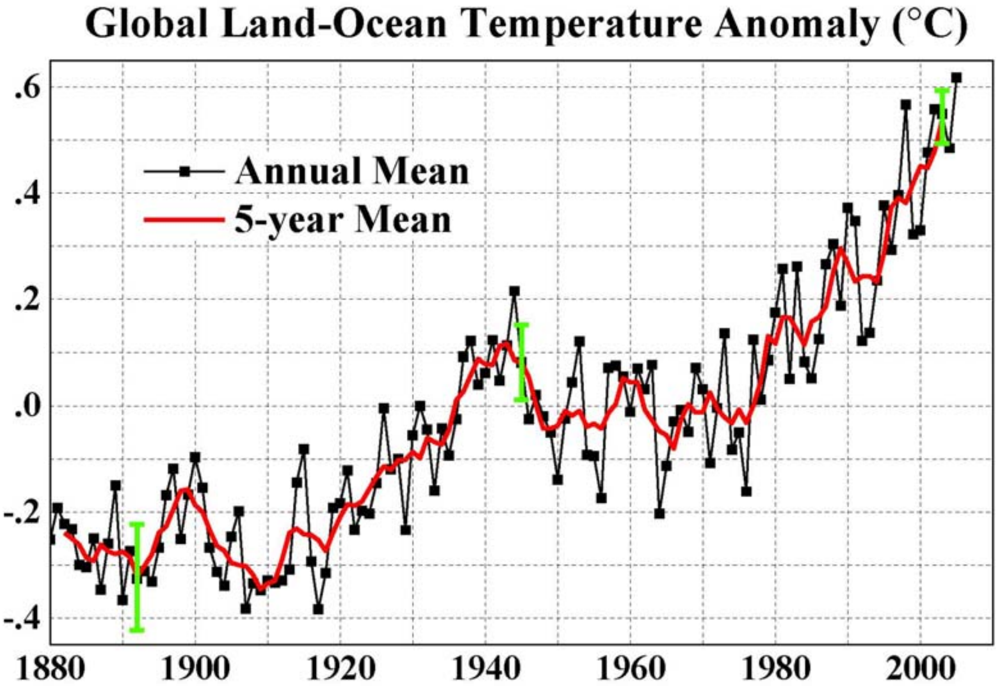

Fig. 1. Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. Source: update of Hansen et al., JGR, 106, 23947, 2001; Reynolds and Smith, J. Climate, 7, 1994; Rayner et al., JGR, 108, 2003.

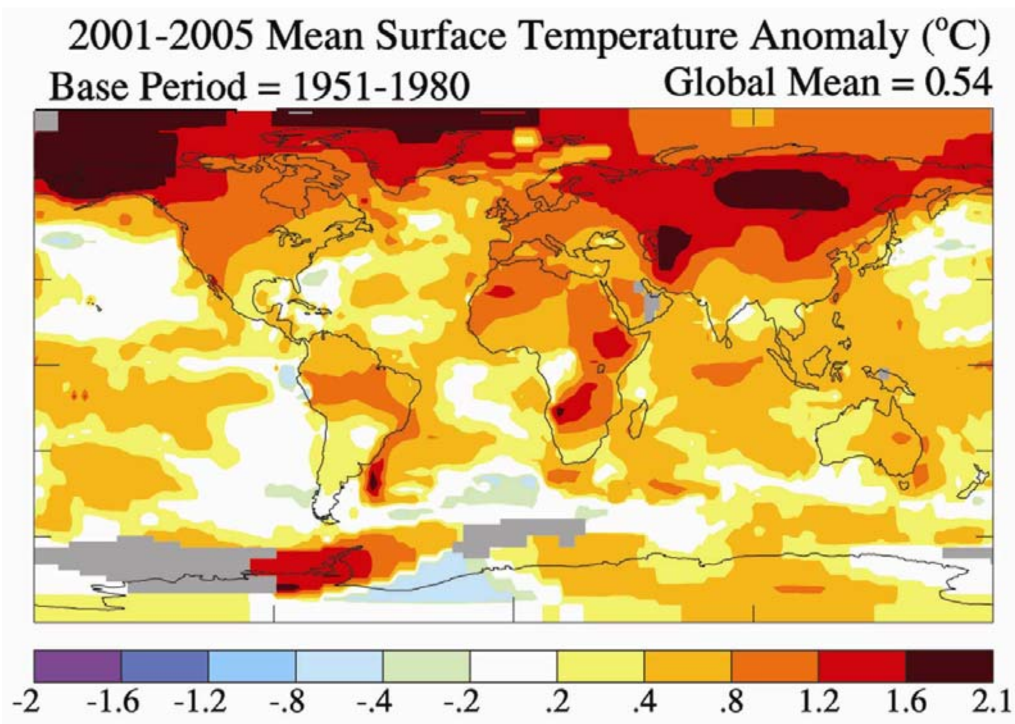

Fig. 2. Global surface temperature anomaly for the first five years of the 21st century relative to 1951-1980. Source: Hansen et al., submitted to Proc. Natl. Acad. Sci., 2006.

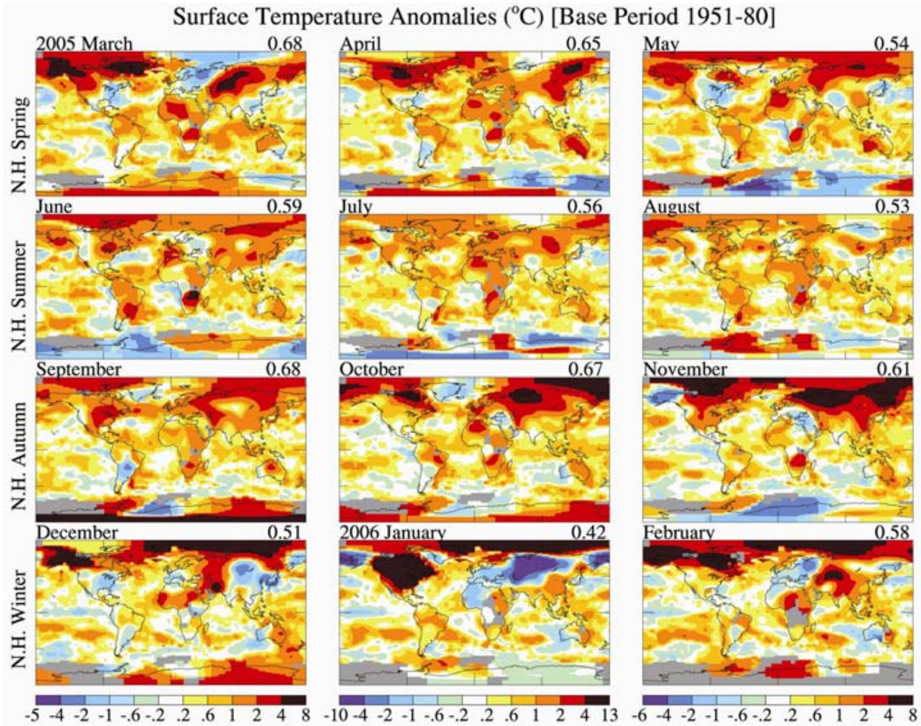

Fig. 3. Monthly surface temperature anomalies for 12 recent months, based on the data sets described in Fig. 1.

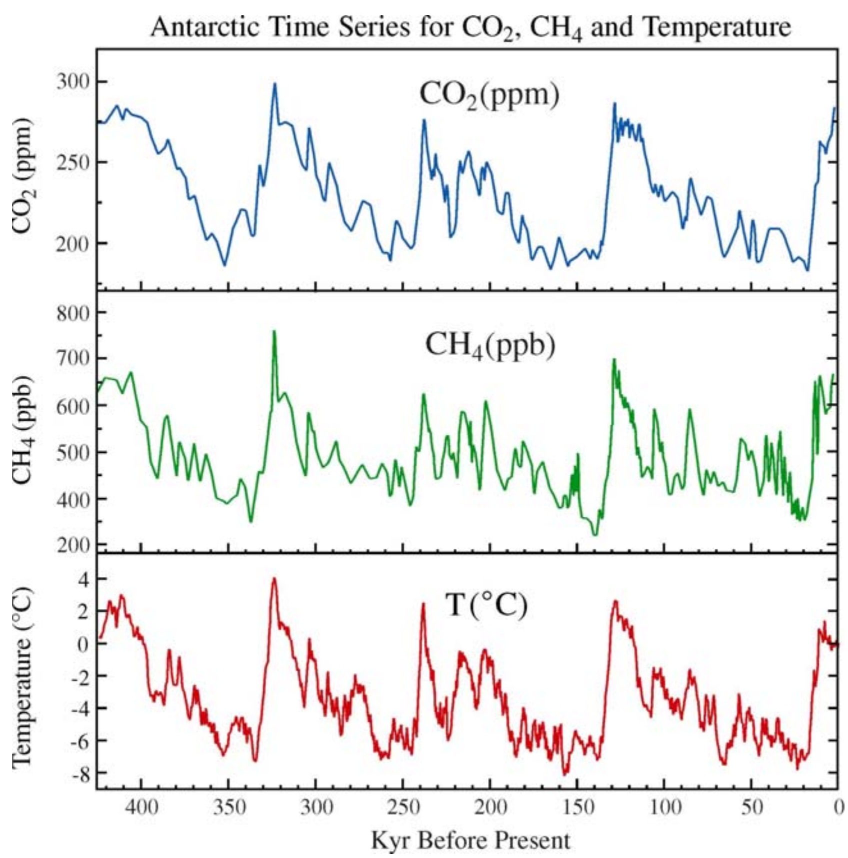

Fig. 4. CO_2, CH_4 and temperature records from Antarctic ice core data. Source: Vimeux et al., Earth Plan. Sci. Lett., 203, 829, 2002.

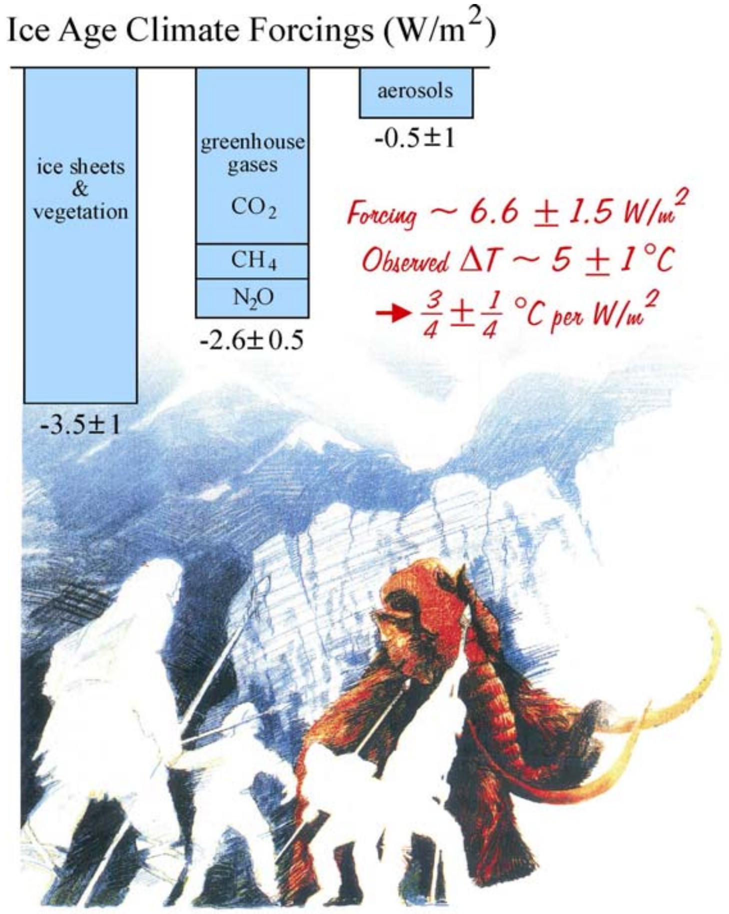

Fig. 5. Ice age climate forcings imply global climate sensitivity ~¾°C per W/m^2. Source: Hansen et al., Natl. Geogr. Res. & Explor., 9, 141, 1993.

