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DEPARTMENT OF COMMERCE
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IN RE:

INTERSTATE
POWER AND LIGHT
COMPANY

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DIRECT TESTIMONY OF DR. 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. What is your educational background?

A. I was trained in physics and astronomy at the University of Iowa in the space science program of Professor James Van Allen. I have a bachelor's degree in physics and mathematics, a master's degree in astronomy, and a Ph.D. in physics, all from the University of Iowa. I also did research as a graduate student at the Universities of Kyoto and Tokyo, and I was a post-doctoral fellow of the United States National Science Foundation studying at the Sterrewacht, Leiden University, Netherlands, under Prof. Henk van de Hulst.

Q. Please describe your professional experience.

A. Upon graduating from the University of Iowa in February 1967 I joined the Goddard Institute for Space Studies, where I have worked ever since, except for 1969 when I was a post-doctoral fellow in the Netherlands. In my first ten years at the Goddard Institute I focused on planetary research. I was Principal Investigator for an experiment on the Pioneer Venus spacecraft to study the clouds of Venus and I was involved in other planetary missions. In the mid-1970s, as evidence of human-made effects on Earth's atmosphere and climate became apparent, I began to spend most of my time in research on the Earth's climate. I became director of the Goddard Institute in 1981, focusing the Institute's program on global change, while maintaining a broad perspective from planetary studies and the Earth's history.

Q: Are you sponsoring any exhibits as part of your testimony?

A: Yes. All the figures referenced in my testimony are included as Exhibit ___ (JEH-1) Schedule A. A 2007 article authored by myself and five colleagues, entitled "Climate change and trace gases", is included as Exhibit ___ (JEH-1) Schedule B.

Q. What is the purpose of your testimony?

A. My aim is to present clear scientific evidence describing the impact that coal-fired power plants (without carbon capture and storage) will have on the Earth's climate, and thus on the well-being of today's and future generations of people and on all creatures and species of creation.

Burning of fossil fuels, primarily coal, oil and gas, increases the amount of carbon dioxide (CO_2) and other gases and particles in the air. These gases and particles affect the Earth's energy balance, changing both the amount of sunlight absorbed by the planet and the emission of heat (long wave or thermal radiation) to space. The net effect is a global warming that has become substantial during the past three decades.

Global warming from continued burning of more and more fossil fuels poses clear dangers for the planet and for the planet's present and future inhabitants. Coal is the largest contributor to the human-made increase of CO_2 in the air. Saving the planet and creation surely requires phase-out of coal use except where the CO_2 is captured and sequestered (stored in one of several possible ways).

Q. Coal is only one of the fossil fuels. Can such a strong statement specifically against coal be justified, given still-developing understanding of climate change?

A. Yes. Coal reserves contain much more carbon than do oil and natural gas reserves, and it is impractical to capture CO_2 emissions from the tailpipes of vehicles. Nor is there any prospect that Saudi Arabia, Russia, the United States and other major oil-producers will decide to leave their oil in the ground. Thus unavoidable CO_2 emissions from oil and gas in the next few decades will take atmospheric CO_2 amounts close to, if not beyond, the level needed to cause dangerous climate change. The only practical way to prevent CO_2 levels from going far into the dangerous range, with disastrous effects for humanity and other inhabitants of the planet, is to phase out use of coal except at power plants where the CO_2 is captured and sequestered.

Q. But why focus on a coal plant in Iowa? Coal-fired power plants are being built at a much faster rate in China.

A. The United States is responsible for more than three times as much of the excess CO_2 in the air than any other country. The United States and Europe together are responsible for well over half of the increase from the pre-industrial CO_2 amount (280 ppm, ppm = parts per million) to the present-day CO_2 amount (about 385 ppm). The United States will continue to be most responsible for the human-made CO_2 increase for the next few decades, even though China's ongoing emissions will exceed those of the United States. Although a portion of human-made CO_2 emissions is taken up by the ocean, there it exerts a 'back pressure' on the atmosphere, so that, in effect, a substantial fraction of past emissions remains in the air for many centuries, until it is incorporated into ocean sediments. Furthermore, even as China's emissions today approximately equal those of the United States, China's per capita CO_2 emissions are only about 20% of those in the United States.

China, India and other developing countries must be part of the solution to global warming, and surely they will be, if developed countries take the appropriate first steps. China and India have the most to lose from uncontrolled climate change, as they have huge populations living near sea level, and they have the most to gain from reduced local air pollution. Analogous to the approach of the Montreal Protocol, developing countries, with technical assistance, will need to reduce their emissions soon after the developed world reduces its emissions.

Furthermore, it makes economic sense for the United States to begin strong actions now to reduce emissions. Required technology developments in efficiency, renewable energies, truly clean coal, biofuels, and advanced nuclear power will produce good high-tech jobs and provide a basis for international trade that allows recovery of some of the wealth that the country has been hemorrhaging to China.

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 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.

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 CO_2 emissions from coal burning. Unless emissions from coal burning are reduced, actions to reduce other climate forcings cannot stabilize climate.

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.

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 CO_2 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.

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. 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 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 change continues to increase.

Coal will determine whether we continue to increase climate change or slow the human impact. Increased fossil fuel CO_2 in the air today, compared to the pre-industrial atmosphere, is due 50% to coal, 35% to oil and 15% to gas. As oil resources peak, coal will determine future CO_2 levels. Recently, after giving a high school commencement talk in my hometown, Denison, Iowa, I drove from Denison to Dunlap, where my parents are buried. For most of 20 miles there were trains parked, engine to caboose, half of the cars being filled with coal. If we cannot stop the building of more coal-fired power plants, those coal trains will be death trains – no less gruesome than if they were boxcars headed to crematoria, loaded with uncountable irreplaceable species.

