

Dangerous Human-Made Interference with Climate

Testimony of

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to

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1. Summary

Crystallizing scientific data and analysis reveal that the Earth is close to dangerous climate change, to tipping points of the system with the potential for irreversible deleterious effects. The information derives in part from paleoclimate data, the record of how climate changed in the past, as well as from measurements being made now by satellites and in the field.

The Earth's history shows that climate is remarkably sensitive to global forcings. Positive feedbacks predominate. This has allowed the entire planet to be whipsawed between climate states. Huge natural climate changes, from glacial to interglacial states, have been driven by very weak, very slow forcings, and positive feedbacks.

Now humans are applying a much stronger, much faster forcing as we put back into the atmosphere, in a geologic heartbeat, fossil fuels that accumulated over millions of years. Positive feedbacks are beginning to occur, on a range of time scales.

The climate system has inertia. Nearly full response to a climate forcing requires decades to centuries. But that inertia is not our friend. It means that there is additional climate change in the pipeline that will occur in coming decades even without additional greenhouse gases.

The upshot is that very little additional forcing is needed to cause dramatic effects. To cause the loss of all summer Arctic ice with devastating effects on wildlife and indigenous people. To cause an intensification of subtropical conditions that would greatly exacerbate water shortages in the American West and many other parts of the world, and likely render the semi-arid states from west and central Texas through Oklahoma, Kansas, Nebraska and the Dakotas increasingly drought prone and unsuitable for agriculture. To cause the extermination of a large fraction of plant and animal species, an indictment of humanity's failure to preserve creation.

For humanity itself, the greatest threat is the likely demise of the West Antarctic ice sheet as it is attacked from below by a warming ocean and above by increased surface melt. There is increasing realization that sea level rise this century may be measured in meters if we follow business-as-usual fossil fuel emissions.

There is a bright side to this planetary emergency. We can successfully address the emergency only by stabilizing climate close to its present state; there is no viable option. Adaptation to a continually rising sea level is not possible. Therefore, if we address the problem, there will be no need to adapt to the highly deleterious regional climate changes mentioned above. In the process we can preserve creation and restore a cleaner, healthier atmosphere.

The dangerous level of CO₂ is at most 450 ppm, and it is probably less. The low limit on CO₂ forces us to move promptly to the next phase of the industrial revolution. Changing light bulbs and making ethanol from corn will not solve the problem, although the former act is useful. Science provides a clear outline for what must be done, a four point strategy:

First, we must phase out the use of coal and unconventional fossil fuels except where the CO₂ is captured and sequestered. There should be a moratorium on construction of old-technology coal-fired power plants.

Second, there must be a rising price (tax) on carbon emissions, as well as effective energy efficiency standards, and removal of barriers to efficiency. These actions are needed to spur innovation in energy efficiency and renewable energies, and thus to stretch oil and gas supplies to cover the need for mobile fuels during the transition to the next phase of the industrial revolution 'beyond petroleum'.

Third, there should be focused efforts to reduce non-CO₂ human-made climate forcings, especially methane, ozone and black carbon.

Fourth, steps must be taken to 'draw down' atmospheric CO₂ via improved farming and forestry practices, including burning of biofuels in power plants with CO₂ sequestration.

Note that I do not specify an exact fraction by which CO₂ emissions must be reduced by 2050 or any other date. Indeed, science is not able to specify an exact requirement now, but we can say that emissions must be reduced to a fraction of their current values. Given the fact that readily available oil will surely be employed for mobile sources, and given the magnitudes of the different fossil fuel reservoirs, it seems best to frame the problem as I have in this four-point strategy, and adjust specific targets and policies as knowledge improves.

Responsibility of the United States for global climate change exceeds that of any other nation by more than a factor of three, even though China is passing the United States in current emissions. The United States will continue to be primarily responsible for climate change for decades to come.

The above conclusions follow from the science. In part because of resistance that the scientific conclusions have met among special interests, and because of misinformation about the science that has been spread, I believe that it is not inappropriate for me to discuss my opinions about implications of this research for citizens in our democratic system. My opinions carry no more weight than those of any other citizen, but conceivably my experience in presenting this research in different circles allows some insight. In any case, I have as much right to express my opinion as do the special interests.

