

Testimony of James Hansen before the Iowa State Utilities Board 2008

It can only be concluded that to prevent dangerous interference with the climate system this century we should be using a climate sensitivity of 4.5°C rising to 6° C , considerably higher than 3° C !

This is a very slightly shortened version of James Hansen's 2008 testimony to the Iowa Utilities Board arguing against a permit for the construction of a new coal fired power plant.

This makes a useful guide to important aspects of the climate system which also answers many of the arguments of the climate denial campaign.

The most important aspect is with respect to the climate sensitivity. Hansen explains that the single metric of climate sensitivity, namely 3° C for a doubling of atmospheric carbon dioxide, applies to the 20th century satisfactorily but does not apply to this 21st century.

This he explains is the difference between fast climate feedbacks and slow climate feedbacks.

The positive fast feedbacks, that amplifies the global temperature increase from the heat radiation of the atmospheric greenhouse gases alone, is essentially the water vapour feedback and clouds.

There is a fast negative cooling feedback due to air pollution aerosols which Hansen says has reduced the greenhouse gas global warming by half..

During this century the fast feedback climate sensitivity of 3 C will increase by the operation of slow feedbacks to 6° C. Hansen says the slow feedback effect is in the main due to albedo changes to the planet which is the loss of the ice sheets and the spread of forests. Carbon feedbacks from permafrost and subsea methane hydrates are also slow feedbacks.

Hansen says that the record of the paleo-climate from the ice cores is to be relied on more than the projections of the scientists climate models.

Hansen also responds to what constitutes dangerous interference with the climate system which he says it is in the main the loss of ice sheets and the rise of global sea level . He also includes the increased extinction of species and makes an inference to regional food security but only in the United States . These are not the metrics defined by the 1992 UN framework convention on climate change.

2008

STATE OF IOWA
BEFORE THE IOWA UTILITIES BOARD

IN RE:

DOCKET NO. GCU-07-1

INTERSTATE POWER AND LIGHT
COMPANY

DIRECT TESTIMONY OF JAMES E. HANSEN

Q. Please state your name and business address.

A. My name is James E. Hansen. My business address is 2880 Broadway, New York, New York 10025.

Q. By whom are you presently employed and in what capacity?

A. I am employed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), which has its home base in Greenbelt, Maryland. I am the director of the Goddard Institute for Space Studies (GISS), which is a division of GSFC located in New York City. I am also a senior scientist in the Columbia University Earth Institute and an Adjunct Professor of Earth and Environmental Sciences at Columbia. I am responsible for defining the research direction of the Goddard Institute, obtaining research support for the Institute, carrying out original scientific research directed principally toward understanding global change, and providing relevant information to the public. I am testifying here as a private citizen, a resident of Kintnersville, Pennsylvania on behalf of the planet, of life on Earth, including all species.

Q. How can one power plant in Iowa be of any significance in comparison with many power-plants in China?

A. The Iowa power plant can make an important difference because of tipping points in the climate system, tipping points in life systems, and tipping points in social behavior. A tipping point occurs in a system with positive feedbacks. When forcing toward a change, and change itself, become large enough, positive feedbacks can cause a sudden acceleration of change with very little, if any, additional forcing.

**Arctic sea ice
tipping point**

Arctic sea ice is an example of a tipping point in the climate system. As the warming global ocean transports more heat into the Arctic, sea ice cover recedes and the darker open ocean surface absorbs more sunlight. The ocean stores the added heat, winter sea ice is thinner, and thus increased melting can occur in following summers, even though year-to-year variations in sea ice area will occur with fluctuations of weather patterns and ocean heat transport.

Arctic sea ice loss can pass a tipping point and proceed rapidly. Indeed, the Arctic sea ice tipping point has been reached. However, the feedbacks driving further change are not 'runaway' feedbacks that proceed to loss of all sea ice without continued forcing. Furthermore, sea ice loss is reversible. If human-made forcing of the climate system is reduced, such that the planetary energy imbalance becomes negative, positive feedbacks will work in the opposite sense and sea ice can increase rapidly, just as sea ice decreased rapidly when the planetary energy imbalance was positive.

**Cut coal
essential**

Planetary energy imbalance can be discussed quantitatively later, including all of the factors that contribute to it. However, it is worth noting here that the single most important action needed to decrease the present large planetary imbalance driving climate change is curtailment of CO₂ emissions from coal burning. Unless emissions from coal burning are reduced, actions to reduce other climate forcings cannot stabilize climate.

**Ice sheet
tipping point**

The most threatening tipping point in the climate system is the potential instability of large ice sheets, especially West Antarctica and Greenland. If disintegration of these ice sheets passes their tipping points, dynamical collapse of the West Antarctic ice sheet and part of the Greenland ice sheet could proceed out of our control. The ice sheet tipping point is especially dangerous because West Antarctica alone contains enough water to cause about 20 feet (6 meters) of sea level rise.

Hundreds of millions of people live less than 20 feet above sea level. Thus the number of people affected would be 1000 times greater than in the New Orleans Katrina disaster. Although Iowa would not be directly affected by sea level rise, repercussions would be worldwide.

Sea level

Ice sheet tipping points and disintegration necessarily unfold more slowly than tipping points for sea ice, on time scales of decades to centuries, because of the greater inertia of thick ice sheets. But that inertia is not our friend, as it also makes ice sheet disintegration more difficult to halt once it gets rolling. Moreover, unlike sea ice cover, ice sheet disintegration is practically irreversible. Nature requires thousands of years to rebuild an ice sheet. Even a single millennium, about 30 generations for humans, is beyond the time scale of interest or comprehension to most people.

Because of the danger of passing the ice sheet tipping point, even the emissions from one Iowa coal plant, with emissions of 5,900,000 tons of CO₂ per year and 297,000,000 over 50 years could be important as “the straw on the camel’s back”. The Iowa power plant also contributes to tipping points in life systems and human behavior.

Species extinction

Q. How can Iowa contribute to tipping points in life systems and human behavior?

There are millions of species of plants and animals on Earth. These species depend upon each other in a tangled web of interactions that humans are only beginning to fathom. Each species lives, and can survive, only within a specific climatic zone. When climate changes, species migrate in an attempt to stay within their climatic niche. However, large rapid climate change can drive most of the species on the planet to extinction. Geologic records indicate that mass extinctions, with loss of more than half of existing species, occurred several times in the Earth's history. New species developed, but that process required hundreds of thousands, even millions, of years. If we destroy a large portion of the species of creation, those that have existed on Earth in recent millennia, the Earth will be a far more desolate planet for as many generations of humanity as we can imagine.

Today, as global temperature is increasing at a rate of about 0.2°C (0.36°F) per decade, isotherms (a line of a given average temperature) are moving poleward at a rate of about 50-60 km (35 miles) per decade (Hansen et al. 2006). Some species are moving, but many can move only slowly, pathways may be blocked as humans have taken over much of the planet, and species must deal with other stresses that humans are causing. If the rate of warming continues to accelerate, the cumulative effect this century may result in the loss of a majority of existing species.

The biologist E.O. Wilson (2006) explains that the 21st century is a "bottleneck" for species, because of extreme stresses they will experience, most of all because of climate change. He foresees a brighter future beyond the fossil fuel era, beyond the human population peak that will occur if developing countries follow the path of developed countries and China to lower fertility rates. Air and water can be clean and we can learn to live with other species of creation in a sustainable way, using renewable energy. The question is: how many species will survive the pressures of the 21st century bottleneck? Interdependencies among species, some less mobile than others, can lead to collapse of ecosystems and rapid nonlinear loss of species, if climate

Q. Alleged implications of continued coal burning without carbon capture are profound and thus require proof of a causal relationship between climate change and CO₂ emissions. What is the nature of recent global temperature change?