So, how many of the exterminated species should be blamed on the 297,000,000 tons of CO_2 that will be produced in 50 years by the proposed Sutherland Generating Station Unit 4 power plant? If the United States and the rest of the world continue with "business-as-usual" increases in CO_2 emissions, a large fraction of the millions of species on Earth will be lost and it will be fair to assign a handful of those to Sutherland

Generating Station Unit 4, even though we cannot assign responsibility for specific species. Moreover, the effect of halting construction of this power plant potentially could be much greater, because of the possibility of positive feedbacks among people.

Q. What tipping points in human behavior are you referring to?

A. As the reality of climate change becomes more apparent, as the long-term consequences of further climate change are realized, and as the central role of coal in determining future atmospheric CO_2 is understood, the pressures to use coal only at power plants where the CO_2 is captured and sequestered will increase. If the public begins to stand up in a few places and successfully opposes the construction of power plants that burn coal without capturing the CO_2, this may begin to have a snowball effect, helping utilities and politicians to realize that the public prefers a different path, one that respects all life on the planet.

The changes in behavior will need to run much broader and deeper than simply blocking new dirty coal plants. Energy is essential to our way of life. We will have to find ways to use energy more efficiently and develop renewable and other forms of energy that produce little if any greenhouse gases. The reward structure for utilities needs to be changed such that their profits increase not in proportion to the amount of energy sold, but rather as they help us achieve greater energy and carbon efficiency. As people begin to realize that life beyond the fossil fuel era promises to be very attractive, with a clean atmosphere and water, and as we encourage the development of the technologies needed to get us there, we should be able to move rapidly toward that goal. But we need tipping points to get us rolling in that direction.

Iowa, and this specific case, can be a tipping point, leading to a new direction. A message that ‘old-fashioned’ power plants, i.e., those without carbon capture and sequestration, are no longer acceptable, would be a message of leadership, one that would be heard across Iowa and beyond the state’s borders.

Q. Alleged implications of continued coal burning without carbon capture are profound and thus require proof of a causal relationship between climate change and CO_2 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 CO_2 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.

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. 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 CO_2 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.

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.

Q. But those paleoclimate records show that the Earth's climate has changed by very large amounts many times in the past. For that reason, the NASA Administrator has suggested that we may not need to "wrestle" with human-made climate change. How do you reach a contrary conclusion?

A. 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.

Q. What is a climate forcing?

A. A climate forcing is an imposed perturbation to the Earth's energy balance, which would tend to alter the planet's temperature. For example, if the sun were to become 1% brighter, that would be a forcing somewhat more than +2 W/m^2, because the Earth absorbs about 238 W/m^2 of energy from the sun. An increase of greenhouse gases, which absorb terrestrial heat radiation and thus warm the Earth's surface, is also a positive forcing. Doubling the amount of atmospheric CO_2 is a forcing of about +4 W/m^2.

Q. How large are natural climate variations?

A. That depends on the time scale. A useful time scale to examine is the past several hundred thousand years. There is good data for the temperature, changes of atmospheric composition, and the most important changes on the Earth's surface. Specifically, we know the amount of long-lived greenhouse gases, CO_2, CH_4 and N_2O, as a function of time from air bubbles in the ice sheets. Ice sheets are formed by snowfall that piles up year by year and compresses into ice as the weight of snow above increases. The date when the snow fell is known accurately for about the past 15,000 years from counting annual layers marked by summer crusting. Annual layers can be clearly distinguished in the upper part of the ice sheet. Less precise ways of dating ice layers are available for the entire depth of the ice sheets. The temperature when the snowflakes fell is inferred from the isotopic composition of the ice.

Figure 2 shows the temperature on the Antarctic ice sheet for the past 425,000 years. Similar curves are found from Greenland and from alpine ice cores, as well as from ocean sediment cores. Layered ocean sediments contain the shells of microscopic animals that lived in the ocean, the proportion of elements in these microscopic shells providing a measure of the ocean temperature at the time the animals lived. Swings of temperature from warm interglacial periods to ice ages occur worldwide, with the glacial-interglacial temperature range being typically 3-4°C in the tropics, about 10°C at the poles, and about 5°C on global average.

We live today in a warm interglacial period, the Holocene, now almost 12,000 years in duration. The last ice age peaked about 20,000 years ago. Global mean temperature was about 5°C colder than today, with an ice sheet more than a mile thick covering Canada and reaching into the United States, covering the present sites of Seattle, Minneapolis, and New York. So much water was locked in this ice sheet, and other smaller ice sheets, that sea level was 110-130 meters (about 350-400 feet) lower during the ice age, thus exposing large areas of continental shelves.

Figure 3 shows that large changes of sea level are the norm as climate changes. Global sea level, global temperature, and atmospheric greenhouse gas amounts are obviously very highly correlated.

Q. The sea level changes are enormous. Is sea level always changing? What have the consequences been?

A. On millennial time scales resolvable in this graph, sea level, CO_2 and global temperature change together. However, close examination shows that sea level has been stable for about the past 7000 years. In that period the planet has been warm enough to prevent an ice sheet from forming on North America, but cool enough for the Greenland and Antarctic ice sheets to be stable. The fact that the Earth cooled slightly over the past 8000 years probably helped to stop further sea level rise.