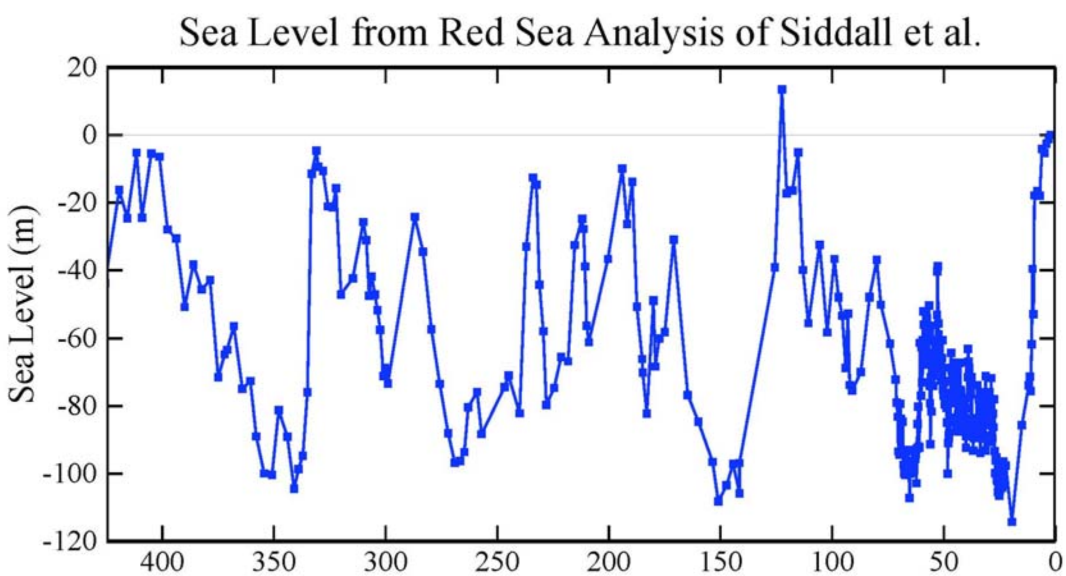

Fig. 6. Global sea level extracted, via a hydraulic model, from an ozygen isotope record for the Red Sea over the past 470 kyr (concatenates Siddall's MD921017, Byrd, & Glacial Recovery data sets; AMS radiocarbon dating). Source: Siddall et al., Nature, 423, 853, 2003.

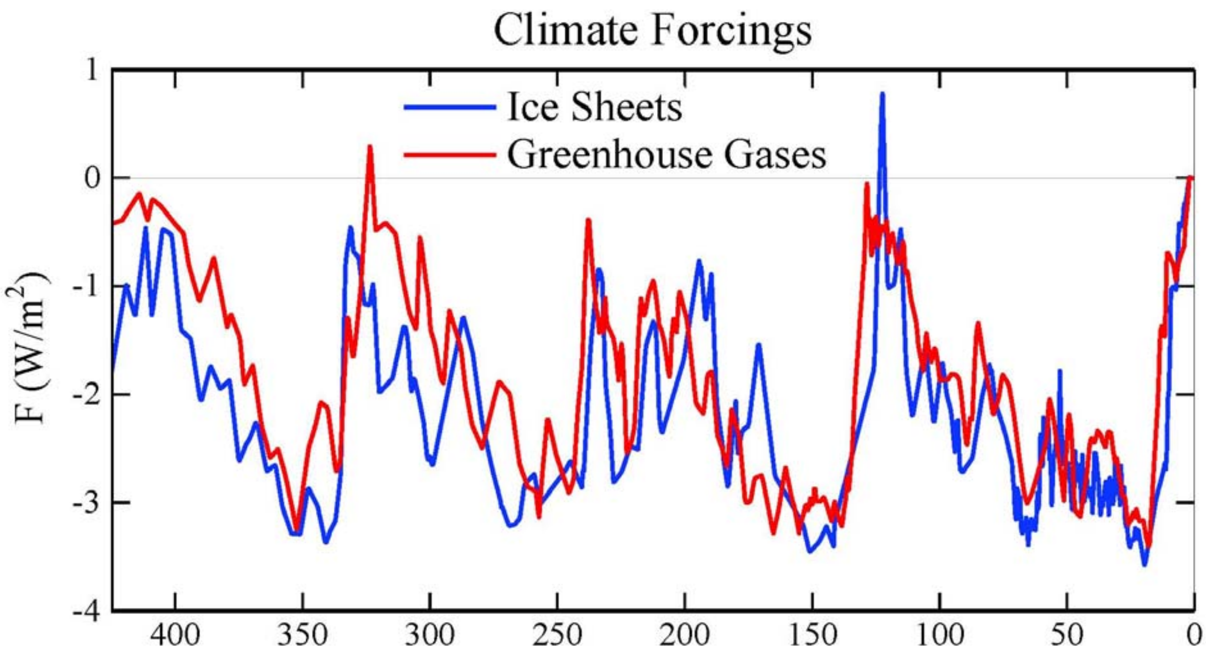

Fig. 7. Calculated climate forcings. Ice sheet forcing is proportional to (sea level)$^{2/3}$ and equal to 3.5 W/m^2 20,000 ybp. GHG forcing is based on Vostok CO_2 and CH_4, with the N_2O forcing 15% of the combined CO_2 and CH_4 forcings. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1,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

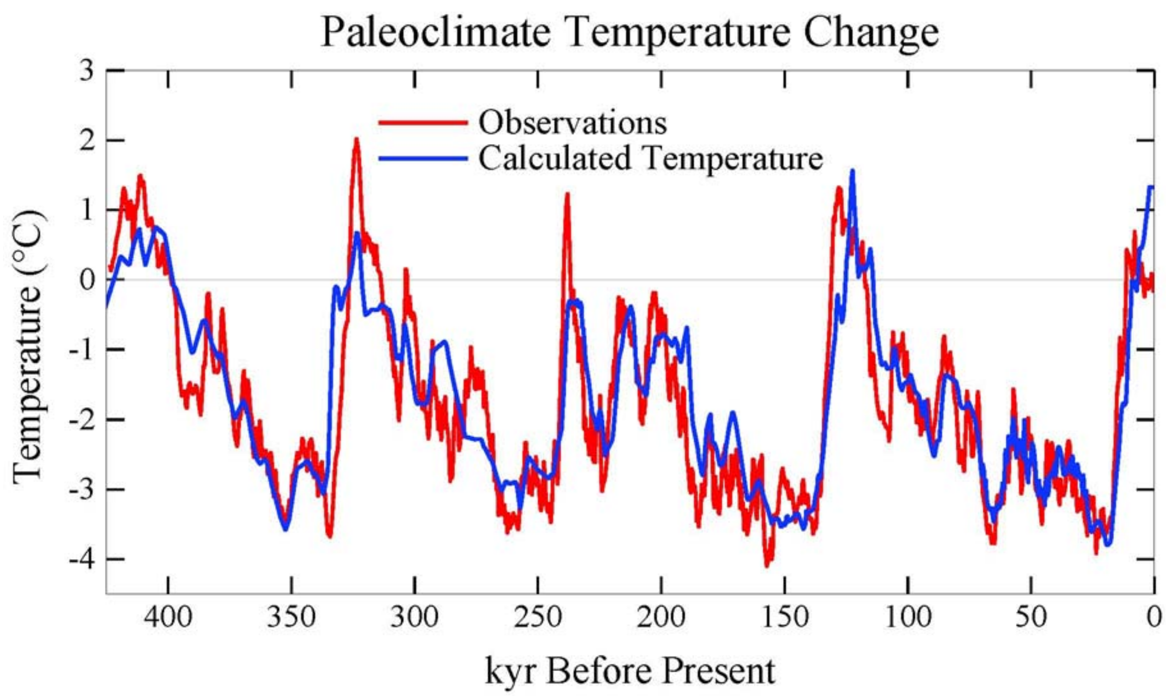

Fig. 8. Calculated and observed temperature for past 400,000 years. Calculated temperature is the forcing from the preceding figure multiplied by climate sensitivity ¾°C per W/m^2. Observation is the measured Vostok Antarctica temperature divided by two. Source: Hansen, Amer. Geo. Union, U23D-01, Dec.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

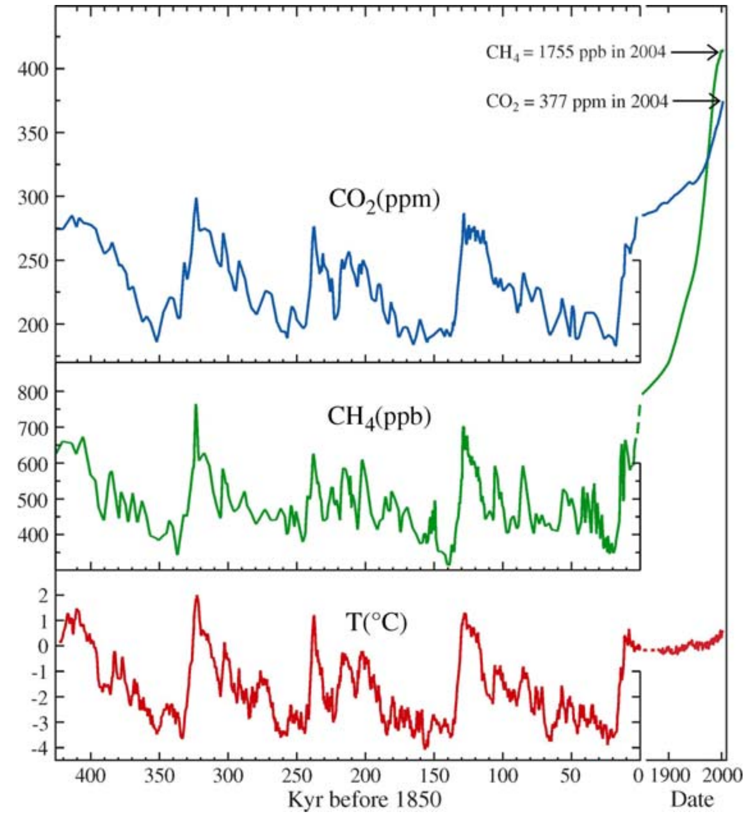

Fig. 9. Extension of CO_2, CH_4 and temperature records of Fig. 4 to 2004. Temperature change since 1880 is the land-ocean temperature index (Fig. 1), with the 1880-1899 mean defined as zero, while the earlier temperature is the Vostok Antarctica temperature change divided by two. Source: Hansen, Amer. 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.