A. Figure 1(a) shows global mean surface temperature change over the period during which instrumental measurements are available for most regions of the globe. The warming since the beginning of the 20th century has been about 0.8°C (1.4°F), with three-quarters of that warming occurring in the past 30 years.

Q. Warming of 0.8°C (1.4°F) does not seem very large. It is much smaller than day to day weather fluctuations. Is such a small warming significant?

A. Yes, and it is important. Chaotic weather fluctuations make it difficult for people to notice changes of underlying climate (the average weather, including statistics of extreme fluctuations), but it does not diminish the impact of long-term climate change.

First, we must recognize that global mean temperature changes of even a few degrees or less can cause large climate impacts. Some of these impacts are associated with climate tipping points, in which large regional climate response happens rapidly as warming reaches critical levels. Already today's global temperature is near the level that will cause loss of all Arctic sea ice. Evidence suggests that we are also nearing the global temperature level that will cause the West Antarctic ice sheet and portions of the Greenland ice sheet to become unstable, with potential for very large sea level rise.

Second, we must recognize that there is more global warming "in the pipeline" due to gases humans have already added to the air. The climate system has large thermal inertia, mainly due to the ocean, which averages 4 km (about 2.5 miles) in depth. Because of the ocean's inertia, the planet warms up slowly in response to gases that humans are adding to the atmosphere. If atmospheric CO₂ and other gases stabilized at present amounts, the planet would still warm about 0.5°C (about 1°F) over the next century or two. In addition, there are more gases "in the pipeline" due to existing infrastructure such as power plants and vehicles on the road. Even as the world begins to address global warming with improved technologies, the old infrastructure will add more gases, with still further warming on the order of another 1°F.

Today's
0.8°C
means
a lot

High latitude And ice sheet warming

Third, eventual temperature increases will be much larger in critical high latitude regions than they are on average for the planet. High latitudes take longer to reach their equilibrium (long-term) response because the ocean mixes more deeply at high latitudes and because positive feedbacks increase the response time there (Hansen et al., 1984). Amplification of high latitude warming is already beginning to show up in the Northern Hemisphere. Figure 1(b) is the geographical pattern of mean temperature anomalies for the first six years of the 21st century, relative to the 1951-1980 base period. Note that warming over land areas is larger than global mean warming, an expected consequence of the large ocean thermal inertia. Warming is larger at high latitudes than low latitudes, primarily because of the ice/snow albedo feedback. Warming is larger in the Northern Hemisphere than in the Southern Hemisphere, primarily because of greater ocean area in the Southern Hemisphere, and the fact that the entire Southern Ocean surface around Antarctica is cooled by deep mixing. Also human-caused depletion of stratospheric ozone, a greenhouse gas, has reduced warming over most of Antarctica. This ozone depletion and CO₂ increase have cooled the stratosphere, increased zonal winds around Antarctica, and thus warmed the Antarctic Peninsula while limiting warming of most of the Antarctic continent (Thompson and Solomon, 2002; Shindell and Schmidt, 2004).

Until the past several years, warming has also been limited in Southern Greenland and the North Atlantic Ocean just southeast of Greenland, an expected effect of deep ocean mixing in that vicinity. However, recent warming on Greenland is approaching that of other landmasses at similar latitudes in the Northern Hemisphere. On the long run, warming on the ice sheets is expected to be at least twice as large as global warming. Amplification of warming at high latitudes has practical consequences for the entire globe, especially via effects on ice sheets and sea level. High latitude amplification of warming is expected on theoretical grounds, it is found in climate models, and it is confirmed in paleoclimate (ancient climate) records.

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In the pipe line

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Paleoclimate data, indeed, reveal large climate changes. But that history of ancient climate changes shows that modest forcing factors can produce large climate change. In fact, paleoclimate data provide our most accurate and certain measure of how sensitive global climate is to climate forcings, including human-made climate forcings.

Climate sensitivity

Q. How can the paleoclimate data reveal the climate sensitivity to forcings?

A. We compare different climate states in the Earth's history, thus obtaining a measure of how much climate responded to climate forcings in the past. In doing this, we must define climate forcings and climate feedbacks clearly. Alternative choices for forcings and feedbacks are appropriate, depending on the time scale of interest.

A famous definition of climate sensitivity is from the 'Charney' problem, in which it is assumed that the distributions of ice sheets and vegetation on the Earth's surface are fixed and the question is asked: how much will global temperature increase if the amount of CO_2 in the air is doubled? The Charney (1979) climate sensitivity is most relevant to climate change on the decadal time scale, because ice sheets and forest cover would not be expected to change much in a few decades or less. However, the Charney climate sensitivity must be recognized as a theoretical construct. Because of the large thermal inertia of the ocean, it would require several centuries for the Earth to achieve its equilibrium response to doubled CO_2 , and during that time changes of ice sheets and vegetation could occur as 'feedbacks', i.e., as responses of the climate system that engender further climate change. Feedbacks can either magnify or diminish climate changes, these effects being defined as positive and negative feedbacks, respectively.

Climate feedbacks include changes of atmospheric gases and aerosols (fine particles in the air). Gases that change in response to climate change include water vapor, but also the long-lived greenhouse gases, CO_2 , CH_4 and N_2O .

Climate sensitivity

Q. Is water vapor not a stronger greenhouse gas than these others?

A. Yes, and that is sometimes a source of confusion. Water vapor readily evaporates into and condenses out of the atmosphere. The amount of H_2O in the air is a function of the climate, primarily a function of temperature. The air holds more water vapor in the summer than in winter, for example. Water vapor is a prime example of what we call 'fast' feedbacks, those feedbacks that respond promptly to changes of climate. Because H_2O causes a strong greenhouse effect, and tropospheric H_2O increases with temperature, it provides a positive feedback.

The Charney climate sensitivity includes the effects of fast feedbacks such as changes of water vapor and clouds, but it excludes slow feedbacks such as ice sheets. We obtain an empirical measure of the equilibrium Charney climate sensitivity by comparing conditions on Earth during the last ice age, about 20,000 years ago with the conditions in the present interglacial period prior to major human-made effects. Averaged over a period of say 1000 years, the planet in each of these two states, glacial and interglacial, had to be in energy balance with space within a small fraction of 1 W/m^2 . Because the amount of incoming sunlight was practically the same in both periods, the 5°C difference in global temperature between the ice age and the interglacial period had to be maintained by changes of atmospheric composition and changes of surface conditions. Both of these are well known.

Figure 5 shows that there was a lesser amount of long-lived greenhouse gases in the air during the last ice age. These gases affect the amount of thermal radiation to space, and they have a small impact on the amount of absorbed solar energy. We can compute the climate forcing due to the glacial-interglacial change of CO_2 , CH_4 , and N_2O with high accuracy. The effective climate forcing (Hansen et al. 2005a), including the indirect effect of CH_4 on other gases, is $3 \pm 0.5 \text{ W/m}^2$.

Changes on the Earth's surface also alter the energy balance with space. The greatest change is due to the large ice sheets during the last ice age, whose high albedo ('whiteness' or reflectivity) caused the planet to absorb less solar radiation. Smaller effects were caused by the altered vegetation distribution and altered shorelines due to lower sea level during the ice age. The climate forcing due to all these surface changes is $3.5 \pm 1 \text{ W/m}^2$ (Hansen et al. 1984).