Sea level stability played a role in the emergence of complex societies. When sea level was rising at the rate of 1 meter per century or faster biological productivity of coastal waters was limited. Thus it is not surprising that when the world's human population abandoned mobile hunting and gathering in the Neolithic (12,000-7000 years ago) they gathered in small villages in foothills and mountains. Day et al. note that within 1000 years of sea level stabilization, urban (>2500 people) societies developed at many places around the world (**Figure 4**). With the exception of Jericho, on the Jordan River, all of these first urban sites were coastal, where high protein food sources aided development of complex civilizations with class distinctions.

Modern societies have constructed enormous infrastructure on today's coastlines. More than a billion people live within 25 meter elevation of sea level. This includes practically the entire nation of Bangladesh, almost 300 million Chinese, and large populations in India and Egypt, as well as many historical cities in the developed world, including major European cities, many cities in the Far East, all major East Coast cities in the United States, among hundreds of other cities in the world.

Q. How much will sea level rise if global temperature increases several degrees?

A. Our best guide for the eventual long-term sea level change is the Earth's history. The last time the Earth was 2-3°C warmer than today, about 3 million years ago, sea level was about 25 meters higher. The last time the planet was 5°C warmer, just prior to the glaciation of Antarctica about 35 million years ago, there were no large ice sheets on the planet. Given today's ocean basins, if the ice sheets melt entirely, sea level will rise about 70 meters (about 230 feet).

The main uncertainty about future sea level is the rate at which ice sheets melt. This is a "nonlinear" problem in which positive feedbacks allow the possibility of sudden ice sheet collapse and rapid sea level rise. Initial ice sheet response to global warming is necessarily slow, and it is inherently difficult to predict when rapid change would begin. I have argued that a "business-as-usual" growth of greenhouse gases would yield a sea level rise this century of more than a meter, probably several meters, because practically the entire West Antarctic and Greenland ice sheets would be bathed in meltwater during an extended summer melt season.

The Intergovernmental Panel on Climate Change calculated a sea level rise of only 21-51 cm by 2095 for "business-as-usual" scenarios A2 and A1B, but their calculation included only thermal expansion of the ocean and melting of alpine glaciers, thus omitting the most critical component of sea level change, that from ice sheets. IPCC noted the omission of this component in its sea level projections, because it was unable to reach a consensus on the magnitude of likely ice sheet disintegration. However, much of the media failed to note this caveat in the IPCC report.

Earth's history reveals many cases when sea level rose several meters per century, in response to forcings much weaker than present human-made climate forcings. Iceberg discharge from Greenland and West Antarctica has recently accelerated. It is difficult to say how fast ice sheet disintegration will proceed, but this issue provides strong incentive for policy makers to slow down the human-made experiment with our planet.

Knowledge of climate sensitivity has improved markedly based on improving paleoclimate data. The information on climate sensitivity, combined with knowledge of how sea level responded to past global warming, has increased concern that we could will to our children a situation in which future sea level change is out of their control.

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 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.

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, including the indirect effect of CH_4 on other gases, is 3 ± 0.5 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 ± 1 W/m^2.

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 ¾°C per W/m^2. 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 ± 1°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 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.

When the sum of greenhouse gas and surface albedo forcings (**Figure 6b**) is multiplied by the presumed climate sensitivity of ¾°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.

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, the uptake and release of greenhouse gases.

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. CO_2, CH_4 and N_2O (not shown) are far outside their range of the past 800,000 years for which ice core records of atmospheric composition are available.

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.

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 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. However, these models do not include realistically all of the slow feedbacks, such as ice sheet and forest dynamics.

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 CO_2 varies a lot because carbon is exchanged among its surface reservoirs:

the atmosphere, ocean, soil, and biosphere. For example, the solubility of CO_2 in the ocean decreases as the ocean warms, a positive feedback causing much of the atmospheric CO_2 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 CO_2 changes than those caused by orbital oscillations. Larger CO_2 changes occur on long time scales because of transfer of carbon between the solid earth and the surface reservoirs. The large CO_2 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 CO_2 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 CO_2 in the air on long time scales?

On long (geologic) time scales CO_2 is exchanged between the surface reservoirs (atmosphere, ocean, soil and biosphere) and the solid Earth. Two processes take CO_2 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.

CO_2 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 CO_2, which makes its way to the atmosphere via volcanic eruptions or related phenomena such as 'seltzer' spring water. This return of CO_2 to the atmosphere is called 'outgassing'.

Outgassing and burial of CO_2, via weathering and organic deposits, are not in general balanced at any given time. 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 CO_2 changes by large amounts on geologic time scales.

Q. How much do these geologic processes change atmospheric CO_2?

A. Rates of outgassing and burial of CO_2 are each typically 2-4 x 10**12 mol C/year. An imbalance between outgassing and burial of say 2 x 10**12 mol C/year, if confined entirely to the atmosphere, would correspond to ~0.01 ppm CO_2 per year. However, the atmosphere contains only of order 10**(-2), i.e., about 1%, of the total CO_2 in the surface carbon reservoirs (atmosphere, ocean, soil, biosphere), so the rate of geologic changes to atmospheric CO_2 is only about 0.0001 ppm CO_2 per year. This compares to the present human-made atmospheric CO_2 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 CO_2 change is negligible compared to measured human-made changes today. However, in one million years a geologic imbalance of 0.0001 ppm CO_2 per year yields a CO_2 change of 100 ppm. Thus geologic changes over tens of millions of years can include huge changes of atmospheric CO_2, of the order of 1000 ppm of CO_2. 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 ~0.5% dimmer than today in the early Cenozoic. 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. 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 ~ 1 W/m^2.