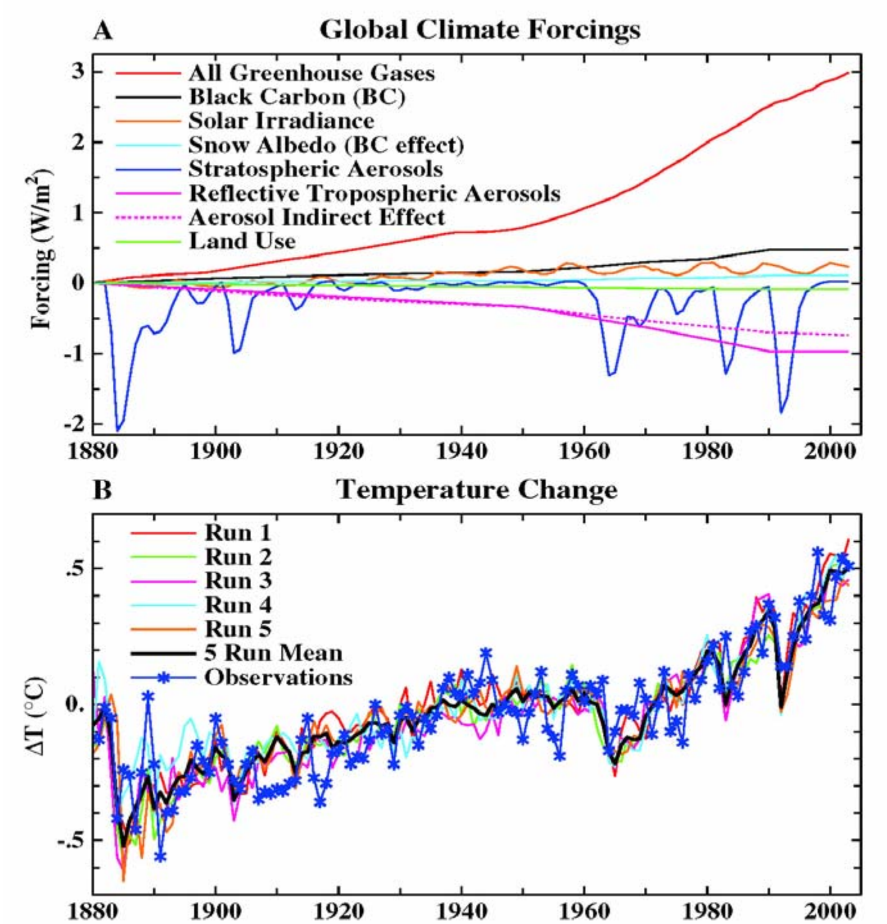

Fig. 11. (A) Climate forcings used to drive the GISS global climate model, and (B) the global temperature change simulated by the model compared with observations. Source: Hansen et al., Science, 308, 1431, 2005.

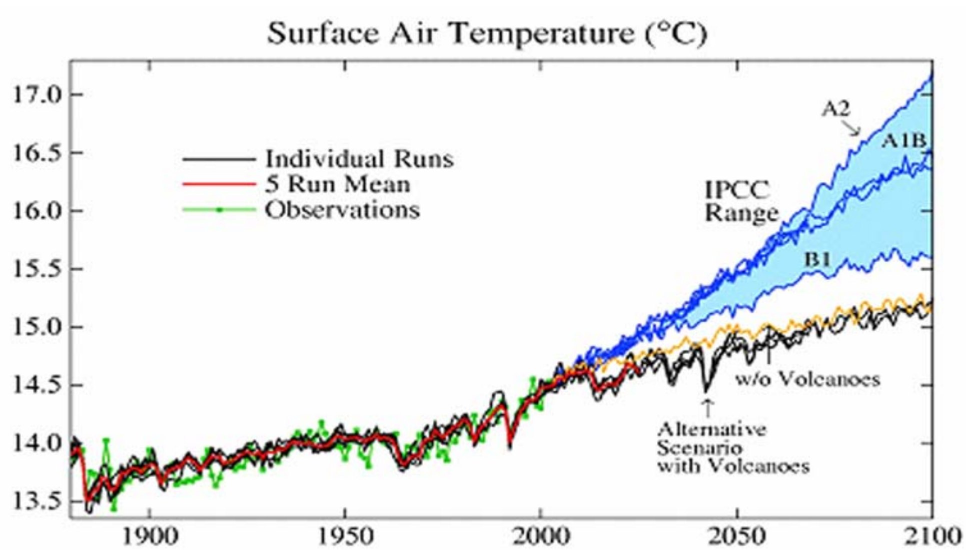

Fig. 12. Extension of the climate simulations in the prior figure through the 21st century for IPCC scenarios (A2 and A1B are "business as usual" scenarios) and the "alternative scenario." Source: Hansen et al., J. Geophys. Res., in review, 2006.

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.

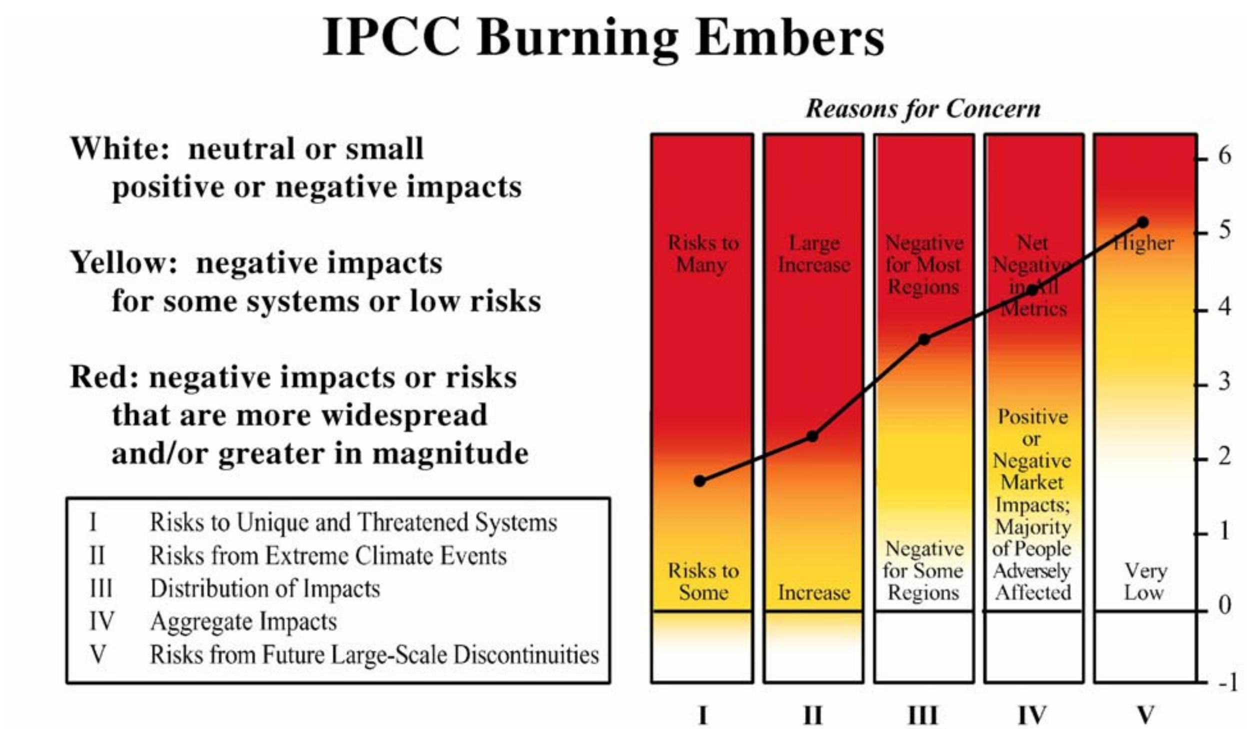

Fig. 14. Reasons for concern about projected climate impact changes. Source: IPCC Climate change 2001; S. Schneider & M. Mastrandrea, PNAS, 102, 15728, 2005.

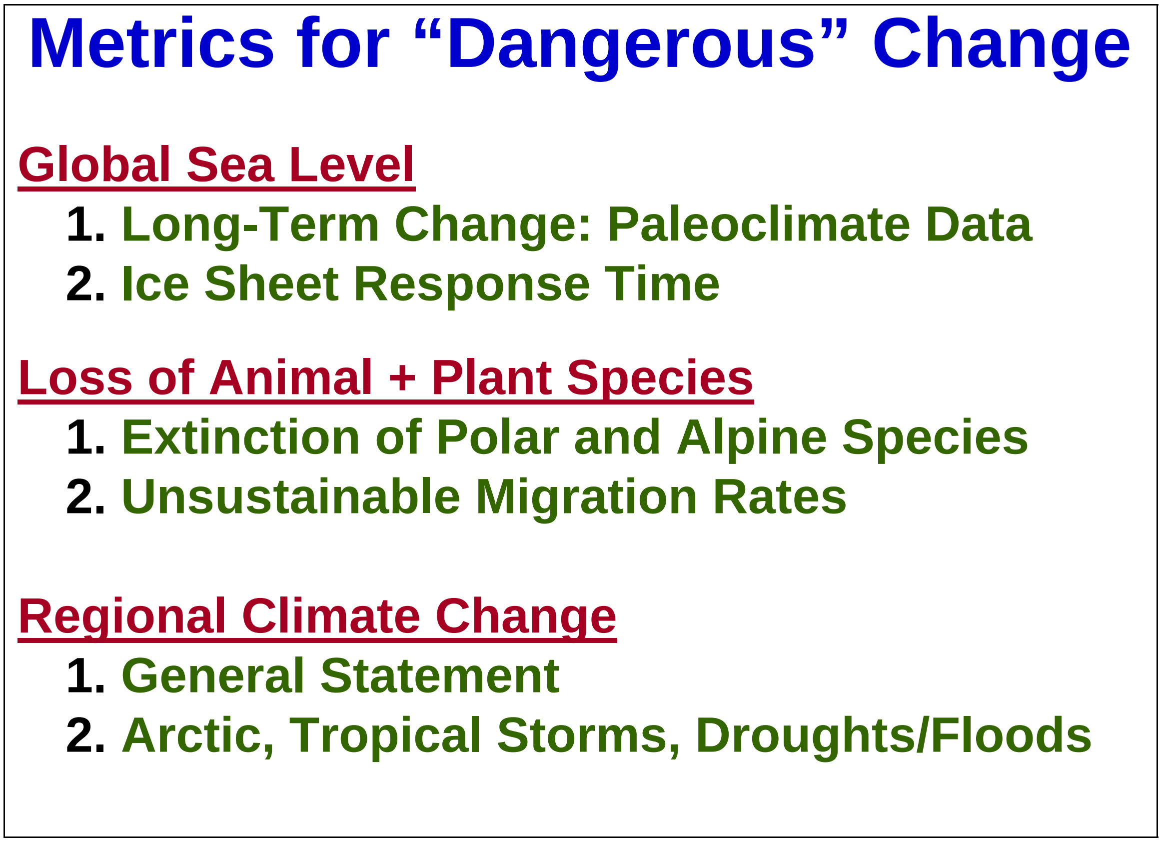

Fig. 15. Principal criteria determining the level of climate change constituting "dangerous" change. Source: Hansen, Apr. 23, Natl. Acad. Sci., www.columbia.edu/~jeh1, 2006.

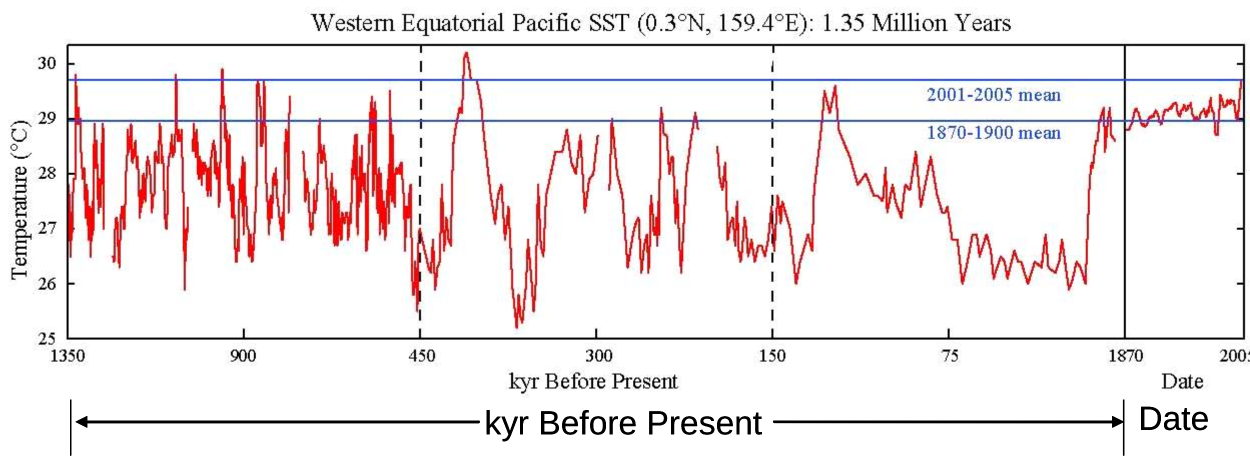

Fig. 16. SST in Pacific Ocean Warm Pool in past millennium, with recent time scale expanded. Data after 1880 is 5-year mean. Source: Medina-Elizade and Lea, ScienceExpress, Oct. 13, 2005; data for 1880-1981 based on Rayner et al., JGR, 108, 2003, after 1981 on Reynolds and Smith, J. Climate, 7, 1994.