Thus the glacial-interglacial climate change of 5°C was maintained by a forcing of about 6.5 W/m^2 , implying a climate sensitivity of about $\frac{3}{4}^\circ\text{C}$ per W/m^2 . This empirical climate

Climate sensitivity

This empirical climate sensitivity includes all fast feedbacks that exist in the real world, including changes of water vapor, clouds, aerosols, and sea ice. Doubled CO_2 is a forcing of 4 W/m^2 , so the Charney climate sensitivity is $3 \pm 1^\circ\text{C}$ for doubled CO_2 . Climate models yield a similar value for climate sensitivity, but the empirical result is more precise and it surely includes all real world processes with 'correct' physics.

Q. This climate sensitivity was derived from two specific points in time. How general is the conclusion?

A. We can check climate sensitivity for the entire past 425,000 years. Ice cores (Figure 5) provide a detailed record of long-lived greenhouse gases. A measure of surface conditions is provided by sediment cores from the Red Sea (Siddall et al. 2003) and other places, which yield a record of sea level change (Figure 6a). Sea level tells us how large the ice sheets were, because water that was not in the ocean was locked in the ice sheets. Greenhouse gas and sea level records allow us to compute the climate forcings due to both atmospheric and surface changes for the entire 425,000 years (Hansen et al. 2007a).

When the sum of greenhouse gas and surface albedo forcings (Figure 6b) is multiplied by the presumed climate sensitivity of $3/4^\circ\text{C}$ per W/m^2 the result is in remarkably good agreement with 'observed' global temperature change (Figure 6c) implied by Antarctic temperature change. Therefore this climate sensitivity has general validity for this long period. This is the Charney climate sensitivity, which includes fast feedback processes but specifies changes of greenhouse gases and surface conditions.

It is important to note that these changing boundary conditions (the long-lived greenhouse gases and surface albedo) are themselves feedbacks on long time scales. The cyclical climate changes from glacial to interglacial times are driven by very small forcings, primarily by minor perturbations of the Earth's orbit about the sun and by the tilt of the Earth's spin axis relative to the plane of the orbit.

Q. Can you clarify cause and effect for these natural climate changes?

A. Figure 7 is useful for that purpose. It compares temperature change in Antarctica with the greenhouse gas forcing. Temperature and greenhouse gas amounts are obtained from the same ice core, which reduces uncertainty in their sequencing despite substantial uncertainty in absolute dating. There is still error in dating temperature change relative to greenhouse gas change, because of the time needed for ice core bubble closure. However, that error is small enough that we can infer, as shown in Figure 7b, that the temperature change tends to slightly precede (by several hundred years) the greenhouse gas changes. Similarly, although the relative dating of sea level and temperature changes are less accurate, it is clear that warming usually precedes ice melt and sea level rise.

Ice core

Data

Feedbacks

These sequencings are not surprising. They show that greenhouse gas changes and ice sheet area changes act as feedbacks that amplify the very weak forcings due to Earth orbital changes. The climate changes are practically coincident with the induced changes of the feedbacks (Figure 7). The important point is that the mechanisms for the climate changes, the mechanisms substantially affecting the planet's radiation balance and thus the temperature, are the atmospheric greenhouse gases and the surface albedo. Earth orbital changes induce these mechanisms to change, for example, as the tilt of the spin axis increases both poles are exposed to increased sunlight. Changed insolation affects the melting of ice and, directly and indirectly,

Q. What is the implication for the present era and the role of humans in climate?

A. The chief implication is that humans have taken control of global climate. This follows from Figure 8, which extends records of the principal greenhouse gases to the present. CO₂, CH₄ and N₂O (not shown) are far outside their range of the past 800,000 years for which ice core records of atmospheric composition are available.

Ice cores show the natural warming out of ice ages is by +ve feedbacks

**Global warming
GHG emissions
have reversed
natural cooling
trend**

Q. Yet the global warming also shown in Figure 8 does not seem to be commensurate with the greenhouse gas increases, if we were to use the paleoclimate as a guide. Can you explain that?

A. Yes. Observed warming is in excellent agreement with climate model calculations for observed greenhouse gas changes. Two factors must be recognized.

First, the climate system has not had enough time to fully respond to the human-made climate forcings. The time scale after 1850 is greatly expanded in Figure 8. The paleoclimate portion of the graph shows the near-equilibrium (~1000 year) response to slowly changing forcings. In the modern era, most of the net human-made forcing was added in the past 30 years, so the ocean has not had time to fully respond and the ice sheets are just beginning to respond to the present forcing.

Second, the climate system responds to the net forcing, which is only about half as large as the greenhouse gas forcing. The net forcing is reduced by negative forcings, especially human-made aerosols (fine particles).

Q. But is not the natural system driving the Earth toward colder climates?

A. If there were no humans on the planet, the long term trend would be toward colder climate. However, the two principal mechanisms for attaining colder climate would be reduced greenhouse gas amounts and increased ice cover. The feeble natural processes that would push these mechanisms in that direction (toward less greenhouse gases and larger ice cover) are totally overwhelmed by human forcings. Greenhouse gas amounts are skyrocketing out of the normal range and ice is melting all over the planet. Humans now control global climate, for better or worse.

Another ice age cannot occur unless humans go extinct, or unless humans decide that they want an ice age. However, 'achieving' an ice age would be a huge task. In contrast, prevention of an ice age is a trivial task for humans, requiring only a 'thimbleful' of CFCs (chlorofluorocarbons), for example. The problem is rather the opposite, humans have already added enough greenhouse gases to the atmosphere to drive global temperature well above any level in the Holocene.

Q. How much warmer will the Earth become for the present level of greenhouse gases?

A. That depends on how long we wait. The Charney climate sensitivity (3°C global warming for doubled CO_2) does not include slow feedbacks, principally disintegration of ice sheets and poleward movement of vegetation as the planet warms. When the long-lived greenhouse gases are changed arbitrarily, as humans are now doing, this change becomes the predominant forcing, and ice sheet and vegetation changes must be included as part of the response in determining long-term climate sensitivity.

**Climate
sensitivity
for
today's
GHGs**

It follows from Figure 7 that equilibrium climate sensitivity is 6°C for doubled CO_2 (forcing of 4 W/m^2) when greenhouse gases are the forcing, not 3°C . (Note: the Antarctic temperature change, shown in Figure 7, is about twice the global mean change.) To achieve this full response we must wait until ice sheets have had time to melt and forests have had time to migrate. This may require hundreds of years, perhaps thousands of years. However, elsewhere (Hansen et al. 2007a) we have discussed evidence that forests are already moving and ice sheet albedos are already responding to global warming, so climate sensitivity is already partially affected by these processes.

Thus the relevant equilibrium climate sensitivity on the century time scale falls somewhere between 3°C and 6°C for doubled CO_2 . The expected temperature change in the 21st century cannot be obtained by simply multiplying the forcing by the sensitivity, as we could in the paleoclimate case, because a century is not long enough to achieve the equilibrium response. Instead we must make computations with a model that includes the ocean thermal inertia, as is done in climate model simulations (IPCC 2007; Hansen et al. 2007b). However, these models do not include realistically all of the slow feedbacks, such as ice sheet and forest dynamics.