In contrast, atmospheric CO_2 reached levels of 1000-2000 ppm in the early Cenozoic, 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. Climate variations in the Cenozoic are too large to be accounted for by such dynamical hypotheses.

Q. **What caused atmospheric CO_2 amount to change?**

A. At the beginning of the Cenozoic era, 65 My BP, India was just south of the Equator (**Figure 9**), but moving north rapidly, at about 15 cm/year. The Tethys Ocean, separating Eurasia from India and Africa, was closing rapidly. The Tethys Ocean had long been a depocenter for carbonate sediments. Thus prior to the collision of the Indian and African plates with the Eurasian plate, subduction of carbonate-rich oceanic crust caused outgassing to exceed weathering, and atmospheric CO_2 increased.

The Indo-Asian collision at ~50 My BP initiated massive uplift of the Himalayas and the Tibetan Plateau, and subsequently drawdown of atmospheric CO_2 by weathering has generally exceeded CO_2 outgassing. Although less important, the Alps were formed in the same time frame, as the African continental plate pushed against Eurasia. With the closing of the Tethys Ocean, the major depocenters for carbonate sediments became the Indian and Atlantic oceans, because the major rivers of the world empty into those basins. For the past 50 million years and continuing today, regions of subduction of carbonate rich ocean crust have been limited. Thus, while the oceans have been a strong sink for carbonate sediments, little carbonate is being subducted and returned to the atmosphere as CO_2. As a result, over the past 50 million years there has been a long-term decline of greenhouse gases and global temperature.

Q. Can you illustrate this long-term cooling trend?

A. Yes. **Figure 10a** shows a quantity, $\delta^{18}O$, that provides an indirect measure of global temperature over the Cenozoic era, with a caveat defined below. $\delta^{18}O$ defines the amount of the heavy oxygen isotope ^{18}O found in the shells of microscopic animals (foramininfera) that lived in the ocean and were deposited in ocean sediments. By taking ocean cores of the sediments we can sample shells deposited over time far into the past. **Figure 10a** shows the average result from many ocean cores around the world obtained in deep sea drilling programs.

The proportion of $\delta^{18}O$ in the foraminifera shell depends on the ocean water temperature at the time the shell was formed, and thus $\delta^{18}O$ provides a proxy measure of temperature. However, an ice sheet forming on the Earth's surface has an excess of ^{16}O in its H_2O molecules, because ^{16}O evaporates from the ocean more readily than ^{18}O, leaving behind a relative excess of ^{18}O in the ocean. As long as the Earth was so warm that little ice existed on the planet, as was the case between 65 My BP and 35 My BP, ^{18}O yields a direct measure of temperature, as indicated by the red curve and the temperature scale on the left side of **Figure 10a**.

The sharp change of δ^{18}O at about 34 My BP was due to rapid glaciation of the Antarctic continent. From 34 My BP to the present, δ^{18}O changes reflect both ice volume and ocean temperature changes. We cannot separate the contributions of these two processes, but both increasing ice volume and decreasing temperature change δ^{18}O in the same sense, so the δ^{18}O curve continues to be a qualitative measure of changing global temperature, chronicling the continuing long-term cooling trend of the planet over the past 50 million years.

The black curve in **Figure 10a** shows the rapid glacial-interglacial temperature oscillations, which are smoothed out in the mean (red and blue) curves. **Figure 10b** expands the time scale for the most recent 3.5 million years, so that the glacial-interglacial fluctuations are clearer. **Figure 10c** further expands the most recent 425,000 years, showing the familiar Pleistocene ice ages punctuated by brief interglacial periods. Note that the period of civilization within the Holocene is invisibly brief with the resolution in **Figure 10a**. *Homo sapiens* have been present for about 200,000 years, and the predecessor species, *Homo erectus*, for about 2 million years, still rather brief on the time scale of **Figure 10a**.

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 CO_2, 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, occurred when CO_2 fell to 500 ±150 ppm.

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 CO_2, perhaps due to the negative feedback caused by reduction of weathering 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 CO_2 was at a low level, about 200-400 ppm 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.

We suggest that the global cooling trend after 15 My BP may due to continued drawdown of atmospheric CO_2 of a degree beneath the detection limit of proxy measures. Little additional drawdown would be needed, because the increasing ice cover on the planet makes climate sensitivity extremely high, and the logarithmic nature of CO_2 forcing makes a small CO_2 change very effective at low CO_2 amounts. There are reasons to expect CO_2 drawdown in this period: the Andes were rising rapidly in this period, at a rate of about 1 mm per year (1 km per My). The mass of the Andes increased so much as to slow down the convergence of the Nazca and South American plates by 30% in the past 3.2 My. Increased weathering and reduced subduction both contribute to drawdown of atmospheric CO_2. Finally, a suggestion that CO_2 has been declining over the relevant period is provided by the increase of C4 plants relative to C3 plants that occurred between 8 and 5 My BP; C4 plants are more resilient to low atmospheric CO_2 levels (C4 and C3 photosynthesis are alternative biochemical pathways for fixing carbon, the C4 path requiring more energy but being more tolerant of low CO_2 and drought conditions). However, given the high climate sensitivity with large ice cover, other small forcings could have been responsible for the cooling trend without additional CO_2 decline.

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 CO_2. Human-made rates of change of climate forcings, including CO_2, now dwarf the natural rates.