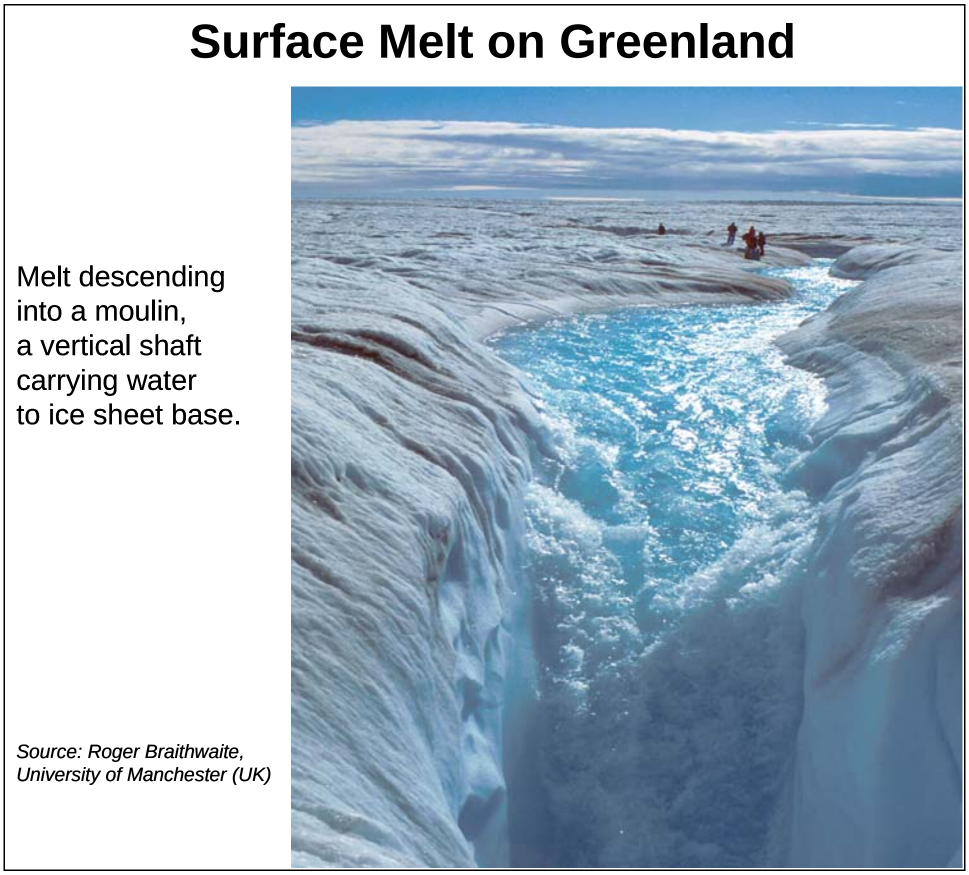

Fig. 17. Melt-water on Greenland descending into a Moulin, a vertical shaft carrying water to the base of the ice sheet. Source: Roger Braithwaite, Univ. Manchester (U.K.).

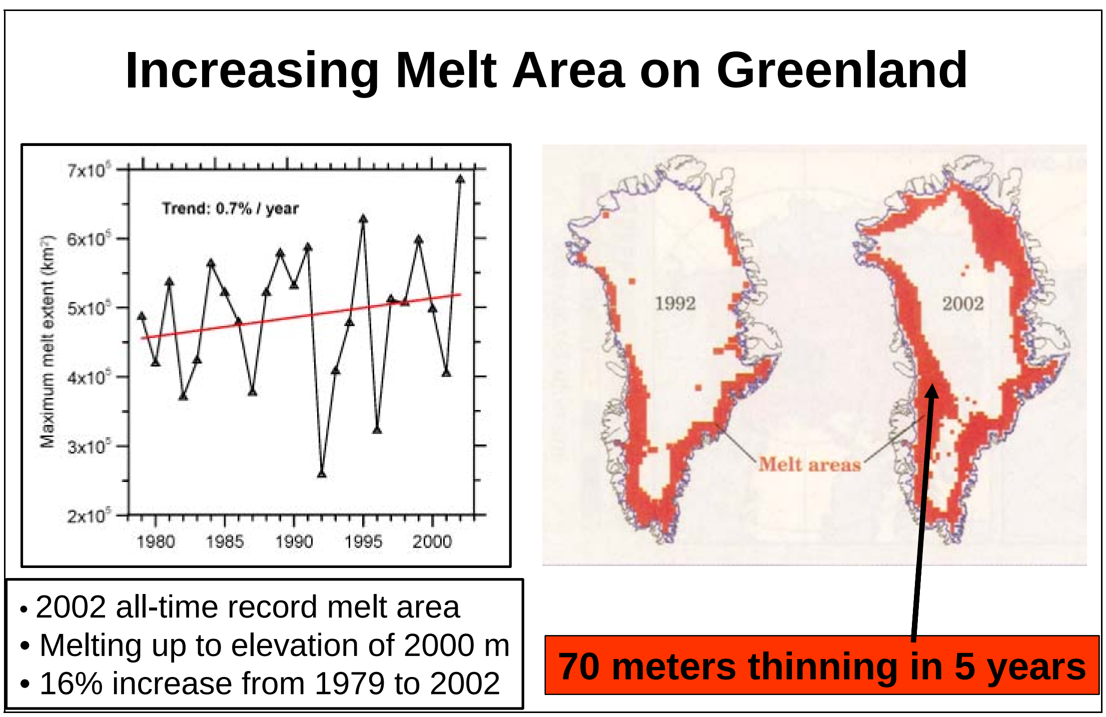

Fig. 18. Increasing area with summer melt on Greenland. The satellite-era record melt area of 2002 was exceeded in 2005. Source: Waleed Abdalati, Goddard Space Flight Center.

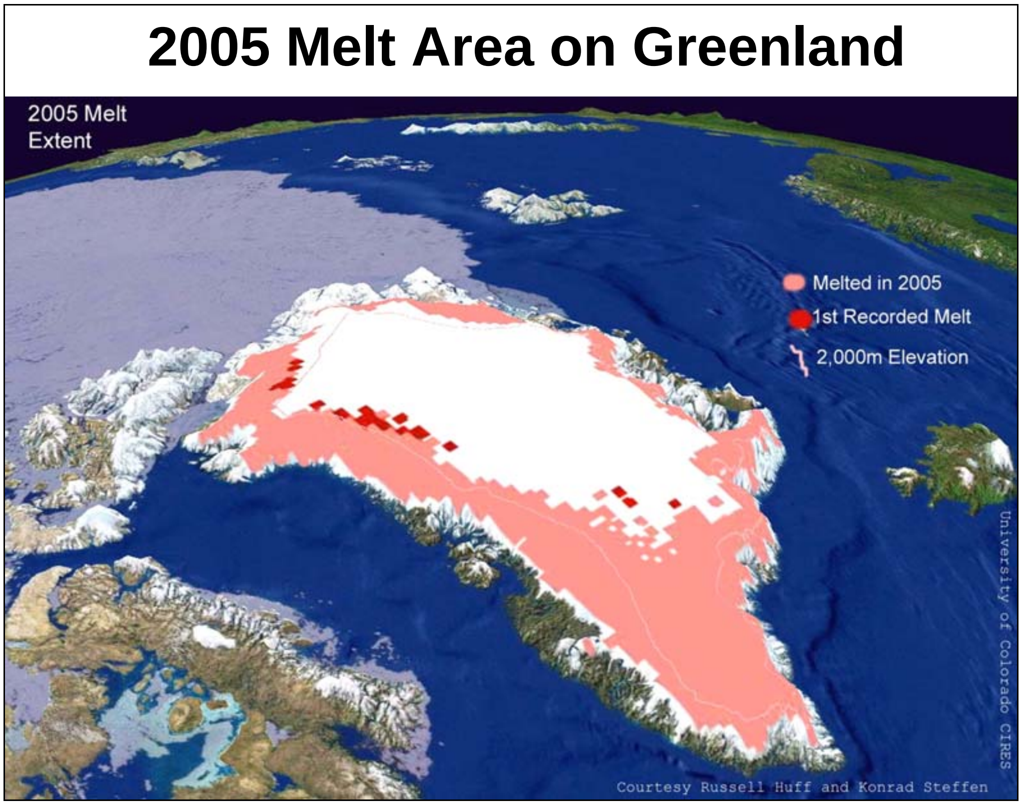

Fig. 19. Area on Greenland with summer melt in 2005, the dark red areas having their first recorded melt in the satellite era. Source: Russell Huff and Konrad Steffen, Univ. Colorado.

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.

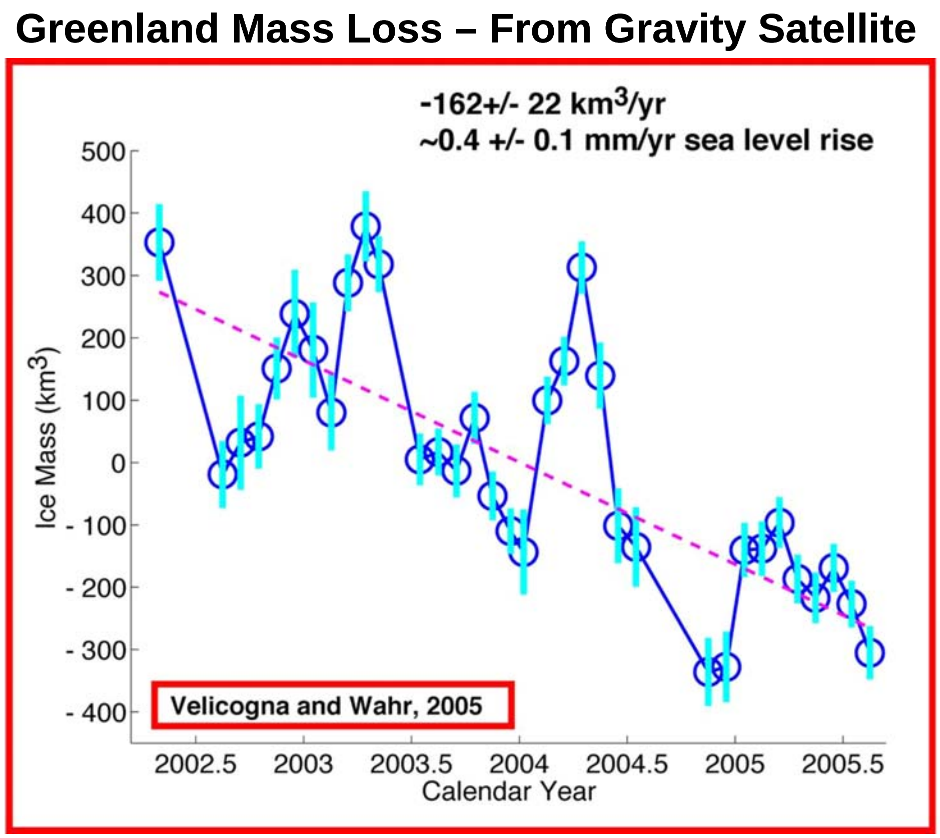

Fig. 21. Mass loss by Greenland as determined from gravity field changes measured by the GRACE satellite. Source: Velicogna and Wahr, Geophys. Res. Lett., 2005.