In my opinion, the United States should recognize openly its leading role in causing human-made climate change and promptly take a leadership role in addressing the matter. We have a moral responsibility to do so.

Moreover, it is in our interest to take actions now. We can benefit economically from extensive technology development, with many good high-tech high-pay jobs. Of course, moving to the next phase of the industrial revolution will require changes, dislocations, sacrifices and hard work. But these provide no reason for inaction.

We cannot let the pleadings and misinformation of special interests determine our actions, special interests driven by motives of short-term profit. And we cannot shrink from our personal responsibilities. We are now, through our government, standing alongside the polluters, officially as a hulking ‘friend of the court’, arguing against limitations on emissions.

Is this the picture of our generation we will leave for our children, a picture of ignorance and greed? We live in a democracy. Policies represent our collective will. We cannot blame others. If we allow the planet to pass tipping points, to set in motion irreversible changes to the detriment of nature and humanity, it will be hard to explain our role to our children and grandchildren.

We cannot claim, with legitimacy, that ‘we did not know’. In my opinion, it is time for the public to demand, from government and industry, priority for actions needed to preserve the planet for future generations.

2. Basis for Testimony

My testimony is derived primarily from the six publications listed below. It is based on a much broader body of knowledge of the scientific community, which is not practical to document in the brief hours available to prepare this testimony.

The first three publications below are now ‘in press’ and will appear in coming weeks. These three papers are in regular peer-reviewed scientific journals, each having been reviewed by either two or three scientific peers. The fourth publication also has been reviewed and recommended for publication by both anonymous referees; I will make some slight edits to that paper before returning it to the journal within the next few weeks. The fifth article is my attempt to describe conclusions from this research in a language intended for a broader audience. The

sixth article is the draft of an article, available as a referenceable preprint in the physics electronic *ArXiv*, which we will soon be submitting to a regular print journal.

A. Dangerous human-made interference with climate: a GISS modelE study

(Hansen, J, and 46 co-authors, *Atmos. Chem. Phys.*, in press, 2007, available at http://pubs.giss.nasa.gov/abstracts/inpress/Hansen_etal_3.html)

B. Climate change and trace gases

(in press: *Phil. Trans. Royal Soc.*)
http://pubs.giss.nasa.gov/abstracts/inpress/Hansen_etal_2.html

C. Climate simulations for 1880-2003 with GISS modelE

(in press: *Climate Dynamics*) <http://arxiv.org/abs/physics/0610115>

D. Scientific reticence and sea level rise

(accepted for publication: *Environ. Res. Lett.*) <http://arxiv.org/abs/physics/0703220>

E. State of the Wild: Perspective of a Climatologist

(accepted, to be edited) <http://www.giss.nasa.gov/~jhansen/preprints/Wild.070410.pdf>

F. Implications of “peak oil” for atmospheric CO₂ and climate

(first draft available in ArXiv) <http://arxiv.org/abs/0704.2782>

3. Crystallizing Science

In the past few years it has become clear that the Earth is close to dangerous climate change, to tipping points of the system with the potential for irreversible deleterious effects. Paleoclimate data show that climate is remarkably sensitive to global forcings. Positive feedbacks have caused the entire planet to be whipsawed between climate states, driven by very weak climate forcings.

The time scale for full glacial-to-interglacial climate changes is millennia. However, this millennial time scale reflects the time scale of the slow weak climate forcing due to Earth orbital changes, not an inherent climate response time. Indeed, the response time of the climate system to rapid forcings, such as human-made greenhouse gases, will be decades to centuries, a function of ocean mixing time and climate feedbacks.

This decade-century climate response time is unfortunate for humanity. It is long enough to prevent people from seeing immediate consequences of human-made climate forcings, as much of the climate change is still ‘in the pipeline’. Yet it is short enough for large climate impacts to occur this century.

The concept of additional global warming ‘in the pipeline’ is not new, but it has become more ominous through the realization that several nominally ‘slow’ climate feedbacks are likely to have significant effect on decadal time scales. These include poleward movement of vegetation, darkening and disintegration of ice sheets, and greenhouse gas feedbacks. These ‘slow’ feedbacks, which are not included in their entirety in standard IPCC simulations, are positive and thus they amplify expected anthropogenic climate change.