Q. Is this relevant to the question of whether we need to "wrestle" with climate change?

A. Yes, it may help resolve the conundrum sensed by some lay persons based on realization that the natural world has undergone huge climate variations in the past. That is true, but those climate variations produced a different planet. If we follow "business as usual" greenhouse gas emissions, putting back into the air a large fraction of the carbon that was stored in the ground over millions of years, we surely will set in motion large climate changes with dramatic consequences for humans and other species.

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 45N 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.

Q. What are the current Earth orbital parameters?

A. Precession has the Earth closest to the sun in January, furthest in July, which would favor growth of Northern Hemisphere ice. But eccentricity is small, about 0.016, so the precession effect is not large. Tilt is about midway between its extremes headed toward smaller tilt, the next minimum tilt occurring in ~10 Ky. Smaller tilt favors ice sheet growth, so, if it were not for humans, we might expect a trend toward the next ice age. But the trend may have been weak, because, by the time tilt reaches its minimum, the sun will be closest to the sun in Northern Hemisphere summer. Thus in this particular cycle the two mechanisms, tilt and eccentricity + precession, will be working against each other, rather than reinforcing each other. In any event, this natural tendency has become practically irrelevant in the age of fossil-fuel-burning humans.

Q. Why is the natural glacial-interglacial cycle irrelevant?

A. Earth orbital changes were only pacemakers for glacial-interglacial climate change, inducing changes of ice area and greenhouse gases. Changes of surface albedo and greenhouse gases were the mechanisms for climate change, providing the immediate causes of the climate changes. We showed in **Figure 6** that these two mechanisms account for the glacial-interglacial climate variations.

Now humans are responsible for changes of these climate mechanisms. Greenhouse gases are increasing far outside the range of natural glacial-interglacial variations (**Figure**

8) and ice is melting all over the planet. The weak effect of slow orbital changes is overwhelmed by the far larger and faster human-made changes.

Humans are now entirely responsible for long-term climate change (**Figure 13**). However, it would be misleading to say that humans are "in control". Indeed, there is great danger that humans could set in motion future changes that are impossible to control, because of climate system inertia, positive feedback, and tipping points.

Q. Can we finally finish with this paleoclimate discussion?

A. Please allow one final comment. For the record, since I could only estimate broad ranges for CO_2 in the Cenozoic era, I should show at least one estimate from the proxy CO_2 data. **Figure 14A** shows estimated CO_2 for the entire Phanerozoic eon, the past 540 million years. I show this longer time interval, because it includes CO_2 changes so large as to make the errors in the proxies less in a relative sense.

Geologic evidence for ice ages and cool periods on this long time frame (**Figure 14B**) shows a strong correlation of climate with CO_2. Climate variations were huge, ranging from ice ages with ice sheets as far equatorward as 30 degrees latitude to a much warmer planet without ice. Although other factors were also involved in these climate changes, greenhouse gases were a major factor.

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 ~3°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 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.

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, 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.

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.

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 CO_2) 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 <u>emissions</u> of greenhouse gases. Atmospheric greenhouse gas amounts may be affected by feedbacks, which thus alter expected climate change.

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, but not to a degree that has prevented near stabilization of atmospheric methane amount over the past several years.

Paleoclimate records show 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.

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.

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".

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 ~3°C for doubled CO_2, driven by the climate forcings in **Figure 15A**, yields an imbalance of 0.75 ± 0.15 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 ~0.5 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 ± 0.25 W/m^2.

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 CO_2. 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) CO_2 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 CO_2 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/m^2, assuming a climate sensitivity of about 3°C for doubled CO_2, and in turn this requires that CO_2 be kept from exceeding about 450 ppm, with the exact limit depending upon how well other climate forcings are constrained, especially methane. **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.

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 raise, (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.

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.

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 Lauren tide 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 Lauren tide 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 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. **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.

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.

However, I also note that there is an enormous difference between global warming less than 1°C and global warming of 2-3C. 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 CO_2, if the additional warming is 2-3°C, it will be impractical to avoid 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. 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 CO_2 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.

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. CO_2 is the one climate forcing that is increasing much more rapidly than in the alternative scenario, and if CO_2 emissions continues on their current path CO_2 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.

Q. Why are CO_2 and coal the focus of climate concerns?

A. **Figure 29a** shows one crucial fact. When a pulse of CO_2 is added to the atmosphere by burning fossil fuels, half of the CO_2 disappears from the air within about 25 years, being taken up by carbon sinks, principally the ocean. However, uptake then slows as the CO_2 added to the ocean exerts a 'back pressure' that inhibits further uptake. About one-fifth of the initial increase is still present in the atmosphere after 1000 years. Complete removal of the pulse depends upon formation of carbonate sediments on the ocean floor, a very slow process. It is this long atmospheric lifetime that makes CO_2, on the long run, the principal climate forcing for human-made climate change.

Q. Why do you focus especially on coal?

A. Part of the reason is the size of the coal carbon reservoir, shown in **Figure 29b**. The coal reservoir is larger than either oil or gas. The amount of CO_2 already emitted to the atmosphere, shown by the purple portions of the bar graphs, is about 50% from coal, 35% from oil and 15% from gas. On the long run, coal will be even much more important.

Proven and estimated reserves of these fossil fuels are uncertain, and the amounts shown in **Figure 29b** for oil and coal both could be substantially over-estimated. Many experts believe that we are already at a point of having used approximately half of the economically recoverable reserves of oil. In that case we are already at approximately the point of 'peak oil' production and oil use will soon begin to noticeably decline because of resource constraints.