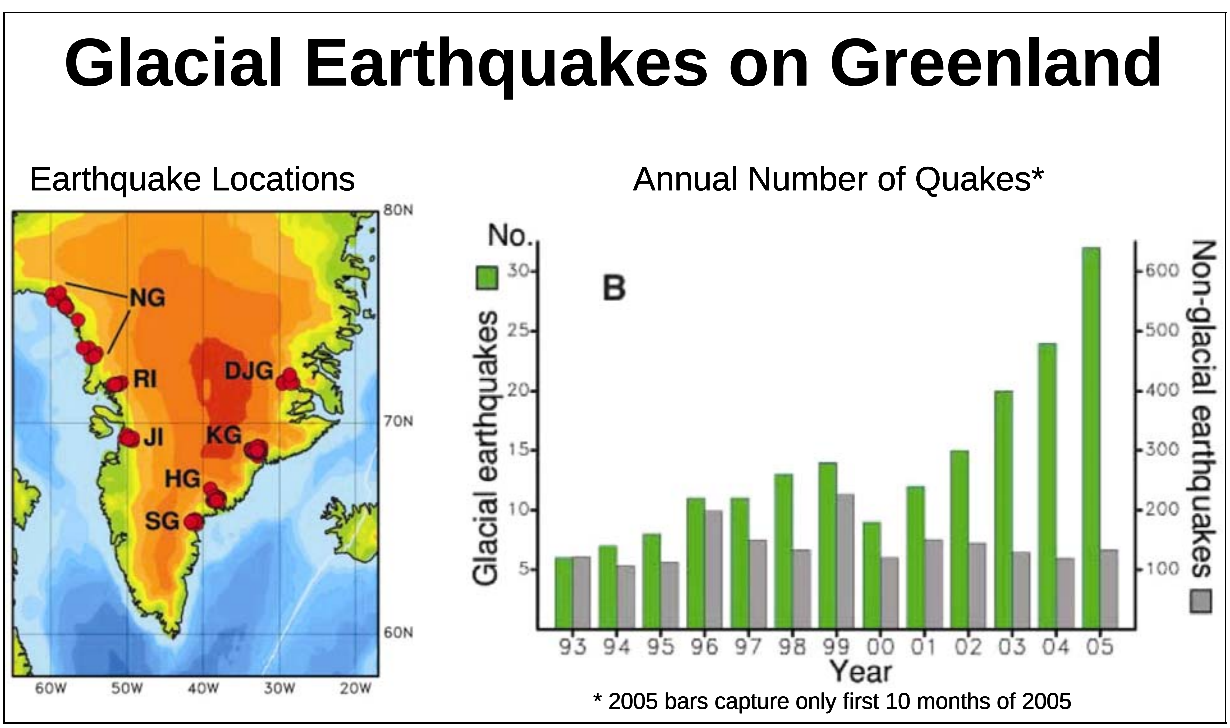

Fig. 22. Location and frequency of earthquakes on Greenland. Magnitudes of the earthquakes are in the range 4.6 to 5.1. Source: Ekstrom, Nettles and Tsai, Science, 311, 1756, 2006.

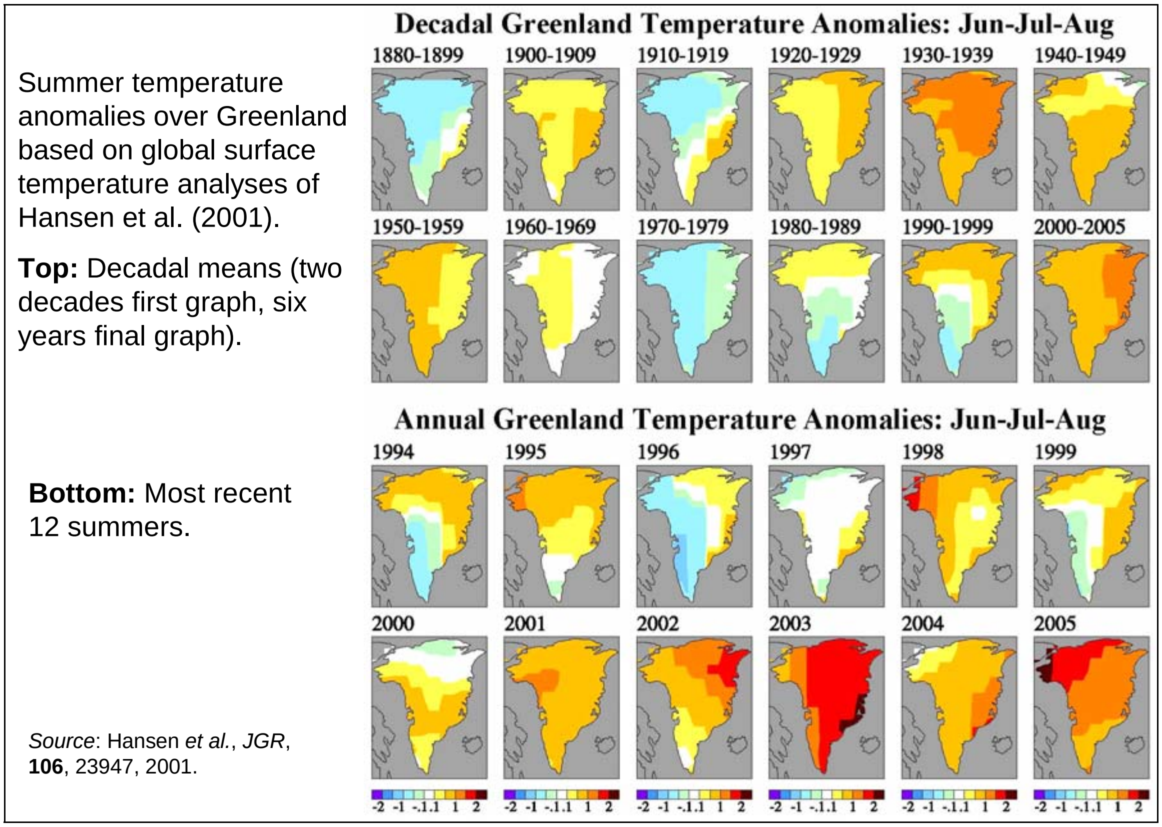

Fig. 23. Decadal (top) and annual summer temperature anomalies over Greenland as estimated from limited station measurements. Source: Hansen et al., JGR, 106, 23947, 2001.

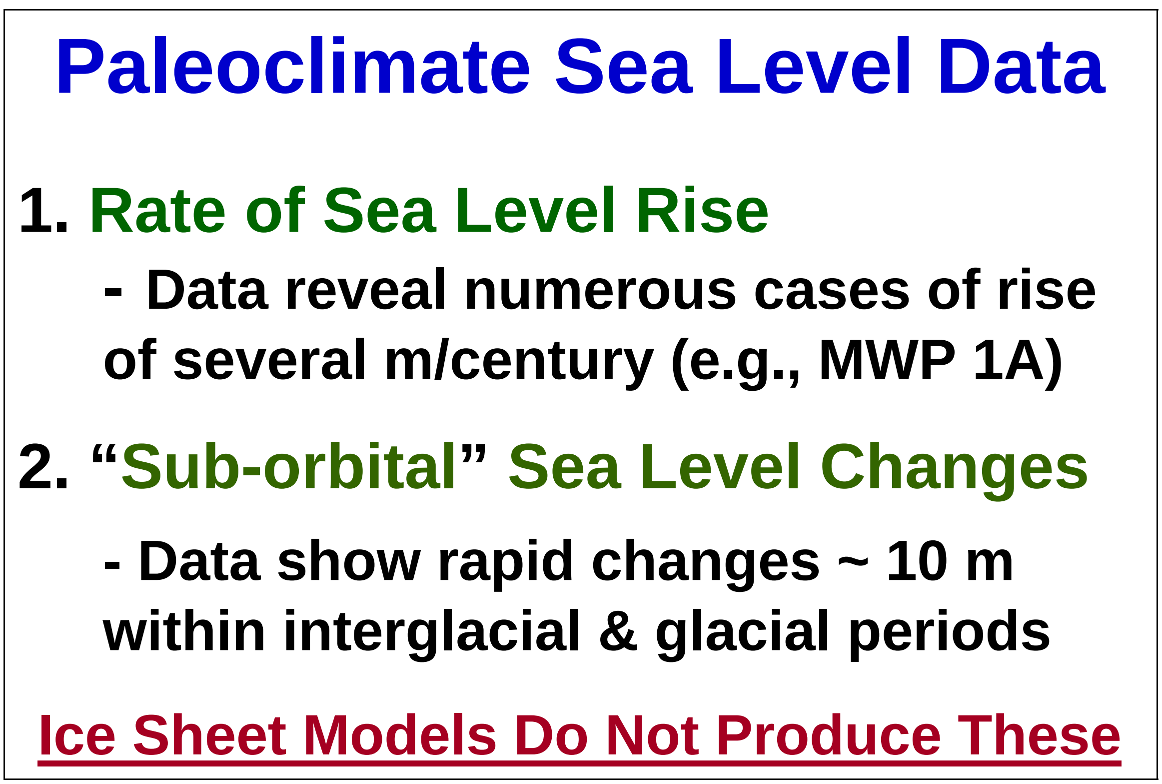

Fig. 24. Comments re: paleoclimate sea level data. Source: Hansen, Amer. Geo. Union, U23D-01, Dec. 6, http://www.columbia.edu/~jeh1, 2005.

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.

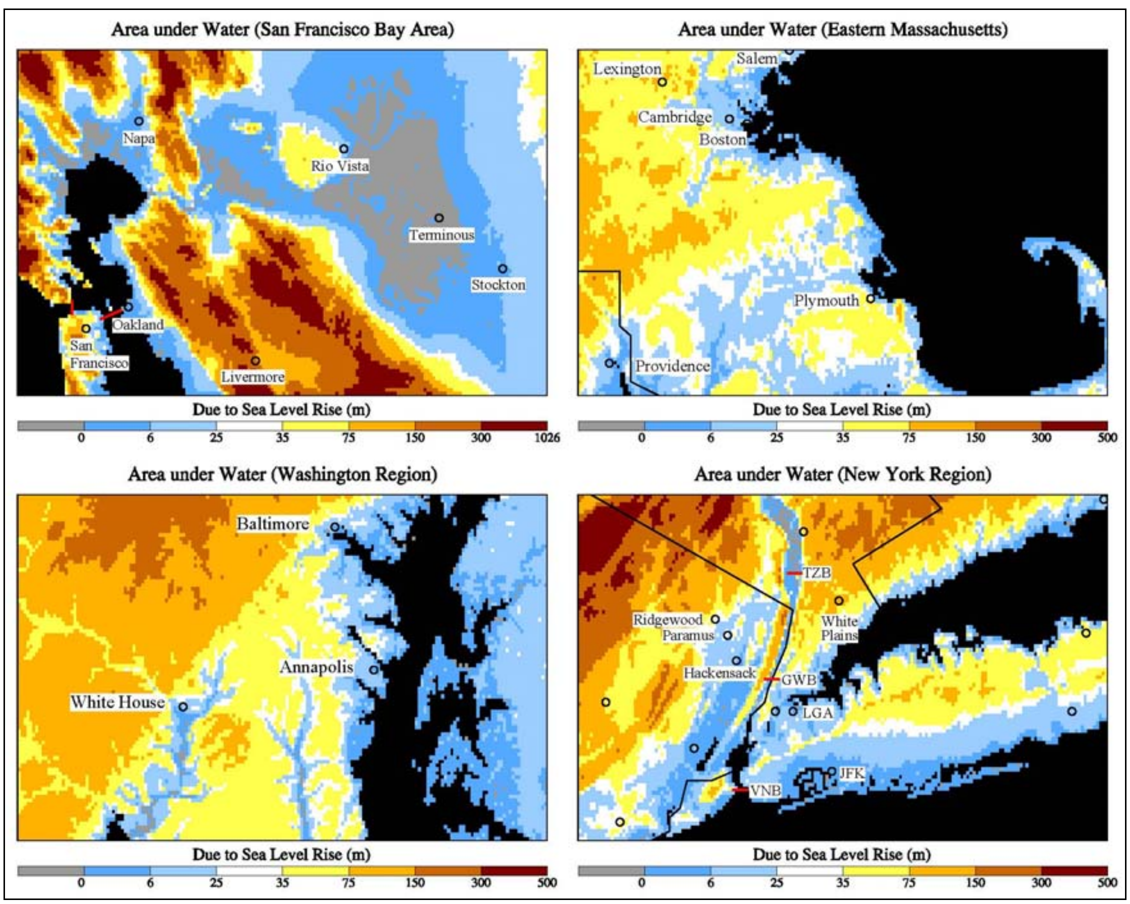

Fig. 26. Additional area under water for sea level rise of 6 m (dark blue), 25 m (light blue), 35 m (white), and 75 m (yellow) for San Francisco, Boston, Washington and New York City regions.