The implication of the crystallizing scientific understanding is that the planet is on the verge of dramatic climate change. It is still possible to avoid the most deleterious effects, but only if prompt actions are taken to stabilize global temperature close to its present value. Because of the profound implications, it is appropriate to clarify the basis of these conclusions.

We first discuss fundamental aspects of the climate system: climate forcings, feedbacks and response times. We then make note of how the Earth’s climate responded to forcings in the

past few million years. Finally, we summarize the basis for the conclusion that present climate is on the verge of critical tipping points.

A. Climate System

Climate is an average of weather over some period, including the variability and extremes within that period. Because day-to-day weather fluctuations are so large, it is not easy to notice small changes of the average weather or climate. However, moderate changes of climate can have significant effects, for example, on the ability of plants and animals to survive in a given region and on the stability of large ice masses and thus sea level.

Climate varies a lot without any help from humans. In part the variations are simply chaotic fluctuations of a complex dynamical system, as the atmosphere and ocean are always sloshing about. The climate also responds to natural forcings, such as changes of the brightness of the sun or eruptions of large volcanoes, which discharge small particles into the upper atmosphere where they reflect sunlight and cool the Earth.

Climate forcing. A climate forcing is a perturbation of the Earth's energy balance that tends to alter the Earth's temperature. For example, if the brightness of the sun increases 2% that is a positive forcing of about 4.5 W/m^2 (watts per square meter), because it results in an increase of that amount in the energy absorbed by the Earth. Such a forcing would upset the normal balance that exists between the amount of solar energy absorbed by the Earth and the amount of heat radiation emitted to space by the Earth. So the Earth responds to this forcing by warming up until its thermal radiation to space equals the energy absorbed from the sun.

Doubling the amount of carbon dioxide (CO_2) in the atmosphere causes a global climate forcing similar in magnitude to that for a 2% increase of solar irradiance. The CO_2 forcing works by making the atmosphere more opaque to infrared radiation, the wavelengths of the Earth's heat radiation. As a result of this increased opacity the heat radiation to space arises from greater heights in the atmosphere. Because the temperature falls off with height in the lower atmosphere, energy radiated to space with doubled CO_2 is reduced by an amount that is readily calculated from radiation physics to be approximately 4 W/m^2 . So the planet's energy imbalance is about the same as for a 2% increase of solar irradiance. In either case, the Earth responds by warming up enough to restore energy balance.

Climate models show that, as might be expected, two forcings of similar magnitude yield similar global temperature change, although variations in the "efficacy" of specific forcings of the order of 20% are not uncommon, and a few more extreme cases have been found. Variations in efficacy are primarily a result of the differences in the physical locations (latitude or altitude) of the forcings, which affects the degree to which the forcings can bring climate feedbacks into play, as discussed below.

Climate sensitivity and climate feedbacks. Global climate sensitivity is usually defined as the global temperature change that occurs at 'equilibrium', i.e., after the climate system has had a long time to adjust, in response to a specified forcing. The specified forcing is commonly taken to be doubled CO_2 , thus a forcing of about 4 W/m^2 .

Climate sensitivity can be evaluated either theoretically, with the help of climate models, or empirically, from the Earth's climate history. In either case, it must be recognized that the climate sensitivity so inferred depends upon what climate variables are fixed as opposed to being allowed to change in response to the climate forcing.

The now famous 1979 National Academy of Sciences study of climate sensitivity chaired by Jules Charney focused on a case in which atmospheric water vapor, clouds and sea ice are allowed to vary with the climate, but other factors such as ice sheets and the global distribution of vegetation are kept fixed as unchanging boundary conditions. Also long-lived greenhouse

gases (GHGs), such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are taken as specified boundary conditions or forcings.

In reality all of these boundary conditions can change in response to climate change, in which case they become climate feedbacks that can be either positive feedbacks (magnifying the climate change) or negative feedbacks (diminishing the climate change). The choice of feedbacks that were allowed to operate in the Charney study (water vapor, clouds, sea ice) was in part based on realization that these variables change rapidly, i.e., they are ‘fast feedbacks’. Thus if one is interested in climate change on the time scale of decades or longer, these feedbacks must be allowed to operate. Ice sheets and forest cover, on the other hand, might be considered ‘slow feedbacks’, not expected to change much on decadal time scales. In addition, climate models were not yet capable of modeling these slower processes.