Uncertainties in the oil and gas reserves have little qualitative effect on the climate discussion, however. The reasons are, first, that remaining oil and gas, used at any feasible rate, can at most only take atmospheric CO_2 to approximately 450 ppm. Second, it is impractical to avoid the use of readily extractable oil and gas, and most of the CO_2 resulting from that oil and gas will be emitted to the atmosphere, because it is emitted by small sources where it is impractical to capture the CO_2.

Coal reserves are also uncertain and it is likely that the estimates in **Figure 29b**, even the smaller estimate of EIA (Energy Information Agency), are too high. Nevertheless, there is more CO_2 in coal than in the other conventional fossil fuels. Indeed, there is enough

CO_2 in coal to take the Earth far into the 'dangerous' zone of climate change, to doubled atmospheric CO_2 and even beyond.

The second critical fact about coal is that it is possible to imagine coal being used only at power plants to generate electricity, with the CO_2 emissions captured and sequestered, with the carbon put back underground where it came from. Indeed, the elementary carbon cycle facts summarized in **Figure 29** dictate the solution to the global warming problem.

Q. Can a solution to global warming be defined?

A. An outline of a practical solution can be defined readily (**Figure 30**). By far the most important element in this solution, indeed 80% of the solution, is phase-out of coal use except at power plants where the CO_2 is captured and sequestered. This requirement is dictated by the fundamental facts of the carbon cycle summarized in **Figure 29**.

The steps needed to achieve termination of CO_2 emissions from coal use are: (1) a moratorium in developed countries on construction of new coal-fired power plants until the technology is ready for carbon-capture and sequestration, (2) a similar subsequent moratorium in developing countries, (3) a phase-out over the next several decades of existing old-technology coal plants, with replacement by coal-fired plants that capture and sequester the CO_2, energy efficiencies, renewable energies, or other sources of energy that do not emit CO_2.

Figure 31 defines a specific scenario: developed countries halt construction by 2012 of any coal-fired power plants that do not capture and sequester CO_2, developing countries halt such construction by 2022, and all existing coal-fired power plants without sequestration are 'bull-dozed' by 2050 (linear decrease of their emissions between 2025 and 2050). The 10-year delay of the moratorium for developing countries is analogous to that allowed by the Montreal Protocol in chlorofluorocarbon phase-out and it is justified by the primary responsibility of developed countries for the current excess of greenhouse gases in the atmosphere as well as by the much higher per capita emissions in developed countries.

Figure 32 shows that continued business-as-usual emission of CO_2 will more than double the pre-industrial amount of CO_2 (280 ppm) in the air, even though we have neglected feedbacks that would likely accompany such large emissions and we have included no emissions from unconventional fossil fuels (tar shale, tar sand, heavy oil, etc.). **Figure 33** shows that this specified phase-out of coal emissions keeps the maximum future atmospheric CO_2 level at about 450 ppm.

Q. Is it plausible for coal-fired power plants without carbon capture to be phased out?

A. The time scale for action used in calculations for **Figures 32 and 33**, with moratoriums in developed countries by 2012 and in developing countries by 2022, are conservative, our aim being to show that it is practical to keep CO_2 below 450 ppm. However, because it is becoming increasingly likely that an additional 1°C global warming will cause substantial climate impacts, it is highly desirable to take action sooner.

I believe that the plausibility of obtaining actions in time depends upon whether citizens become informed and place pressure on the decision-making process. It seems highly unlikely that national governments, which are under the strong influence of fossil fuel special interests, will exercise the required leadership. Even Germany, among the ‘greenest’ of all nations, is making plans to build coal-fired power plants without carbon capture. Clearly decision-makers do not yet ‘get it’. The public must become more involved, if they hope to preserve creation.

Those who argue that it is implausible to ‘bulldoze’ old technology power plants, while energy efficiency and clean energy sources are expanded, might compare the task with the efforts put into World War II. It is a feasible undertaking.

Q. If coal is 80% of the solution, what is the other 20%?

A. There must be a gradually increasing price on carbon emissions. A carbon price is essential to wean us off of our fossil fuel addiction. Without such a phased withdrawal we will soon begin to exhibit the behavior of a desperate addict, attempting to squeeze carbon fuels out of unconventional or remote sources, e.g., ‘cooking’ the Rocky Mountains to drip oil out of tar shale and traveling to extreme environments such as the Arctic National Wildlife Refuge to extract every last drop of oil from the ground.

The irrationality of this behavior is apparent from the realization that fossil fuels are finite. We must learn to live without them as they dwindle. If we begin sooner, we can live with cleaner air and water, preserve creation, and pass on to our children a healthy planet with almost all of the species that we found when we arrived.

Q. A carbon price? Does that mean a tax?

A. It could be a tax, but there are various options, and it does not need to increase the amount of money extracted from citizens by the government. It might include rations that could be bought and sold, cap and trade emission quotas for industries, and other alternatives that stimulate energy and carbon efficiencies, including renewable energies and other forms of energy that do not produce greenhouse gases. This price can start small, the key requirement being certainty that it will continue to rise, because this is the stimulus that the business community needs to make the essential long-term investments. The price must promise to be large enough that it stimulates technology development, but it must not be so large or rise so rapidly that it harms the economy.