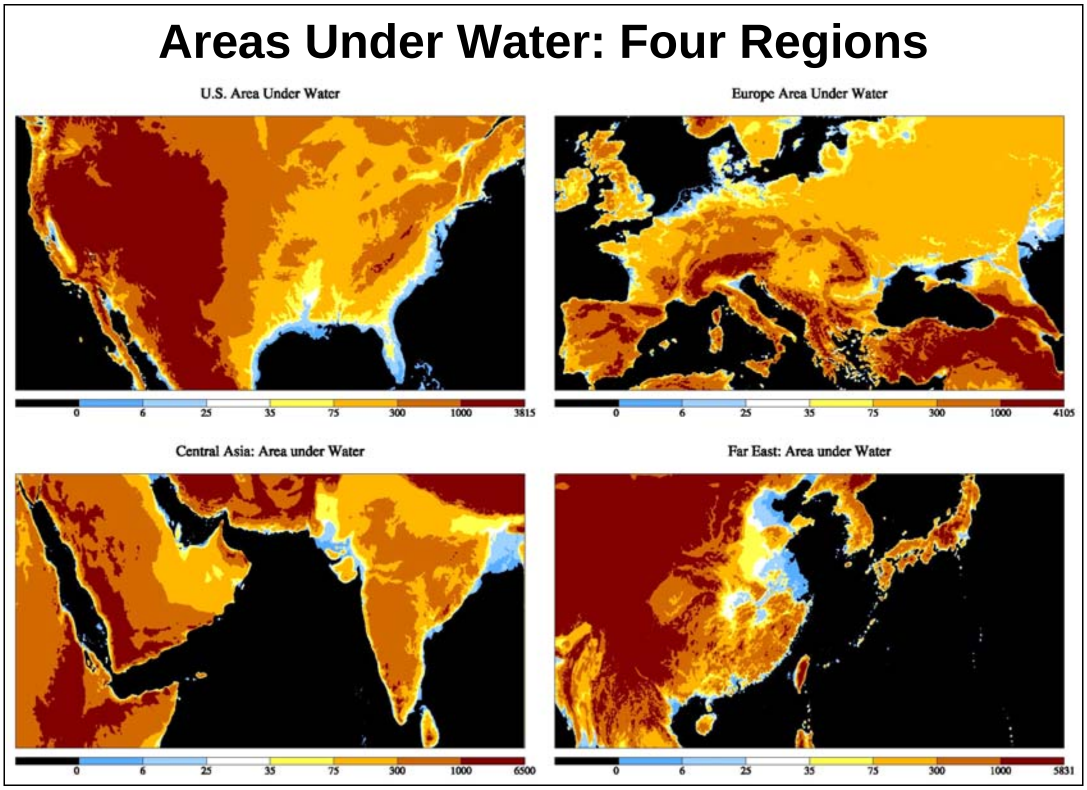

Fig. 27. Additional area under water for sea level rise of 6 m (dark blue), 25 m (light blue), 35 m (white), and 75 m (yellow) in regions focused on the United States, Europe, India and China.

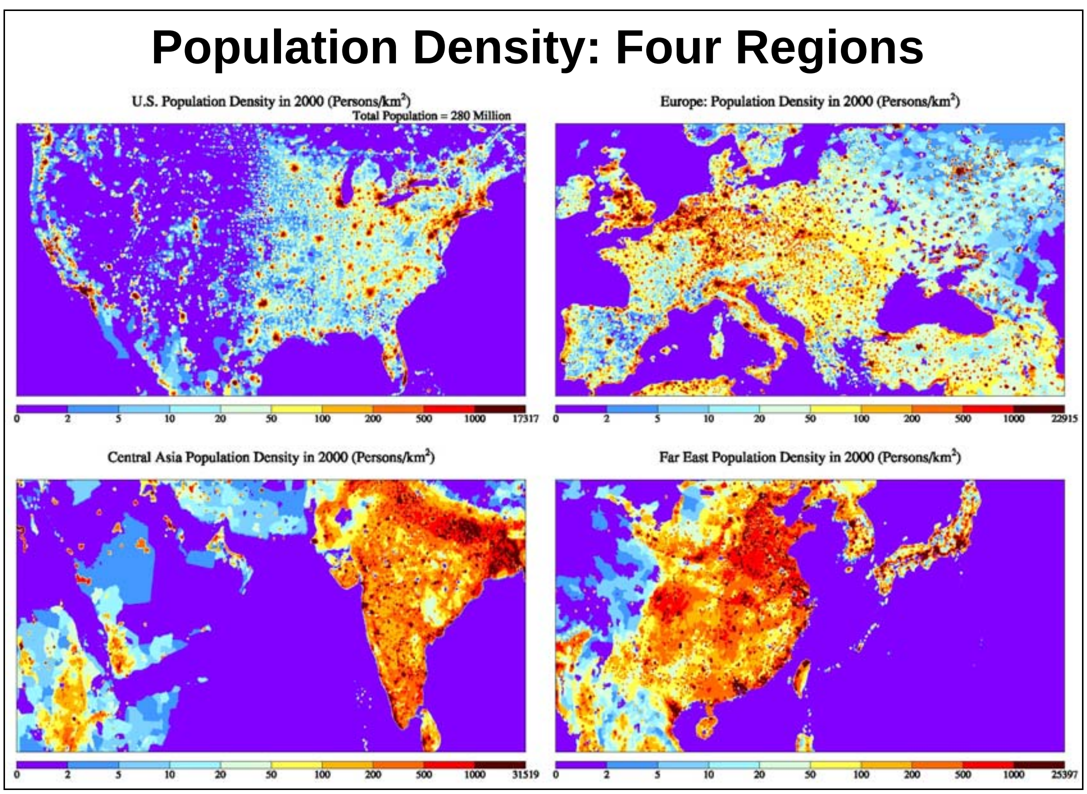

Fig. 28. Population density of the four regions shown in the preceding sea level maps.

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.

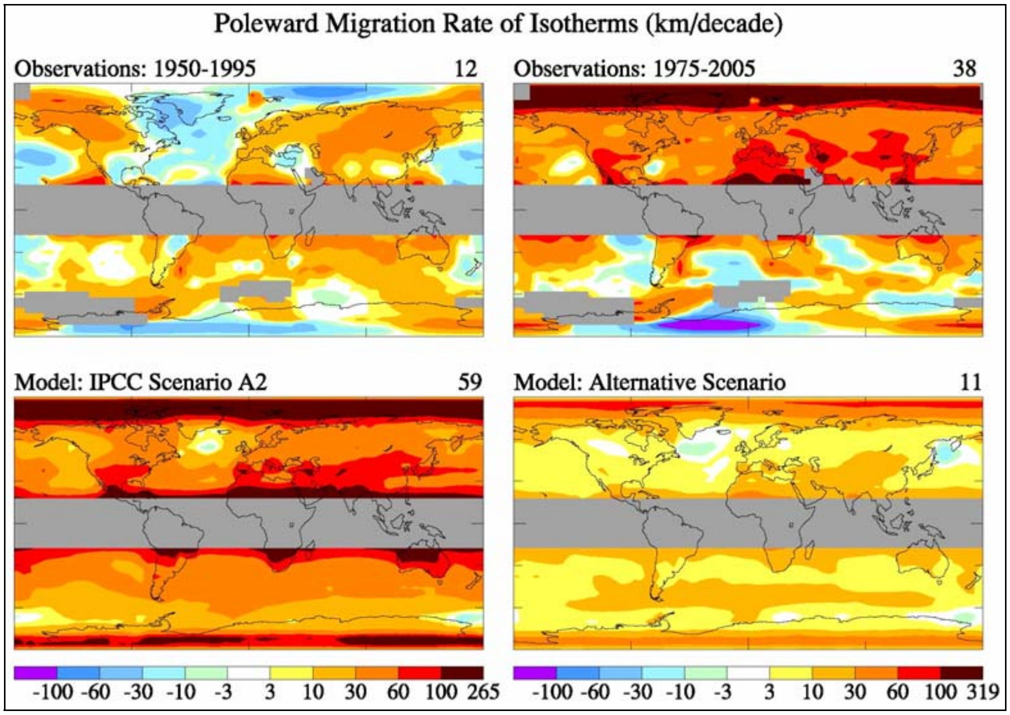

Fig. 33. Poleward migration rate of isotherms based on observed surface temperatures for two periods and in 21st century simulations for IPCC scenario A2 and the Alternative scenario.

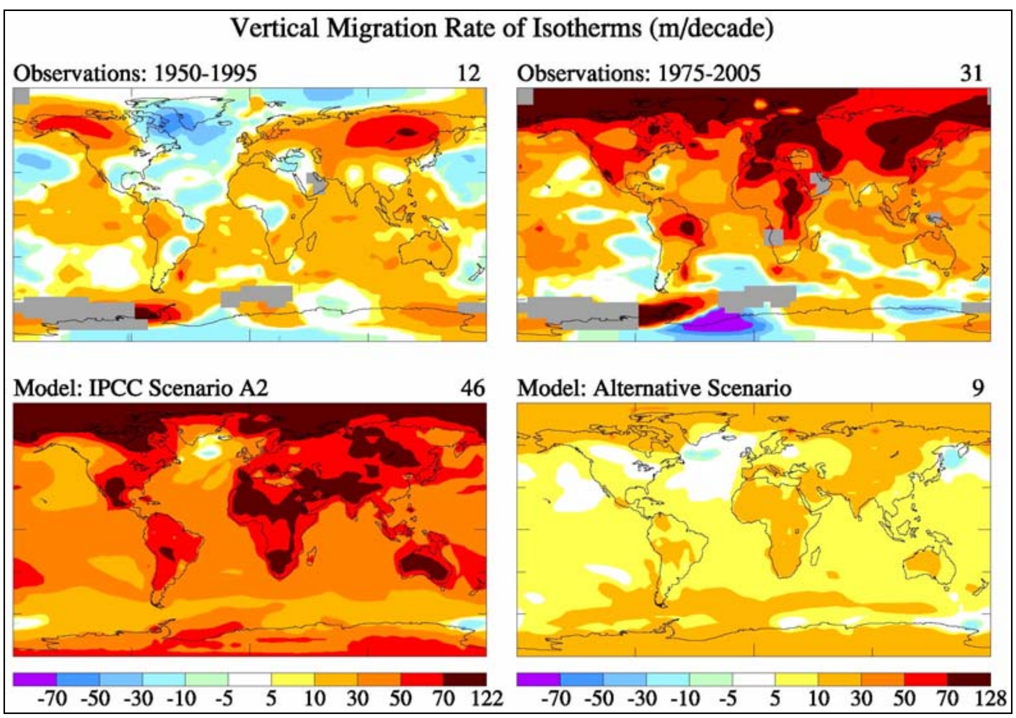

Fig. 34. Vertical migration rate of isotherms based on observations for two periods and in 21st century simulations for IPCC scenario A2 and the Alternative scenario.