The Charney study suggested that equilibrium climate sensitivity was ~3°C (5.4°F) for doubled CO₂, with uncertainty at least 50% (1.5°C). Improving climate models continue to yield global climate sensitivity ~3°C for doubled CO₂, but uncertainty remains because of the difficulty of accurately simulating clouds.

A more definitive evaluation of climate sensitivity is provided by the Earth’s history. With the same choices for the variables specified as forcings, empirical data for climate change over the past 700,000 years yield a climate sensitivity of ¾°C for each W/m² of forcing, or 3°C for a 4 W/m² forcing. (see Figure 2 of Reference B). This empirical evaluation of climate sensitivity eliminates the concern with climate models, that they may inadvertently exclude important processes. The real world climate change included any cloud feedbacks that exist.

Climate response time. A practical difficulty with climate change arises from the fact that the climate system does not respond immediately to climate forcings. Figure 1 shows the climate response to a forcing introduced at time t = 0. It requires about 30 years for 50% of the eventual (equilibrium) global warming to be achieved, about 250 years for 75% of the response, and perhaps a millennium for 90% of the surface response.

The exact shape of this response function depends upon the rate of mixing in the ocean, thus upon the realism of the ocean model that is used for its calculation. The response time also depends upon climate sensitivity, the response being slower for higher sensitivity. The reason for this is that climate feedbacks come into play in response to climate change, not in response to the forcing per se, and thus with stronger feedbacks and higher climate sensitivity the response time is longer. The curve in Figure 1 was calculated for sensitivity 3°C for doubled CO₂.

This long response time means that even when GHGs stop increasing, there will be additional warming “in the pipeline”. Thus we have not yet felt the full climate impact of the gases that have already been added to the atmosphere. This lag effect makes mitigation strategies more arduous.

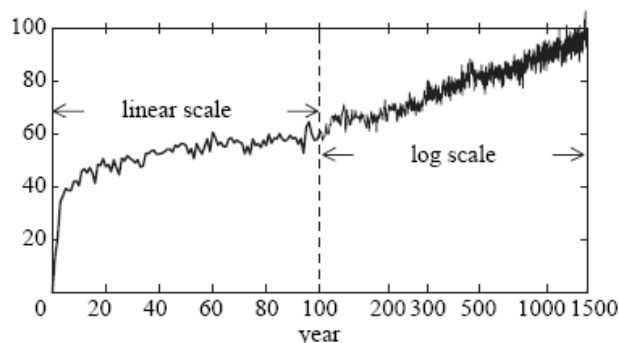


Figure 1. Climate response function (percent of equilibrium response) based on global surface air warming of GISS modelE coupled to Russell ocean model (Reference B).

Slow climate feedbacks. The ‘Charney’, or fast feedback, climate sensitivity is intended to be relevant to decadal time scales. But it is becoming clear that other feedbacks, omitted because they are ‘slow’ and difficult to deal with, may also be important.

One ‘slow’ feedback is the poleward movement of forests with global warming. If evergreen forests replace tundra and scrubland vegetation, it makes the surface much darker. Trees are ‘designed’ to capture photosynthetic radiation efficiently, and thus they can provide a strong positive climate feedback. Forest cover is a powerful positive feedback at Northern Hemisphere high latitudes, and significant changes are already beginning.

Another ‘slow’ feedback is associated with ice sheets. An ice sheet does not need to disappear for significant feedback to occur: just the change of ice surface albedo (reflectivity) that occurs with increased area and melt season duration contributes a large local climate feedback. This feedback occurs in a region where warming is especially important, because of the effect of warming on ice sheet disintegration and sea level rise. Increased areas of surface melt, and lengthening melt season, are observed on both Greenland and West Antarctica.

Still another ‘slow’ feedback is the effect of warming on emissions of long-lived GHGs from the land or ocean. Melting of tundra in North America and Eurasia is observed to be causing increased ebullition of methane from methane hydrates.