**Climate sensitivity is 6°C for the long term equilibrium response.
For this century he implies sensitivity of 4.5°C (upper IPCC range).
But the models do not include all the slow feedbacks.**

- Q. The huge climate changes over the past few hundred thousand years show the dramatic effects accompanying global temperature change of only a few degrees. And you infer climate sensitivity from the documented climate variations. Yet the climate changes and mechanisms are intricate, and it is difficult for the lay person to grasp the details of these analyses. Is there other evidence supporting the conclusion that burning of the fossil fuels will have dramatic effects upon life on Earth?**
- A.** Yes. Climate fluctuations in the Pleistocene (past 1.8 million years) are intricate, as small forcings are amplified by feedbacks, including 'carbon cycle' feedbacks. Atmospheric CO₂ varies a lot because carbon is exchanged among its surface reservoirs: the atmosphere, ocean, soil, and biosphere. For example, the solubility of CO₂ in the ocean decreases as the ocean warms, a positive feedback causing much of the atmospheric CO₂ increase with global warming. That feedback is simple, but the full story of how weak forcings create large climate change is indeed complex.

A useful complement to Pleistocene climate fluctuations is provided by longer time scales with larger CO₂ changes than those caused by orbital oscillations. Larger CO₂ changes occur on long time scales because of transfer of carbon between the solid earth and the surface reservoirs. The large CO₂ changes on these long time scales allow the Earth orbital climate oscillations to be viewed as 'noise'. Thus long time scales help provide a broader overview of the effect of changing atmospheric composition on climate.

A difficulty with long time scales is that knowledge of atmospheric composition changes is not as good. Samples of ancient air preserved in ice cores exist for only about one million years. But there are indirect ways of measuring ancient CO₂ levels to better than a factor of two beyond one million years ago. Atmospheric composition and other climate forcings are known well enough for the combination of Pleistocene climate variations and longer-term climate change to provide an informative overview of climate sensitivity and a powerful way to assess the role of humans in altering global climate.

Q. What determines the amount of CO₂ in the air on long time scales?

A. On long (geologic) time scales CO₂ is exchanged between the surface reservoirs (atmosphere, ocean, soil and biosphere) and the solid Earth. Two processes take CO₂ out of the surface reservoirs: (1) chemical weathering of silicate rocks, which results in the deposition of (calcium and magnesium) carbonates on the ocean floor, and (2) burial of organic matter, some of which eventually forms fossil fuels. Weathering is the more dominant process, accounting for ~80% of carbon removal from surface reservoirs (Berner 2004).

CO₂ is returned to the atmosphere principally via subduction of oceanic crustal plates beneath continents. When a continental plate overrides carbonate-rich ocean crust, the subducted ocean crust experiences high temperatures and pressures. Resulting metamorphism of the subducted crust into various rock types releases CO₂, which makes its way to the atmosphere via volcanic eruptions or related phenomena such as 'seltzer' spring water. This return of CO₂ to the atmosphere is called 'outgassing'.

Outgassing and burial of CO₂, via weathering and organic deposits, are not in general balanced at any given time (Edmond and Huh 2003). Depending on the movement of continental plates, the locations of carbonate-rich ocean crust, rates of mountain-building (orogeny), and other factors, at any given time there can be substantial imbalance between outgassing and burial. As a result, atmospheric CO₂ changes by large amounts on geologic time scales.

**Full ultra
long
carbon
cycle & sink**

Q. How much do these geologic processes change atmospheric CO₂?

A. Rates of outgassing and burial of CO₂ are each typically $2\text{--}4 \times 10^{12}$ mol C/year (Staudigel et al. 1989; Edmond and Huh 2003). An imbalance between outgassing and burial of say 2×10^{12} mol C/year, if confined entirely to the atmosphere, would correspond to ~ 0.01 ppm CO₂ per year. However, the atmosphere contains only of order $10^{(-2)}$, i.e., about 1%, of the total CO₂ in the surface carbon reservoirs (atmosphere, ocean, soil, biosphere), so the rate of geologic changes to atmospheric CO₂ is only about 0.0001 ppm CO₂ per year. This compares to the present human-made atmospheric CO₂ increase of ~ 2 ppm per year. Fossil fuels burned now by humans in one year contain the amount of carbon buried in organic sediments in approximately 100,000 years.

The contribution of geologic processes to atmospheric CO₂ change is negligible compared to measured human-made changes today. However, in one million years a geologic imbalance of 0.0001 ppm CO₂ per year yields a CO₂ change of 100 ppm. Thus geologic changes over tens of millions of years can include huge changes of atmospheric CO₂, of the order of 1000 ppm of CO₂. As a result, examination of climate changes on the time scale of tens of millions of years has the potential to yield a valuable perspective on how climate changes with atmospheric composition.

Q. What is the most useful geologic era to consider for that purpose?

A. The Cenozoic era, the past 65 million years, is particularly valuable for several reasons. First, we have the most complete and most accurate climate data for the most recent era. Second, climate changes in that era are large enough to include ice-free conditions. Third, we know that atmospheric greenhouse gases were the principal global forcing driving climate change in that era.

Q. How do you know that greenhouse climate forcing was dominant in the Cenozoic?

A. Climate forcings, perturbations of the planet's energy balance, must arise from either changes in the incoming energy, changes that alter the planetary surface, or changes within the atmosphere. Let us examine these three in turn.

Solar luminosity is growing on long time scales, at a rate such that the sun was $\sim 0.5\%$ dimmer than today in the early Cenozoic (Sackmann et al. 1993). Because the Earth absorbs about 240 W/m^2 of solar energy, the solar climate forcing at the beginning of the Cenozoic was about -1 W/m^2 relative to today. This small growth of solar forcing through the Cenozoic era, as we will see, is practically negligible.

Changing size and location of continents can be an important climate forcing, as the albedo of the Earth's surface depends on whether the surface is land or water and on the angle at which the sun's rays strike the surface. A quarter of a billion years ago the major continents were clumped together (Figure 9) in the super-continent Pangea centered on the equator (Keller and Pinter 1996). However, by the beginning of the Cenozoic (65 million years before present, 65 My BP, the same as the end of the Cretaceous) the continents were close to their present latitudes. The direct (radiative) climate forcing due to this continental drift is no more than $\sim 1 \text{ W/m}^2$.

In contrast, atmospheric CO_2 reached levels of 1000-2000 ppm in the early Cenozoic (Pagani et al. 2005; Royer 2006), compared with values as low as ~ 180 ppm during recent ice ages. This range of CO_2 encompasses about three CO_2 doublings and thus a climate forcing more than 10 W/m^2 . So it is clear that changing greenhouse gases provided the dominant global climate forcing through the Cenozoic era.

We are not neglecting the fact that dynamical changes of ocean and atmospheric currents can affect global mean climate (Rind and Chandler 1991). Climate variations in the Cenozoic are too large to be accounted for by such dynamical hypotheses.

Natural global cooling trend due to CO₂

Q. Can you explain the nature of the global climate change illustrated in Figure 10?

A. The long-term cooling from 50 My BP to the present must be due primarily to decreasing greenhouse gases, primarily CO₂, which fell from 1000-2000 ppm 50 My BP to 180-280 ppm in recent glacial-interglacial periods. Full glaciation of Antarctica, at about 34 My BP (Lear et al. 2000; Zachos et al. 2001), occurred when CO₂ fell to 500 ± 150 ppm (Hansen and Sato 2007).