It is a truism that a strong economy is needed to afford the investments needed for a clean environment and stable climate. It is desirable to separate the decisions on altering the carbon price from short-term political considerations. One way to achieve this would be via a "Carbon Tsar", analogous to the Chairman of the Federal Reserve, who would carefully adjust the carbon price so as to optimize economic and environmental gain.

Q. Can coal phase-out and a gradually rising carbon price solve the climate problem?

A. These would need to be accompanied by sensible actions. A gradually rising price is not sufficient for the demand reductions that will be needed to phase off the fossil fuel addiction fast enough. There need to be improved efficiency standards on buildings, vehicles, appliances, lighting, electronic devices, etc. Regulations on utilities need to be modified so that profits grow when the utilities help consumers waste less energy, rather than profits being in proportion to amount of energy sold. The government should be supporting more energy research and development, and more effectively, than it is now.

However, the coal phase-out and carbon price are the essential underpinnings. Without these, other actions are nearly fruitless, only yielding a modest slowing of emissions growth.

Q. But are even these enough, if we are so close to a dangerous greenhouse gas level?

A. There are additional actions that could close the gap between where we are and where we need to be to stabilize climate, even if we are slightly overshooting the dangerous level. However, these other actions can close the gap only if we get onto a path to stabilize CO_2

in the near future. Without getting onto a downward path of CO_2 emissions, these other actions provide little respite.

The planet is now out of energy balance by something between 0.5 and 1 W/m^2. If we reduced human-made climate forcings by that amount, the warming 'in-the-pipeline' would be eliminated, the forcing leading to a continual warming tendency would be eliminated. **Figure 35** shows that there is a large enough climate forcing in pollutant forcings, specifically, tropospheric ozone, especially its precursor methane, and black soot, to offset the present planetary energy imbalance, if we should make major reductions of these pollutants.

Some of these non-CO_2 forcings are particularly effective in the Arctic, so it may even be possible to save the Arctic from further ice loss by means of special efforts to reduce these forcings, coupled with stabilization of atmospheric CO_2. There are other benefits of such an effort: these pollutants are harmful to human health, being a primary cause of asthma and other respiratory and cardiovascular problems, and they reduce agricultural productivity.

Q. Even if these forcings are reduced, will not the benefits soon be erased by inevitable increases of CO_2? It is said that even a 450 ppm limit on CO_2 in inconceivable.

A. It is said by whom? Fossil fuel companies, and government energy departments, take it as a god-given fact that all fossil fuels will be burned because they are there. That may almost be true for the readily mined oil and gas. However, we have shown above that even with generous estimates for undiscovered oil and gas reserves, CO_2 never exceeds 450 ppm if coal use is phased out except at power plants that capture and sequester the CO_2. Old technology coal-fired power plants must be replaced by 2050, but the pressure for doing so will mount as climate change and its consequences become more apparent, especially the consequences for China, India and Bangladesh.

Q. But CO_2 is already 385 ppm and increasing about 2 ppm per year. Does not simple arithmetic say that we will pass 450 ppm within a few decades?

A. Yes, if we keep increasing fossil fuel CO_2 emissions. But that is not a god-given fact.

Q. But even if emissions from coal use are reduced, today's oil plus gas emissions exceed coal emissions. How can coal be so important?

A. Phasing out coal emissions will reduce the annual growth rate of atmospheric CO_2. Today, and for the period of accurate CO_2 data, the annual increase of CO_2 in the air averages 57% of the fossil fuel emissions (**Figure 36**), despite the fact that we (the world) have not done a good job of limiting deforestation and we have not done a good job of encouraging agricultural practices that would sequester CO_2 in the soil. If we reduce CO_2 emissions from coal, the airborne fraction of CO_2 will decrease in the near and medium term, so there would be a more than proportionate decrease of the annual growth in atmospheric CO_2.

Q. But will not a decrease in emissions of CO_2 from coal be offset by a continuing increase in emissions of CO_2 from oil?

A. On the contrary, oil production is going to peak and CO_2 emissions from oil will inevitably decline, if not now then surely within the next few decades. And there is considerable potential, via improved forestry and agricultural practices, to do much better at sequestering CO_2 in soil and in forests, as opposed to the loss (emission) of CO_2 from forests and soils in the past.

Q. But you admit that we are likely to pass the dangerous level of CO_2. Is there anything that can be done in that case?

A. In the short-term we only have to reduce CO_2 emissions by more than 57% for atmospheric CO_2 to begin to decline (in the long run the reduction must be larger). However, there is at least one feasible way to draw CO_2 from the atmosphere. As summarized in **Figure 37**, if biofuels were burned in power plants, with the CO_2 captured and sequestered, atmospheric CO_2 could be drawn down. The growing vegetation would take in CO_2 from fossil fuel-elevated atmospheric levels, and this CO_2 would then be captured at the power plant. In effect, fossil fuel CO_2 would be put back underground, where it had come from.

The biofuels should be extracted from natural grasses or other cellulosic fibers farmed in a way that promotes soil conservation and carbon storage in the soil. Such an approach contrasts with production of corn-based ethanol, which in net is ineffective at reducing atmospheric CO_2.

Q. Rather than go to this trouble, can we not adapt to the impacts of climate change?

A. Yes, leaving aside the effects of large changes in regional climate extremes and the extermination of species, we could deal with a one meter rise of sea level by making a lake large enough to hold that much water. Two hundred meter dams at the locations indicated in **Figure 38** could hold that much water. A large number of people would be displaced by this lake. It may require difficult negotiations with Canada. And if we allow ice sheets to disintegrate to the point of one meter sea level rise, we can be quite sure that another meter is on the way.