It is apparent that these ‘slow’ feedbacks, which are primary causes of the extremely high climate sensitivity on paleoclimate time scales, as discussed below, are beginning to operate already in response to the clear global warming trend of the past three decades.

B. Earth’s History

Civilization developed during the present interglacial period, the Holocene, a period of relatively stable climate, now almost 12,000 years in duration. In this period the Earth has been warm enough to prevent formation of ice sheets in North America or Eurasia, but cool enough to keep ice sheets on Greenland and Antarctica. Sea level rose by more than 100 meters between the peak of the last ice age, 20,000 years ago and the Holocene. After sea level finally stabilized, about 7,000 years ago, the first urban centers developed at many points around the globe, perhaps because of the increase in coastal margin productivity that occurred with sea level stabilization and thus the increased availability of high quality food necessary for urban development (Day et al., Emergence of complex societies after sea level stabilized, *EOS Trans. Amer. Geophys. Union* **88**, 10 April, 2007).

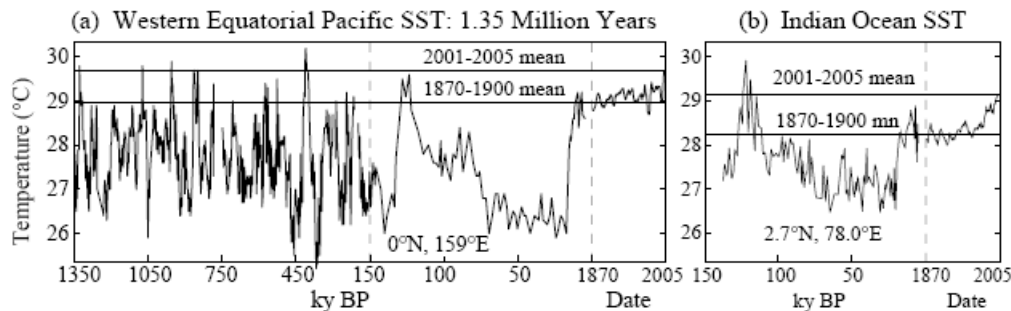


Figure 2. Western Equatorial Pacific (Medina-Elizade and Lea, The mid-Pleistocene transition in the tropical Pacific, *Science* **310**, 1009-1012, 2005).

How much warmer does the Earth need to be to destabilize ice sheets and initiate eventual sea level rise of several meters or more? Figures 2 and 3 provide useful indications.

With the warming of the past 30 years, key tropical regions are now within 1°C or less of the warmest interglacial periods of the past million years (Figure 2). In the warmest of these interglacial periods, when global mean temperature was not more than about 1°C warmer than today, sea level is estimated to have been 4 ± 2 m higher than today (specifically during the previous interglacial period, about 130,000 years ago).

It is important to note that the large global climate changes illustrated in Figure 2 are entirely accounted for by two mechanisms: changes in the surface albedo of the planet (due to ice sheet area, vegetation distribution, and exposure of continental shelves) and changes in the amount of long-lived greenhouse gases (CO_2 , CH_4 , N_2O) in the atmosphere. Both the albedo and GHG changes occurred as feedbacks on these long time scales, the principal instigator of the climate changes being changes of the Earth's orbital elements (the tilt of the Earth's spin axis to the orbital plane, the eccentricity of the orbit, and the season of Earth's closest approach to the sun) due to gravitational pull of Jupiter, Saturn and Venus on Earth.

As feedbacks, the albedo and GHG changes tended to lag the climate change by several hundred years. It is probably not coincidental that the lag time is comparable to the ~500 year time scale for ocean turnover. It is important to note that the response time for the 'slow' feedbacks is much faster than the time scale of the orbital forcing changes.

The principal orbital forcing is change of the tilt of the Earth's spin axis, which varies from about $22\frac{1}{2}^\circ$ to $24\frac{1}{2}^\circ$ at a frequency of about 41,000 years (41 kyr). When the tilt is large it exposes both poles (at 6 month intervals) to increased summer insolation that tends to melt ice sheets, while small tilt allows polar ice sheets to grow. This is the most important orbital forcing, because it has the same sign in the two hemispheres. And this forcing is always present, independent of the eccentricity of the Earth's orbit.