Between 34 and 15 My BP global temperature fluctuated, with Antarctica losing most of its ice at about 27 My BP. Antarctica did not become fully glaciated again until about 15 My BP. Deglaciation of Antarctica was associated with increased atmospheric CO₂ (Pagani et al. 2005), perhaps due to the negative feedback caused by reduction of weathering (Lear et al. 2004) as ice and snow covered Antarctica as well as the higher reaches of the Himalayas and the Alps.

Cooling and ice growth resumed at about 15 My BP continuing up to the current Pleistocene ice age. During the past 15 My CO₂ was at a low level, about 200-400 ppm (Zachos et al. 2001; Pagani et al. 2005) and its proxy measures are too crude to determine whether it had a long-term trend. Thus it has been suggested that the cooling trend may have been due to a reduction of poleward ocean heat transports, perhaps caused by the closing of the Isthmus of Panama at about 12 My BP or the steady widening of the oceanic passageway between South America and Antarctica.

In summary, there are many uncertainties about details of climate change during the Cenozoic era. Yet important conclusions emerge, as summarized in Figure 11. The dominant forcing that caused global cooling, from an ice free planet to the present world with large ice sheets on two continents, was a decrease in atmospheric CO₂. Human-made rates of change of climate forcings, including CO₂, now dwarf the natural rates.

Ice age cycles

Q. Why are climate fluctuations in the past few million years (Figure 10b) so regular?

A. The instigator is the distribution of sunlight on the Earth, which continuously changes by a small amount because of the gravitational pull of other planets, especially Jupiter and Saturn, because they are heavy, and Venus, because it comes close. The most important effect is on the tilt of the Earth's spin axis relative to the plane of the Earth's orbit (Figure 12). The tilt varies by about 2° with a regular periodicity of about 41 Ky (41,000 years). When the tilt is larger it exposes both polar regions to increased sunlight at 6-month intervals. The increased heating of the polar regions melts ice in both hemispheres.

The 41 Ky climate variability is apparent in Figure 10b and is present in almost all climate records. However, glacial-interglacial climate variations became more complex in the most recent 1.2 My, with large variations at ~ 100 Ky periodicity, as well as ~ 41 Ky and ~ 23 Ky periods. As the planet became steadily colder over the past several million years, the amplitude of glacial-interglacial climate swings increased (Figure 10b) as ice sheet area increased. Ice sheets on Northern Hemisphere continents, especially North America, extended as far south as 45°N latitude. Similar ice sheets were not possible in the Southern Hemisphere, which lacked land at relevant latitudes.

Hemispheric asymmetry in ice sheet area allows two additional Earth orbital parameters, which work in concert, to come into play. Gravitational tugs of the planets cause the eccentricity of the Earth's orbit about the sun to vary from near zero (circular) to an eccentricity of about 0.06. When the orbit is significantly non-circular, this allows another orbital parameter, axial precession, to become important. Precession, which determines the date in the year at which the Earth in its elliptical orbit is closest to the sun, varies with a periodicity of ca. 23 Ky. When the Earth is closest to the sun in Northern Hemisphere winter, thus furthest from the sun in summer, ice sheet growth in the Northern Hemisphere is encouraged by increased winter snowfall and cool summers. The effect of eccentricity + precession on ice sheet growth is opposite in the two hemispheres, so the effect is important only when the area of high albedo ice and snow is much different in the two hemispheres, as it has been in the past million years. Climate variations then include all three periodicities, ~ 23 Ky precession, ~ 41 Ky tilt, and ~ 100 Ky eccentricity, as has been demonstrated for the recent ice age cycles (Hays et al 1976).

Q. Are climate models consistent with paleoclimate estimates of high climate sensitivity and with observed global warming in the past century?

A. Yes. Climate models yield equilibrium sensitivity (the response after several centuries) of typically about 3°C for doubled CO_2 . Figure 15B shows the resulting global warming when such a climate model (one with $\sim 3^{\circ}\text{C}$ sensitivity for doubled CO_2) is driven by climate forcings measured or estimated for the period 1880-2003 (Figure 15A). The calculated and observed warmings are similar. Good agreement might also be obtained using a model with higher sensitivity and a smaller forcing or using a model with lower sensitivity and a larger forcing. But the sensitivity of this model (Hansen et al. 2007b) agrees well with the empirical sensitivity defined by paleoclimate data.

Q. I am confused. Did you not say earlier that climate sensitivity is about 6°C for doubled CO_2 ?

A. Yes. That is an important point that needs to be recognized. We showed that the real world climate sensitivity is 6°C for doubled CO_2 , when both fast and slow feedback processes are included, based on data that covered climate states ranging from interglacial periods 1°C warmer than today to ice ages 5°C cooler than today. That 6°C sensitivity is also the appropriate estimate for the range of warmer climates up to the point at which all ice sheets are melted and high latitudes are fully vegetated.

This higher climate sensitivity, 6°C for doubled CO_2 , is the appropriate sensitivity for long time scales, when greenhouse gases are the specified forcing mechanism and all other slow feedbacks are allowed to fully respond to the climate change. The substantial relevant slow feedbacks are changes of ice sheets and surface vegetation.

Climate
sensitivity

The correct climate sensitivity for a temperature range of up to $+1.8^{\circ}\text{C}$ is 6°C . Obviously we must now use 6°C .

Q. Yet you employed a climate model with 3°C sensitivity, a model excluding these slow feedbacks. Does this cause a significant error?

A. No, not in simulations of the 20th century climate change as in Figure 15. Feedbacks come into play not in response to climate forcing but in response to climate change. Ocean thermal inertia introduces a lag, shown by the climate response function in Figure 15c. The response function is the fraction of the equilibrium surface response that is achieved at a given time subsequent to introduction of the forcing. About half of the equilibrium response occurs within a quarter century, but further response at the Earth's surface is slowed by mixing of water between the ocean surface layer and the deeper ocean. Nearly full response requires several centuries.

Furthermore, the response time to a climate forcing increases in proportion to the square of climate sensitivity (Hansen et al. 1985), so the response time for 6°C climate sensitivity is about four times greater than that shown in Figure 15c. The explanation for this strong dependence of response time on climate sensitivity is simple: the rate of heating is fixed, so to warm the ocean mixed layer would take twice as long for 6°C sensitivity as for 3°C sensitivity. But this additional time allows more mixing of heat into the deeper ocean. For diffusive mixing it follows analytically, as shown in the referenced paper, that the response time goes as the square of climate sensitivity.

In addition, some climate feedback processes can increase response time above that associated with ocean thermal inertia alone. A fast feedback such as atmospheric water vapor amount occurs almost instantly with temperature change. However, ice sheets require time to disintegrate or grow, and vegetation migration in response to shifting climate zones also may require substantial time.

Climate
sensitivity

Climate sensitivity

Ice sheet and vegetation responses were not important factors affecting the magnitude of 20th century global warming, so simulations of 20th century global temperature change were not compromised by exclusion of those feedbacks. However, with a substantial and almost monotonic global warming now in place (Figure 1A), the ice sheet and vegetation feedbacks should begin to contribute significantly to climate change in the 21st century. Ice sheet and vegetation changes will continue to alter the planetary energy balance over century time scales and must be accounted for in projecting future climate change.