Q. Is there not a good place for another lake?

A. Yes, it would require higher dams (242 meters), but one meter of sea level could be stored in Russia (**Figure 39**). This also displaces a large number of people. And if we let the ice sheets go that far, there is probably two more meters of sea level on the way. There are no remaining geological candidates for storing that much water. So the historic coastal cities are sunk. It seems that the adaptation path is a lot like appeasement; it just gets you into deeper trouble.

Q. Well then, is there still time to avoid the climate problems?

A. Yes, there is still time (**Figure 40**). As shown above, we can just barely still avoid 450 ppm by phasing out coal use except at power plants that capture and sequester CO_2. It requires an almost immediate moratorium on new coal-fired power plants in the West, and, within a decade later, a moratorium in the developing world.

Q. Isn't this going to cause energy shortages and blackouts?

A. Not if we exploit the potentials in energy efficiency, renewable energies, nuclear power, or other energy sources that do not produce greenhouse gases. We are going to have to learn to do that someday anyhow, and it is an enormous economic advantage to us if we learn it sooner rather than later. Others, including China, will need better technologies. If we get there first, we will have something to sell them. We might get some of the money back that we have been sending over there.

Q. Why take the first step? Why not demand that China act at the same time?

A. I already mentioned the economic reason. In addition, we are responsible for the problem. China has just passed us in current emissions, but the climate change is due to cumulative emissions, not current emissions. The United States is responsible for more than three times as much of cumulative CO_2 emissions as any other country, and we will continue to be most responsible for decades. Even with China's high current emissions, our per capita emissions are five times as great as China's.

Q. Is there any evidence that such an approach would work?

A. Certainly. The prior global atmospheric threat, destruction of the ozone layer, was solved with just such an approach. When the science suggested that chlorofluorocarbons (CFCs) had the potential to destroy the stratospheric ozone layer, there was an immediate moratorium on building of more CFC factories. Consumers played a big role in reducing demand, and immediately annual CFC production stabilized (**Figure 43**). Later, when the Antarctic Ozone hole was discovered, the Montreal Protocol was adopted and later strengthened several times, phasing out production of these chemicals. A key aspect of this protocol was that developing countries should have an extra ten years to implement the phase-out, and they should be provided with technical assistance to achieve it.

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 become 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, not 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.

Q. So you think that replacing some people in congress can solve the problem?

A. It is important to replace members of Congress who place the profits of special interests above the future of our children and grandchildren, but even with personnel changes I would not expect Congress to solve the climate crisis without more direct help from the public. Strong specific messages are needed. Rejection of a coal-fired power plant that does not capture CO_2 is such a message.

Of course such an action then places obligations on various parties. Steps must be taken to promote greater energy efficiency and acquisition of alternative energy sources. These are challenges that can be met and that will yield benefits in the future.

Q. Do you see reason for optimism if such steps are taken?

A. Yes. CO_2 is the main problem. **Figure 49d** shows that the growth of CH_4 is falling below even the alternative scenario, far below all IPCC scenarios. **Figure 49e** shows that the growth of N_2O is close to the alternative scenario and below most IPCC scenarios. **Figure 49f** shows that the growth of Montreal Protocol trace gases and other trace gases is falling below all IPCC scenarios and is approaching the alternative scenario. So the growth of the non-CO_2 climate forcings is encouraging.

Indeed, if we look at the growth rate of the sum of all long-lived greenhouse gases (**Figure 50**), we see that is it falling between the IPCC scenarios and the alternative scenario. The reason that the net forcing is higher than in the alternative scenario is that the actual CO_2 growth rate has exceeded the growth rate for CO_2 assumed in the alternative scenario. Actual recent CO_2 increases have averaged close to 2 ppm per year, while the alternative scenario requires the growth rate of the late 1990s (1.7 ppm) to decline to ~1.3 ppm per year by mid century. (If it turns out that 1°C additional global warming is dangerous, then an even steeper decline may be needed.)

Clearly a much more promising future than in IPCC business-as-usual scenarios is possible. The issue is CO_2 and more specifically it is coal. It is still possible to get on the alternative scenario track, and even do better than that scenario, but only if coal emissions begin to decline. Once the CO_2 emissions are in the air we cannot get them back – a large fraction will stay in the air more than 1000 years.

Q. Can you summarize the status of the matter?

A. **Figures 51 and 52** are my summary and my personal observations, my personal opinion. The climate surely is approaching tipping points, with the potential for us to lose control of the consequences. A solution is feasible and the required actions would have many side benefits. Opposition, it seems to me, stems primarily from short-term special financial interests, whose effective misinformation campaigns make the struggle to inform difficult.

This is a matter which should unite those of conservative and liberal bents. The core issue is one of generational inequity. Younger people can help by making clear that they recognize the difference between words and deeds. Stalling and misinformation may help keep short-term profits flowing, but the legacy that it leaves on the planet will not be erased or forgotten.

Q. Do you have any final comment for the Board?

A. Yes. I would like to express my gratitude to the State of Iowa, which has always been so generous in providing educational opportunities to its people, even as many graduates go on to careers in other states across the nation. I was extremely fortunate to be able to attend the University of Iowa, and especially to learn in the Department of Physics and Astronomy of Prof. James Van Allen. I thank Bruce Johansen and Ines Horovitz for comments on this testimony, and Makiko Sato for technical scientific assistance and my wife Anniek for her tolerance of inordinate obsessions.

Q. Does this conclude your prepared Direct Testimony?

A. Yes.