The eccentricity (non-circularity) of the Earth's orbit varies irregularly from about zero (circular orbit) to about 0.06. The time scale of the changes, as the Earth is tugged by several planets, is not so regular as for tilt, but the largest changes are on ~100 kyr time scales. When the eccentricity is significantly different than zero the third orbital parameter comes into play: the season when the Earth is closest to the sun, or, stated differently, the precession of the equinoxes. This precession is the most rapid of the orbital forcings, going through a complete cycle in about 23 kyr.

Eccentricity and precession, working together, cause climate change on ~23 kyr and ~100 kyr periodicities, but the forcing has opposite sign in the two hemispheres, so the net global effect tends to be small, except in special cases as noted below. The eccentricity/precession forcing functions via its effect on seasonal insolation. Today, for example, the Earth is closest to the sun in January and furthest away in July. This situation favors growth of ice sheets at high latitudes in the Northern Hemisphere, as the relatively warm winters increase atmospheric moisture and snowfall, while the cool summers allow a budding ice sheet to survive.

Thus the natural tendency today, absent humans, would be toward the next ice age, albeit the tendency would not be very strong because the eccentricity of the Earth's orbit is rather small (~0.017). However, another ice age will never occur, unless humans go extinct. Although orbital changes are the 'pacemaker' of the ice ages, the two mechanisms by which the Earth becomes colder in an ice age are reduction of the long-lived GHGs and increase of ice sheet area. But these natural mechanisms are now overwhelmed by human-made emissions, so GHGs are skyrocketing and ice is melting all over the planet. Humans are now in control of global climate, for better or worse. An ice age will never be allowed to occur if humans exist, because it can be prevented by even a 'thimbleful' of CFCs (chlorofluorocarbons), which are easily produced.

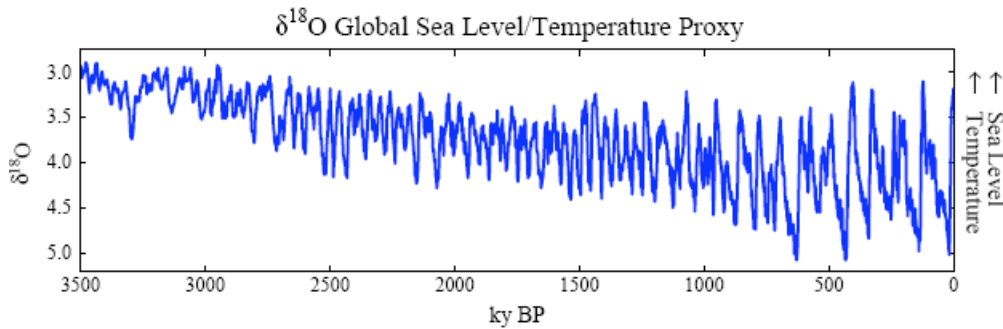


Figure 3. Proxy record of Plio-Pleistocene (3.5 million years) temperature and ice volume. Based on oxygen isotope preserved in shells of benthic (deep ocean dwelling) foraminifera. (Lisiecki and Raymo, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanogr.* **20**, PA1003, doi:10.1029/2004PA001071).

But back to the natural world: why did the principal periodicity of ice ages change about one million years ago from 41 kyr to 100 kyr? Figure 3 illustrates this change. H_2O molecules that contain the oxygen isotope ^{18}O are heavier and thus move more slowly than H_2O molecules containing the more abundant ^{16}O . Therefore H_2O molecules with ^{18}O evaporate from the ocean less readily. As a result, ice sheets are depleted in ^{18}O , and as ice sheets grow the proportion of ^{18}O in ocean water increases. These changes are recorded in the ^{18}O of shells of microscopic marine animals preserved now in oceans sediments.