**The 20th century was covered by a climate sensitivity of 3.
For the 21st current century the climate sensitivity increases to 6.**

Q. Can we move on from this technical discussion of feedbacks and response time?

A. Please allow one final comment. The 6°C sensitivity (for doubled CO₂) is valid for a specified change of greenhouse gases as the climate forcing. That is relevant for human-made change of atmospheric composition, and this sensitivity yields the correct answer for long-term climate change if actual greenhouse gas changes are used as the forcing mechanism. However, climate model scenarios for the future usually incorporate human-made emissions of greenhouse gases. Atmospheric greenhouse gas amounts may be affected by feedbacks, which thus alter expected climate change.

Feedbacks

Greenhouse gas feedbacks are not idle speculation. Paleoclimate records reveal times in the Earth's history when global warming resulted in release of large amounts of methane to the atmosphere. Potential sources of methane include methane hydrates 'frozen' in ocean sediments and tundra, which release methane in thawing. Recent Arctic warming is causing release of methane from permafrost (Christensen et al. 2004; Walter et al. 2006)

Hansen and Sato (2004) have shown from paleoclimate records that the positive feedbacks that occur for all major long-lived greenhouse gases (carbon dioxide, methane, and nitrous oxide) are moderate for global warming less than 1°C. However, no such constraints exist for still larger global warming, because there are no recent interglacial periods with global

Hansen and Sato (2004) have shown from paleoclimate records that the positive feedbacks that occur for all major long-lived greenhouse gases (carbon dioxide, methane, and nitrous oxide) are moderate for global warming less than 1°C. However, no such constraints exist for still larger global warming, because there are no recent interglacial periods with global warming greater than about 1°C. Based on other metrics (avoiding large sea level rise, extermination of species, and large regional climate disruption) we argue that we must aim to keep additional global warming, above the level in 2000, less than 1°C. Such a limit should also avert massive release of frozen methane.

6°C is the proper climate sensitivity to use for long term mitigation.

Q. Observed (and modeled) global warming of 0.8°C in the past century seems small in view of the large changes of greenhouse gases shown in Figure 8. Why is that?

A. There are two reasons.

First, there is the large thermal inertia of the ocean. It takes a few decades to achieve just half of the global warming with climate sensitivity of 3°C for doubled CO_2 , as shown in Figure 15C. And the slow feedbacks that contribute half of the paleoclimate change are now just beginning to come into play.

Second, the greenhouse gases are not the only climate forcing. Human-made tropospheric aerosols, Figure 15A, are estimated to cause a negative forcing about half as large as the greenhouse forcing, but opposite in sign.

Q. There must be some uncertainty in the climate forcings, especially the aerosol forcing. Can you verify that the estimated forcings are realistic?

A. Yes. The aerosol forcing is difficult to verify directly, but there is an exceedingly valuable diagnostic that relates to the net climate forcing. Given that the greenhouse gas forcing is known accurately, the constraint on net forcing has implications for the aerosol forcing, because other forcings are either small or well-measured (Figure 15A). The diagnostic that I refer to is the planetary energy imbalance (Hansen et al. 2005b).

The Earth's energy imbalance, averaged over several years, is a critical metric for several reasons. First and foremost, it is a direct measure of the reduction of climate forcings required to stabilize climate. The planetary energy imbalance measures the climate forcing that has not yet been responded to, i.e., multiplication of the energy imbalance by climate sensitivity defines global warming still "in the pipeline".

Several decades for half global warming from emissions due to ocean heat lag.

Aerosol cooling is 50% of GHG warming.

Slow feedbacks are beginning.

Climate
sensitivity
is high

A good period to evaluate the Earth's energy imbalance is the eleven-year period 1995-2005, because this covers one solar cycle from solar minimum to solar minimum. A climate model with sensitivity $\sim 3^{\circ}\text{C}$ for doubled CO_2 , driven by the climate forcings in Figure 15A, yields an imbalance of $0.75 \pm 0.15 \text{ W/m}^2$ for 1995-2005. Observations of heat gain in measured portions of the upper 700 m of the ocean yield a global heat gain of $\sim 0.5 \text{ W/m}^2$. Measured or estimated heat used in sea ice and land ice melt, warming of ground and air, and ocean warming in polar regions and at depths below 700 m yield a total estimated heat gain of $0.75 \pm 0.25 \text{ W/m}^2$ (Hansen 2007b).

The observed planetary energy imbalance thus supports the estimated climate forcings used in the climate simulations of Figure 15. This check is not an absolute verification, because the results also depend upon climate sensitivity, but the model's sensitivity is consistent with paleoclimate data. Indeed, the existence of a substantial planetary energy imbalance provides confirmation that climate sensitivity is high. Climate response time varies as the square of climate sensitivity, so if climate sensitivity were much smaller, say half as large as indicated by paleoclimate data, it would not be possible for realistic climate forcings to yield such a large planetary energy imbalance.

Comment: The planetary energy imbalance is the single most critical metric for the state of the Earth's climate. Ocean heat storage is the largest term in this imbalance; it needs to be measured more accurately, present problems being incomplete coverage of data in depth and latitude, and poor inter-calibration among different instruments. The other essential measurement for tracking the energy imbalance is continued precise monitoring of the ice sheets via gravity satellite measurements.

Q. How much is global warming expected to increase in the present century, and how does this depend upon assumptions about fossil fuel use?

A. We can project future global warming with reasonable confidence, for different assumed scenarios of greenhouse gases, by extending the climate model simulations that matched well the observed global temperature change in the past century. Figure 16 shows such a projection based on the GISS global climate model, which has climate sensitivity close to 3°C for doubled CO₂. The model excludes slow climate feedbacks such as changes of ice sheet area and global vegetation distributions, but the effects of those slow feedbacks on global mean temperature should be small during the next several decades.

‘Business-as-Usual’ climate scenarios, such as IPCC scenarios A1B and A2, yield additional global warming of at least 2°C in the 21st century. Actual warming for ‘business-as-usual’ climate forcing could be larger because: (1) slow climate feedbacks such as ice sheet disintegration, vegetation migration, and methane release from melting permafrost are not included, (2) atmospheric aerosols (small particles, especially sulfates) that have a cooling effect are kept fixed, but it is expected that they could decrease this century. (3) CO₂ emissions as high as in business-as-usual scenarios may have climate effects large enough to alter the ability of the biosphere to take up the assumed proportion of CO₂ emissions.

The ‘alternative scenario’ is defined with the aim of keeping additional global warming, beyond that of 2000, less than 1°C. This requires that additional climate forcing be kept less than about 1.5 W/m², assuming a climate sensitivity of about 3°C for doubled CO₂, and in turn this requires that CO₂ be kept from exceeding about 450 ppm, with the exact limit depending upon how well other climate forcings are constrained, especially methane (Hansen et al. 2000). Figure 16 shows that additional global warming in the alternative scenario is about 0.8°C by 2100, and it remains less than 1°C under the assumption that a slow decrease in greenhouse gas forcing occurs after 2100.

A climate sensitivity of 3 may be good for The next decades

Models omit Ice, vegetation expansion, permafrost.

Q. How do these levels of global warming relate to dangerous climate change?

A. That is the fundamental issue, because practically all nations, including the United States, have signed the Framework Convention on Climate Change, agreeing to stabilize greenhouse gas emissions at a level that prevents “dangerous” anthropogenic interference with the climate system (Figure 17). In just the past few years it has become clear that atmospheric composition is already close to, if not slightly beyond, the dangerous level of greenhouse gases. In order to understand this situation, it is necessary to define key metrics for what constitutes “danger”, to examine the Earth’s history for levels of climate forcing associated with these metrics, and to recognize changes that are already beginning to appear in the physics of the climate system.