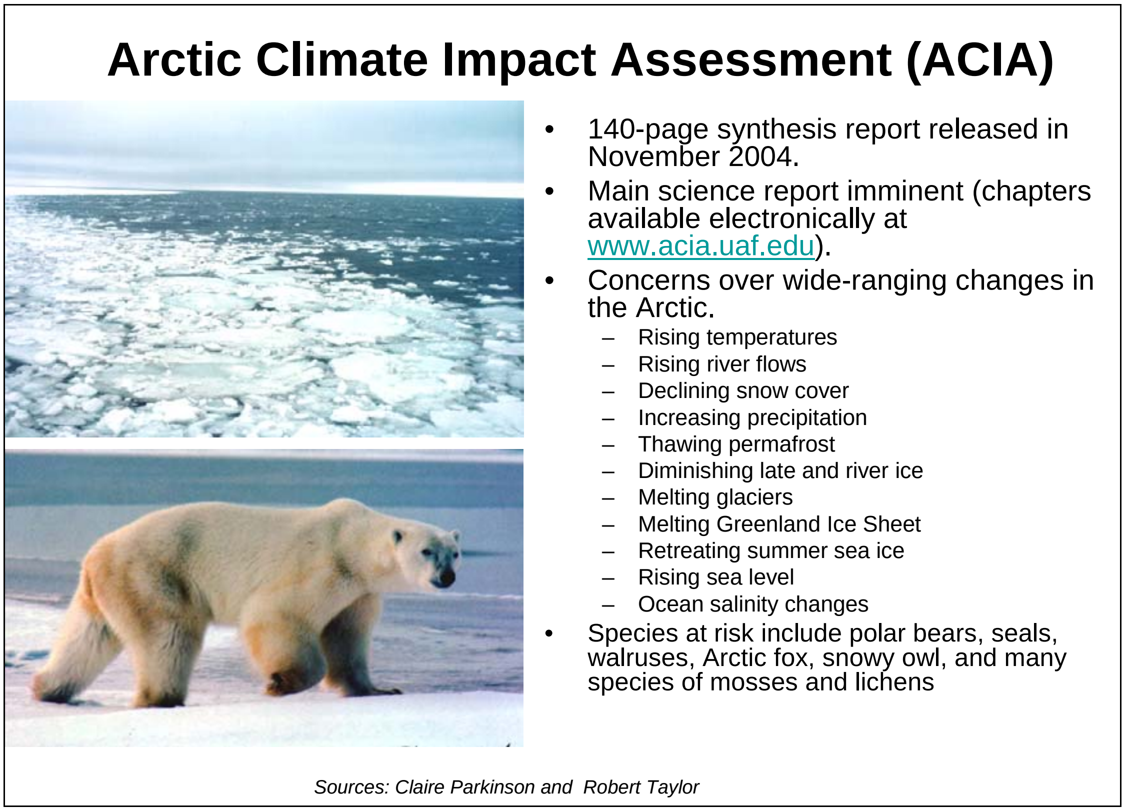

Fig. 35. Arctic climate impact assessment (www.acia.uaf.edu).

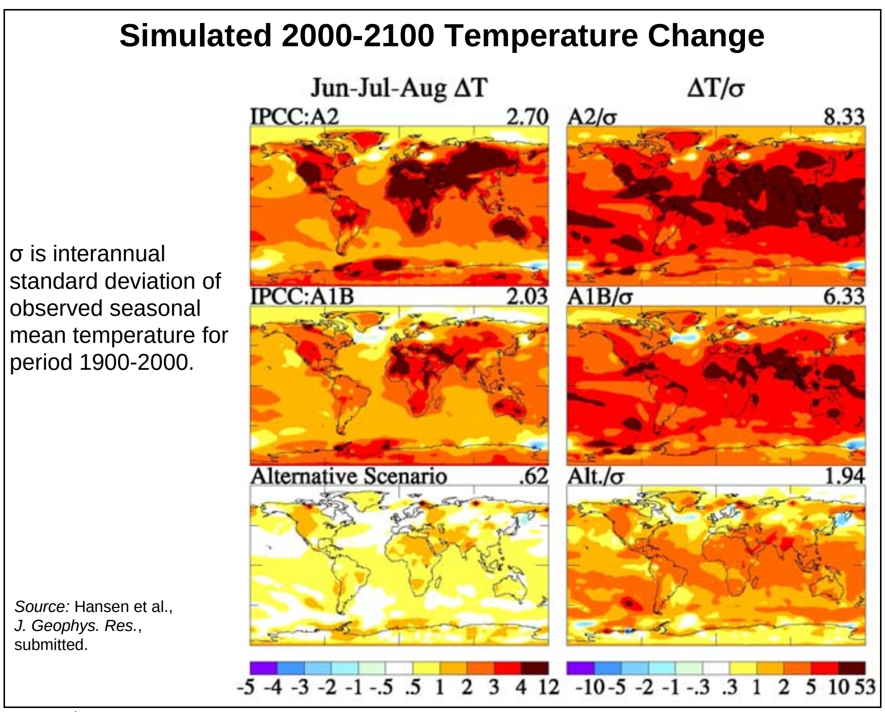

Fig. 36. Simulated 21st century seasonal (Jun-Jul-Aug) temperature change for Business-as-Usual and Alternative GHG scenarios, and the ratio of temperature change to the observed standard deviation of temperature in the prior century. Source: Hansen et al., J. Geophys. Res., in review, 2006.

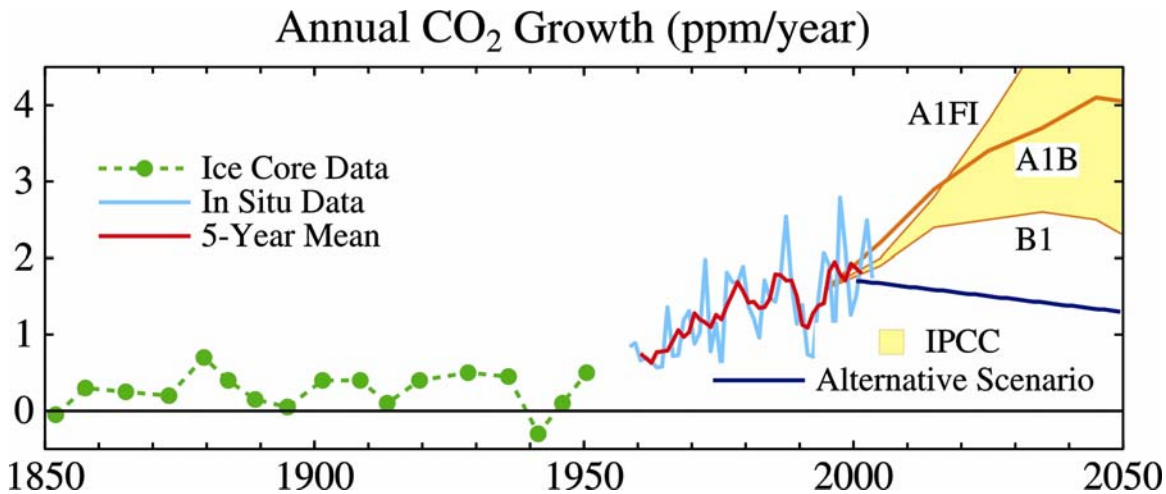

Fig. 37. Annual growth of atmospheric CO_2 (ppm/year) in observations and scenarios. Source: Hansen and Sato, PNAS, 101, 16109, 2004.

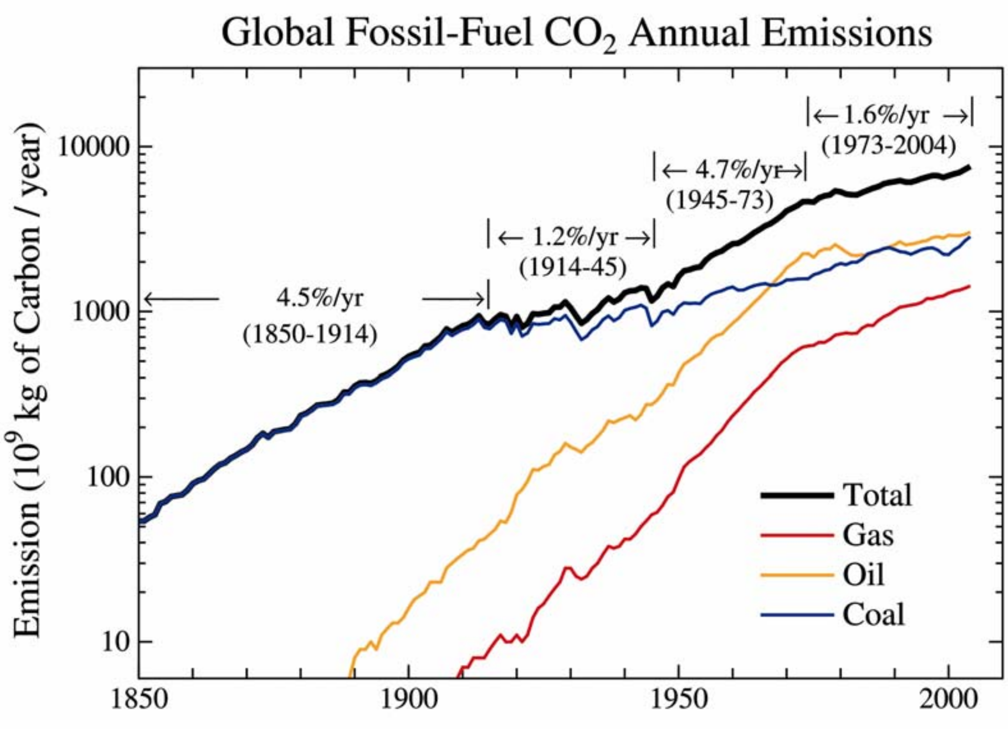

Fig. 38. Global fossil fuel annual CO_2 emissions based on data of Marland and Boden (DOE, Oak Ridge) and recent data from British Petroleum that is normalized in year of overlap with Marland and Boden data. Source: Hansen and Sato, PNAS, 98, 14778, 2001.