Figure 3 shows a record of ^{18}O in ocean sediments around the world (from Lisiecki and Raymo, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanogr.* **20**, PA1003, doi:10.1029/2004PA001071). $\delta^{18}\text{O}$ (δ means ‘the change of’ relative to a standard case) in Figure 3 shows the 41 kyr frequency of global temperature that existed up until about one million years ago when it changed to a frequency of about 100 kyr. Before noting the explanation for this transition, which may be very simple, I need to first note that there are two factors that influence $\delta^{18}\text{O}$ significantly: one, already mentioned, is the amount of ice locked in ice sheets (i.e., sea level), and the other is the ocean temperature at the location where the microscopic creatures (benthic, i.e., deep ocean dwelling, foraminifera, whose shells carry the $\delta^{18}\text{O}$ record) lived.

The long-term trend in Figure 3 is a consequence of both the ocean becoming colder over that period and more (isotopically light) water being locked in ice sheets on the continents. At the beginning of this period (3.5 million years ago, the middle of the Pliocene epoch) the world was 2-3°C warmer than today and sea level was 25 ± 10 m (80 ± 30 feet) higher.

Figure 3 also shows that the amplitude of the glacial-interglacial climate fluctuations increased as the world became colder. This is because the ice/snow albedo feedback becomes larger as the planet becomes colder and has larger area of ice and snow.

The period of the glacial-interglacial swings was ~41 kyr up until one million years ago, because the areas of ice and snow in the two hemispheres were comparable, and thus the effects of eccentricity and precession, opposite in the two hemispheres, tended to largely offset each other in global effect. However, by one million years ago the Earth had become cold enough for a huge ice sheet (called the Laurentide ice sheet) to cover most of Canada, reaching into parts of the United States. A comparable area of ice/snow could not form in the Southern Hemisphere, because at those latitudes (~60°) there is no land in the Southern Hemisphere, but rather roaring east-west ocean currents. This huge asymmetry between the hemispheres allowed the

eccentricity/ precession effects to become important, so thereafter the global temperature contains signature of all of the ~23, ~41 and ~100 kyr periodicities.

The astute reader is probably asking: why was the Earth gradually getting colder, ice area growing, and sea level falling, overall, during the past several million years. The reason, almost surely, was the strong orogeny (mountain building) during the past 10-20 million years. The South American continent has been hitting a rough spot, pushing up the Andes rapidly. It is hard to determine the exact rate, but available evidence indicates, for example, that between 11 and 7 kyr BP (before present) the Andes were rising at a rate of about 1 mm per year, i.e., 1 km per million years (Ghosh et al., Rapid uplift of the Altiplano revealed through ^{13}C - ^{18}O bonds in paleosol carbonates, *Science*, **311**, 511-515, 2006). The Himalayas have also been rising rapidly during the past 40 million years (Raymo and Ruddiman, Tectonic forcing of the late Cenozoic climate, *Nature*, **359**, 117-122, 1992), as the Indian plate is crashing into Asia.

Rising mountains increase the rate of weathering of the rocks, and thus the deposition of carbonates on the ocean floor, thus drawing down atmospheric CO_2 amount. The precise ice core records of atmospheric CO_2 amount go back only about 700,000 years, so we must use much more crude estimates of the atmospheric CO_2 content, for example, the stomata of leaves change as atmospheric CO_2 changes. From such evidence, it is estimated that the CO_2 amount $3\frac{1}{2}$ million years ago was probably in the range 350-450 ppm.

It is apparent that the Earth's history has much to tell us about what degree of atmospheric change will constitute "danger". I have described some of the empirical information about climate sensitivity and climate feedbacks. There is another vital piece of information in the paleoclimate data that warrants special attention, because it is relevant to what may be the greatest danger that humanity faces with climate change: sea level rise.

One thing that the paleoclimate record shows us is that ice sheet disintegration and sea level rise are usually much more rapid than the opposite process of ice sheet growth and sea level fall. This is reasonable because ice sheet disintegration is a wet process with many positive feedbacks, so it can proceed more rapidly than ice sheet growth, which is limited by the snowfall rate in cold, usually dry, places. At the end of the last ice age sea level rose more than 100 m in less than 10,000 years, thus more than 1 m per century on average. At times during this deglaciation, sea level rose as fast as 4-5 m per century.

If we follow "business-as-usual" GHG emissions, yielding global warming this century of a few degrees Celsius, how long will it take for West Antarctica and Greenland to begin to disintegrate? In the past, an answer to this question has been given based on ice sheet models that were built to try to match paleoclimate records of sea level change. These models tend to require millennia for ice sheets to change by large amounts. It is now reasonably clear that those models were based on a false premise and incomplete physics.