Principal metrics defining dangerous include: (1) ice sheet disintegration and sea level rise, (2) extermination of species, and (3) regional climate disruptions (Figure 18). Ice sheet disintegration and species extinction proceed slowly at first but have the potential for disastrous non-linear collapse later in the century. The consequences of ice sheet disintegration and species extinction could not be reversed on any time scale of interest to humanity. If humans cause multi-meter sea level rise and exterminate a large fraction of species on Earth, they will, in effect, have destroyed creation, the planet on which civilization developed over the past several thousand years.

Regional climate disruptions also deserve attention. Global warming intensifies the extremes of the hydrologic cycle. On the one hand, it increases the intensity of heavy rain and floods, as well as the maximum intensity of storms driven by latent heat, including thunderstorms, tornados and tropical storms. At the other extreme, at times and places where it is dry, global warming will lead to increased drought intensity, higher temperatures, and more and stronger forest fires. Subtropical regions such as the American West, the Mediterranean region, Australia and parts of Africa are expected to be particularly hard hit by global warming. Because of earlier spring snowmelt and retreat of glaciers, fresh water supplies will fail in many locations, as summers will be longer and hotter.

DAI

He says we may beyond dangerous interference.

His principal metrics are ice sheets, species extermination and regional climate disruption.

The UN FCCC metrics are climate safety for ecosystems, food and human health.

Q. Is it possible to say how close we are to deleterious climate impacts?

A. Yes. I will argue that we are near the dangerous levels for all three of these metrics.

In the case of sea level, this conclusion is based on both observations of what is happening on the ice sheets today and the history of the Earth, which shows how fast ice sheets can disintegrate and the level of warming that is needed to spark large change.

Figure 19 shows that the area on the Greenland ice sheet with summer melt has been increasing over the period of satellite observations, the satellite view being essential to map this region. The area with *summer melt* is also increasing on West Antarctica.

Figure 20 shows summer meltwater on Greenland. The meltwater does not in general make it to the edge of the ice sheet. Rather it runs to a relative low spot or crevasse on the ice sheet, and there burrows a hole all the way to the base of the ice sheet. The meltwater then serves as lubrication between the ice sheet and the ground, thus speeding the discharge of giant icebergs to the ocean (Figure 21).

Q. Is it not true that global warming also increases the snowfall rate, thus causing ice sheets to grow faster?

A. The first half of that assertion is correct. The inference drawn by 'contrarians', that global warming will cause ice sheets to become bigger, defies common sense as well as abundant paleoclimate evidence. The Earth's history shows that when the planet gets warmer, ice sheets melt and sea level increases. Ice sheet size would not necessarily need to decrease on short time scales in response to human-made perturbations. However, we now have spectacular data from a gravity satellite mission that allows us to evaluate ice sheet response to global warming.

The gravity satellite measures the Earth's gravitational field with sufficient precision to detect changes in the mass of the Greenland and Antarctic ice sheets. As shown by Figure 22, the mass of the ice sheet increases during the winter and decreases during the melting season. However, the net effect is a downward trend of the ice sheet mass. In the past few years Greenland and West Antarctica have each lost mass at a rate of the order of 150 cubic kilometers per year.

DAI

Sea level

Q. Is sea level increasing at a significant rate?

A. Sea level is now increasing at a rate of about 3.5 cm per decade or 35 cm per century, with thermal expansion of the ocean, melting of alpine glaciers, and the Greenland and West Antarctic ice sheets all contributing to this sea level rise. That is double the rate of 20 years ago, and that in turn was faster than the rate a century earlier. Previously sea level had been quite stable for the past several millennia.

Q. Is the current level of sea level rise dangerous?

A. This rate of sea level rise is more than a nuisance, as it increases beach erosion, salt water intrusion into water supplies, and damage from storm surges. However, the real danger is the possibility that the rate of sea level rise will continue to accelerate. Indeed, it surely will accelerate, if we follow business-as-usual growth of greenhouse gas emissions.

Q. How fast can sea level rise and when would rapid changes be expected?

A. Those questions are inherently difficult to answer for a non-linear process such as ice sheet disintegration. Unlike ice sheet growth, which is a dry process limited by the rate of snowfall, ice sheet disintegration is a wet process that can proceed rapidly and catastrophically once it gets well underway.

Some guidance is provided by the Earth's history. When the Laurentide ice sheet, which covered Canada and reached into the northern edges of the United States, disintegrated following the last ice age, there were times when sea level rose several meters per century. The Greenland and West Antarctic ice sheets are at somewhat higher latitudes than the Laurentide ice sheet, but West Antarctica seems at least as vulnerable to rapid disintegration because it rests on bedrock below sea level. Thus the West Antarctic ice sheet is vulnerable to melting by warming ocean water at its edge as well as surface melt. In addition, if we follow business-as-usual, the human-made climate forcing will be far larger and more rapid than the climate forcings that drove earlier deglaciations.

I have argued (Hansen 2005, 2007a) that business-as-usual greenhouse gas growth almost surely will cause multi-meter sea level rise within a century. High latitude amplification of global warming would result in practically the entire West Antarctic and Greenland ice sheets being bathed in meltwater for a lengthened melt season. A warmer ocean and summer rainfall could speed flushing of the ice sheets. If we wait until rapid disintegration begins, it will be impossible to stop.

Q. What consequences would be expected with multi-meter sea level rise?

A. Most of the world's large cities are on coast lines (Figure 23). The last time that global mean temperature was 2-3°C warmer than now was in the Pliocene, when sea level was about 25 meters higher than today. About one billion people live within 25-meter elevation of sea level. As shown by Figure 24, most East Coast cities in the United States would be under water with a sea level rise that large, almost the entire nation of Bangladesh, the State of Florida, and an area in China that presently contains about 300 million people. There are historical coastal cities in most countries. A sea level rise of 5-7 meters, which could be provided by West Antarctica alone, is enough to displace a few hundred million people.

Q. Does sea level provide a precise specification of 'dangerous' warming?

A. I suggest that it is useful to look at prior interglacial periods, some of which were warmer than our current interglacial period. In some of these periods, e.g., the interglacials ~125 and ~425 thousand years ago, sea level was higher than today by as much as a few meters, but sea level did not approach the level in the Pliocene. Although we do not have accurate measurements of global mean temperature for the earlier interglacial periods, we do have local measurements at places of special relevance.

Figure 25a is the temperature in the Western Pacific Warm Pool, the warmest ocean region on the planet, a region of special importance because it strongly affects transport of heat to higher latitudes via both the atmosphere and ocean. Figure 26b is the temperature in the Indian Ocean, the place that has the highest correlation with global mean temperature during the period of instrumental data, the period when an accurate global mean temperature can be calculated (Hansen et al. 2006). Figure 25 concatenates modern instrumental temperatures with proxy paleo measures. In both of these regions it appears that the warming of recent decades has brought recent temperatures to within about 1°C or less of the warmest interglacial periods.

Tropical ocean temperature change is only moderately smaller than global mean temperature change in both recent times and glacial-interglacial climate change. For this reason, I assert that it would be foolhardy for humanity to allow additional global warming to exceed about 1°C.

DAI

- Q. But if additional global warming is kept less than 1°C that does not seem to guarantee that sea level rise of a few meters would not occur, given the changes that occurred in the previous interglacial periods, does it?**
- A.** You are right, and I am not recommending that the world should aim for additional global warming of 1°C. Indeed, because of potential sea level rise, as well as the other critical metrics that I will discuss, I infer that it is desirable to avoid any further global warming.