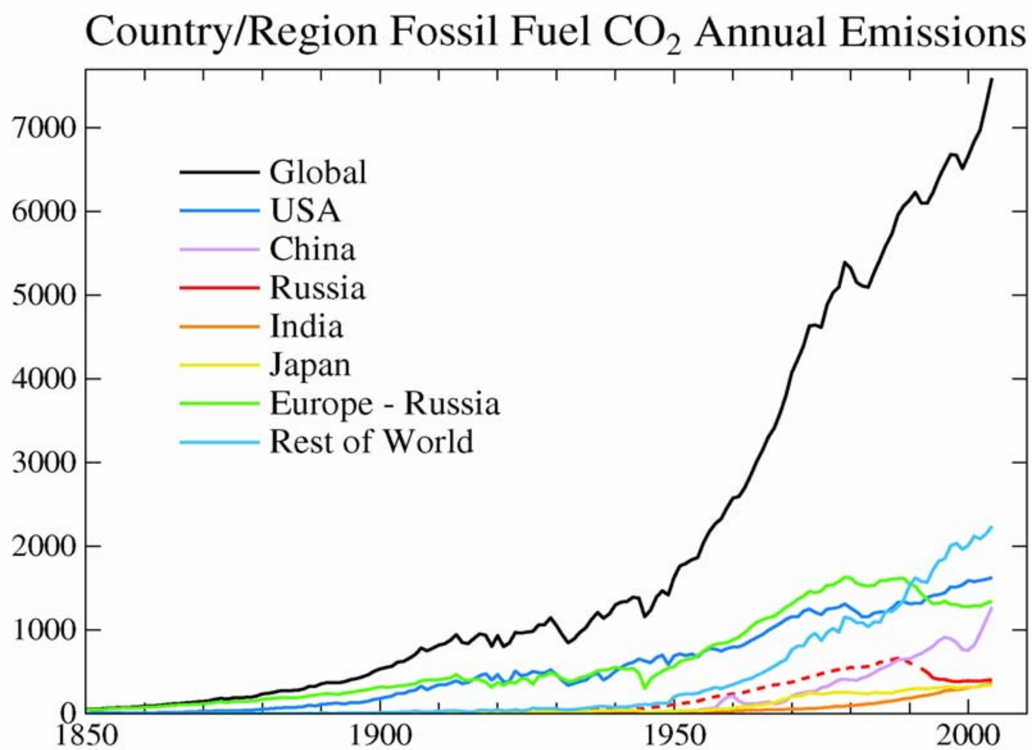

Fig. 39. CO_2 fossil fuel emissions data as in previous figure, but on a linear scale and divided into source regions. Source: Hansen et al., J. Geophys. Res., in review, 2006.

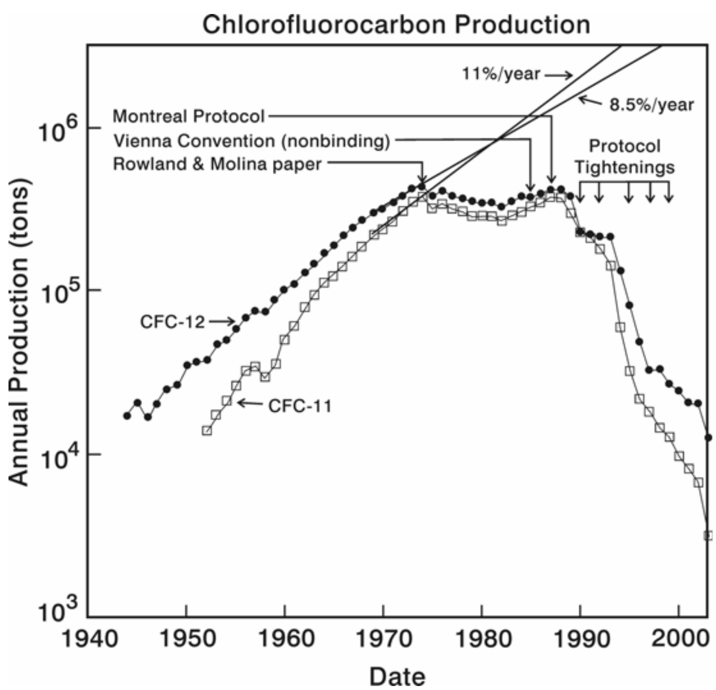

Fig. 40. Chlorofluorocarbon production (CFC-11 and CFC-12) versus time. Source: update of Hansen et al., JGR, 94, 16417, 1989.

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, uninterested

↓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.

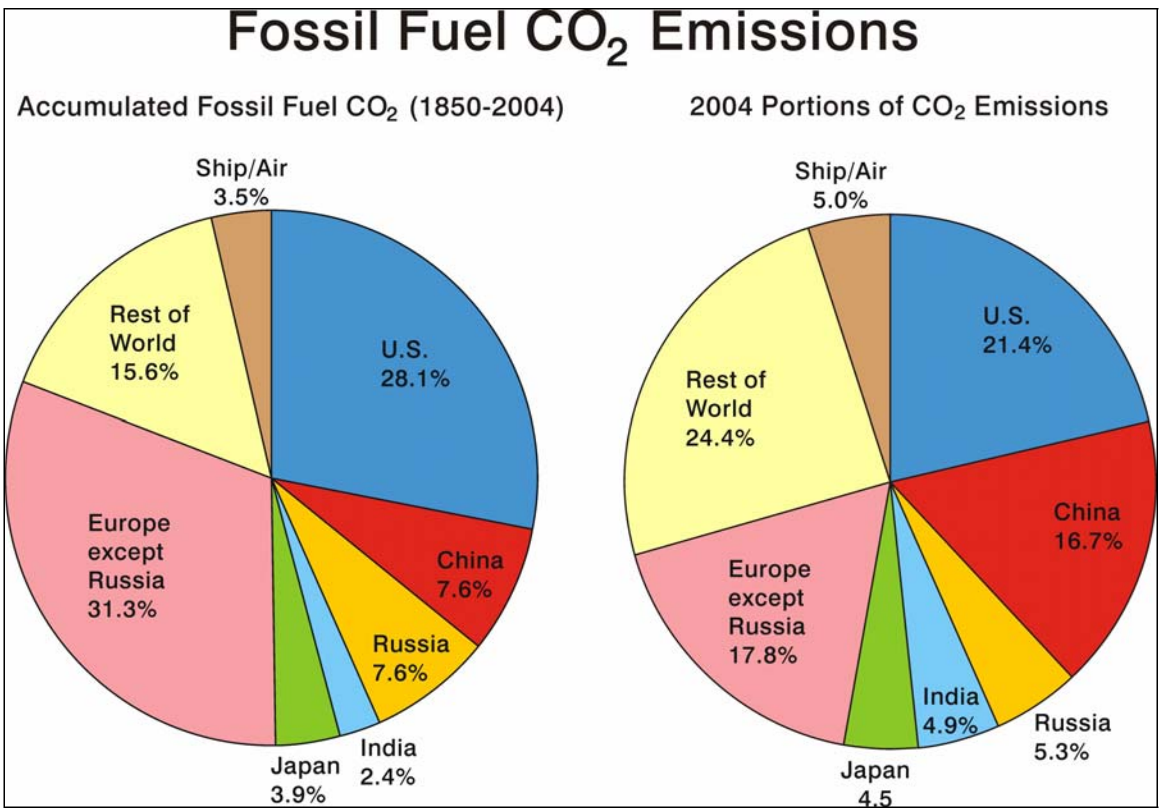

Fig. 44. Apportionment of accumulated (1850-2004) and recent (2004) fossil fuel CO_2 emissions.

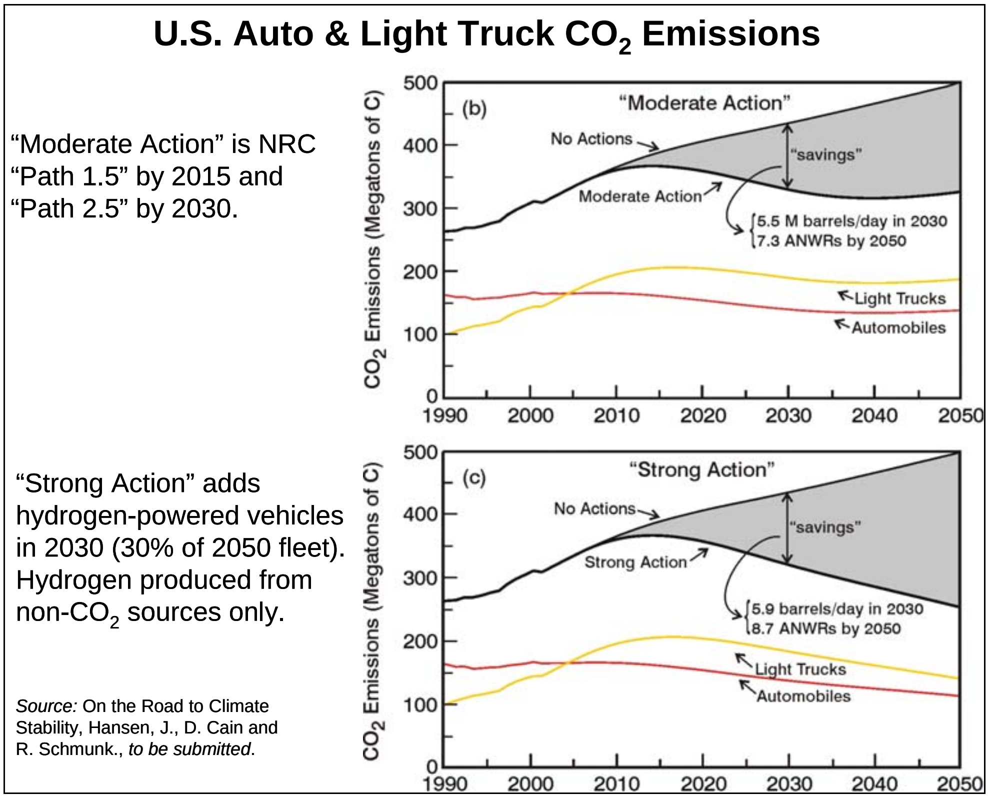

Fig. 45. CO_2 emissions by automobiles and light trucks in the United States based on past real-world data and alternative scenarios. ANWR refers to the amount of oil estimated by the United States USGS to exist in the Arctic National Wildlife Refuge. Source: Hansen et al., unpublished manuscript, 2005.

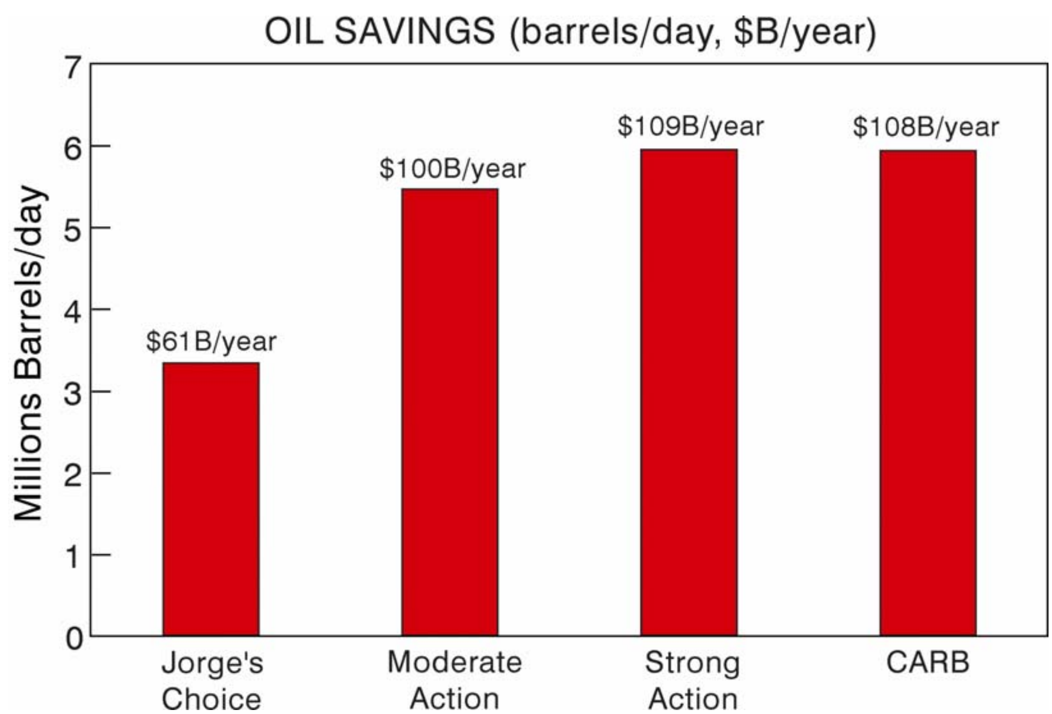

Fig. 46. Oil savings (barrels/day and $B/year) that would be saved in 2004 dollars at a price of $50 per barrel. Source: Source: Hansen et al., unpublished manuscript, 2005.

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?