DAI He says is it desirable (because unsafe) to avoid any further global warming

However, I also note that there is an enormous difference between global warming less than 1°C and global warming of 2-3°C. The latter warming would have the global climate system pointed toward an eventual sea level rise measured in the tens of meters. In that case we should expect multi-meter sea level rise this century and initiation of ice sheet disintegration out of our control with a continually rising sea level and repeated coastal disasters unfolding for centuries. Economic and social consequences are difficult to fathom.

With global warming less than 1°C it is possible that sea level rise this century would be less than 1 meter. Ice sheet changes would likely unfold much more slowly than with 2-3°C global warming. If the maximum global warming is kept less than 1°C, it may be practical to achieve moderate adjustments of global climate forcings that would avert the occurrence of large sea level change. Human-made gases in the air will decrease when sources are reduced sufficiently, so as events unfold and understanding improves, it may prove necessary to set goals that yield a declining global temperature beyond the human-induced maximum temperature. However, considering the 1000-year lifetime of much of the CO₂, if the additional warming is 2-3°C, it will be impractical to avoid disastrous consequences.

2 to 3°C means disastrous consequences

Q. What other ghosts of climate future can be seen?

A. Another potential consequence that would be irreversible is extermination of species. Animal and plant species can survive only within certain climatic zones. As climate changes, animals and plants can migrate, and in general they deal successfully with fluctuating climate. However, large climate changes have caused mass extinctions in the past. Several times in the Earth's history global warming of five degrees Celsius or more led to extinction of a majority of species on the planet. Of course other species came into being over many thousands of years. But mass extinctions now would leave a far more desolate planet for as long as we can imagine.

Global warming of 0.6°C in the past three decades has initiated a systematic movement of climatic zones, with isotherms moving poleward at a rate of typically 50-60 km per decade (Hansen et al. 2006). As this movement continues, and as it would accelerate with business-as-usual increases of fossil fuel use, it will add a strong climatic stress to the other stresses that humans have placed on many species. Species at high latitudes (Figure 26) and high altitudes (Figure 27) are in danger of, in effect, being pushed off the planet by global warming. Many other species will be threatened as the total movement of climatic zones increases, because some species are less mobile than others. Interdependencies of species leave entire ecosystems vulnerable to collapse.

It can be argued, as E.O. Wilson has suggested, that the world beyond the 21st century, post fossil fuel domination and post the human population peak, could have an environment that is more tolerant of all species. It is difficult to project how many of the species of creation will survive the bottleneck in the 21st century (Figure 28), but surely the number will be much smaller if the stresses include business-as-usual climate change.

Realization that we are already near 'dangerous' climate change, for sea level rise and other effects, has a bright side. It means that we must curtail atmospheric CO₂ and other climate forcings more sharply than has generally been assumed. Thus various problems that had begun to seem almost inevitable, such as acidification of the ocean, cannot proceed much further, if we are to avoid other catastrophes. If the needed actions are taken, we may preserve most species.

Q. Are there other criteria, besides sea level and species extinction, for “danger”?

A. There are many regional effects of global warming. Large natural weather and climate fluctuations make it difficult to identify global warming effects, but they are beginning to emerge. If we follow business-as-usual, the southernmost parts of our country are likely to have much less tolerable climate. Fresh water shortages could become a frequent problem in parts of the country, especially those dependent on snowpack runoff, as spring comes earlier and summers are longer, hotter and drier, and forest fires will be an increasing problem. Other parts of the country, and in some cases the same places, will experience heavier rain, when it occurs, and greater floods. The tier of semi-arid states, from West Texas through the Dakotas, is subject to the same expected increase of hydrologic extremes, but overall they are likely to become drier and less suited for agriculture, if we follow business-as-usual and large global warming ensues.

Given that effects of global warming on regional climate are already beginning to emerge, the regional climate criterion also implies that further global warming much above the present level is likely to be deleterious.

His answer ignores human population health and survival.

He ignores food security to regions other than the US.

DAI

Q. Is it still possible to avoid dangerous climate change?

A. It is possible, but just barely. Most climate forcings are increasing at a rate consistent with, or even more favorable (slower), than the 'alternative scenario' which keeps warming less than 1°C. CO₂ is the one climate forcing that is increasing much more rapidly than in the alternative scenario, and if CO₂ emissions continues on their current path CO₂ threatens to become so dominant that it will be implausible to get the net climate forcing onto a path consistent with the alternative scenario. Furthermore, as I have discussed, there are reasons to believe that even the smaller warming of the alternative scenario may take us into the dangerous range of climate change. It is likely that we will need to aim for global warming even less than 1°C.

His 1C is 1.6C from pre-industrial, so he saying we need to aim for under 1.6C.

DAI

Why no progress

The ozone story was a success story (Figure 44), as scientists transmitted a clear message, the media informed the public, the public responded in a positive way, and the United States government exercised strong leadership. Special interests, the chemical companies producing CFCs, denied the science for several years, but they cooperated once it became clear that they could make money producing substitute chemicals.

Q. Why has the global warming story not followed a similar path?

A. The blame can be spread around. I believe that we scientists have not done as good a job in making clear the threat to the planet and creation. Special interests have been extremely effective in casting doubt on the science. Moreover, they have managed to have a great impact on the media, demanding that the story be presented as “fair and balanced” even when the evidence became “clear and unambiguous”. I also infer, based on numerous observations, that special interests have had undue influence (exceeding the one person one vote concept) on governments, especially in Washington.

Although the responsibility can be spread widely (Figure 46), the consequences of our profligate use of resources will be borne primarily by young people, today’s children and grandchildren, and later generations.

Q. Are you saying that the blame belongs on past generations?

A. No. They can genuinely say “we did not know”. The blame will fall squarely on today’s adults, if we do not act. We can no longer feign ignorance. Scientific consensus has been reached. If we stay on the business-as-usual course that our energy departments take for granted, when climate events unfold in the future it is not likely that our children and grandchildren will look back on our generation with equanimity, nor should they. If we allow climate to deteriorate and

creation to be destroyed, we will be the generation that knew enough and still had time, but for selfish reasons declined to take actions. Instead, we built more coal-fired power plants. In that event, rather than the “greatest generation”, how will our epitaph read?

- Q. I am the one asking questions. Is there still time?**
- A.** There is still time (Figure 47). However, it is clear that Congress does not 'get it'. They stand ready to set a goal of 60% reductions, 80%, 90%! Horse manure. Those are meaningless numbers, serving nothing but their campaign purposes. Before you cast a vote for a politician ask whether they will support actions that can actually solve the problem. Specifically, I suggest that you ask them whether they will support the Declaration of Stewardship (Figure 48).

The most important question, by far, is the moratorium on new coal-fired power plants in the United States and Europe, the places that have created the climate problem. Until we take that action, we have no basis for a successful discussion with China, India, and other developing countries.

Summary: Cenozoic Era

1. Dominant Forcing: Natural ΔCO_2

- Rate ~ 100 ppm/My (0.0001 ppm/year)
- Human-made rate today: ~ 2 ppm/year

Humans Overwhelm Slow Geologic Changes

2. Climate Sensitivity High

- Antarctic ice forms if $\text{CO}_2 < \sim 500$ ppm
- Ice sheet formation reversible

Humans Could Produce "A Different Planet"

Figure 11. Principal inferences from Cenozoic Era relevant to present-day climate.