The large sea level changes between glacial and interglacial times typically require several thousand years. However, this corresponds to the time scale of the changing forcing, not an inherent response time of the ice sheets. On the contrary, there is no evidence of any substantial lag between the forcing and the ice sheet response (references B and D above). The most rapidly changing paleoclimate forcing has a time scale of 11-12 ky from minimum forcing to maximum forcing, and the changes of sea level are practically coincident with the changes of forcing, suggesting that ice sheets can respond to forcings within centuries.

C. Current Situation

People are just beginning to notice that climate is changing. Global warming, 1°F in the past 30 years, is much smaller than day to day weather fluctuations or even monthly mean local temperature anomalies. However, the warming is larger over land than over ocean, and the

astute observer can note changes that have occurred over the past several decades. A typical isotherm (line of a given average temperature) is now moving poleward, in typical land areas, by about 50 km per decade. As this warming continues, or accelerates with “business-as-usual” GHG emissions, it will begin to have dramatic effects, as discussed in the next section.

To understand the urgency of addressing the global warming problem, it is necessary to recognize a critical distinction that exists among pollution problems arising in the fossil-fuel-driven industrial revolution. When the industrial revolution began in Britain it was powered first by coal, the most abundant of the fossil fuels. Later discoveries of oil and gas, which are more mobile and convenient fossil fuels, provided energy sources that helped power the developed world to ever greater productivity and living standards.

We did not face up to the dark side of the industrial revolution until it was thrust in our face. London choked on smog. A river in the United States burned. Forests were damaged by acid rain. Fish died in many lakes. These problems were traced to pollutants from fossil fuels.

We have solved or are solving those pollution problems, at least in developed countries. But we did not address them until they hit us with full force. That approach, to wait and see and fix the problems post facto, unfortunately, will not work in the case of global climate change. On the contrary, because of the inertia of the climate system, the fact that much of the climate change due to gases already in the air is still ‘in the pipeline’, and the time required for economically-sensible phase-out of existing technologies, ignoring the climate problem at this time, for even another decade, would serve to lock in future catastrophic climatic change and impacts that will unfold during the remainder of this century and beyond (references A and B).

But there is no reason for gloom and doom. On the contrary, there are many bright sides to the conclusion that the ‘dangerous’ level of CO₂ is no more than 450 ppm, and likely much less than that. It means that we, humanity, are forced to find a way to limit atmospheric CO₂ more stringently than has generally been assumed. In so doing, many consequences of high CO₂ that were considered inevitable can be avoided. We will be able to avoid acidification of the ocean with its destruction of coral reefs and other ocean life, retain Arctic ice, prevent the West from become intolerably hot with desertification of presently semi-arid regions, and the other undesirable consequences of large global warming.

It is becoming clear that we must make a choice. We can resolve to move rapidly to the next phase of the industrial revolution, and in so doing help restore wonders of the natural world, of creation, while maintaining and expanding benefits of advanced technology. Or we can continue to ignore the problem, creating a different planet, with eventual chaos for much of humanity as well as the other creatures on the planet.

4. Metrics for Dangerous Climate Change

I have argued elsewhere (Hansen, *New York Review of Books*, LIII no. 12, July 13, 2006) that ice sheet disintegration and extermination of species deserve high priority as metrics for dangerous climate change, because, for all practical purposes, these consequences are irreversible. Regional climate change also has great impacts on humanity.

A. Sea Level Rise

The sharpest criterion for defining dangerous climate change is probably maintenance of long-term sea level close to the present level (reference A), as about one billion people live within 25 m elevation of today’s sea level. These areas (Figure 4) include many East Coast U.S. cities, almost all of Bangladesh, and areas occupied by more than 250 million people in China.

The Earth's history suggests that a CO₂ level exceeding 450 ppm is almost surely dangerous, in the sense of risking sea level rise of several meters or more. Indeed, the Earth's history suggests that the CO₂ limit may be significantly lower than that. Reduction of non-CO₂ forcings provides some, but only moderate, flexibility in the CO₂ ceiling.

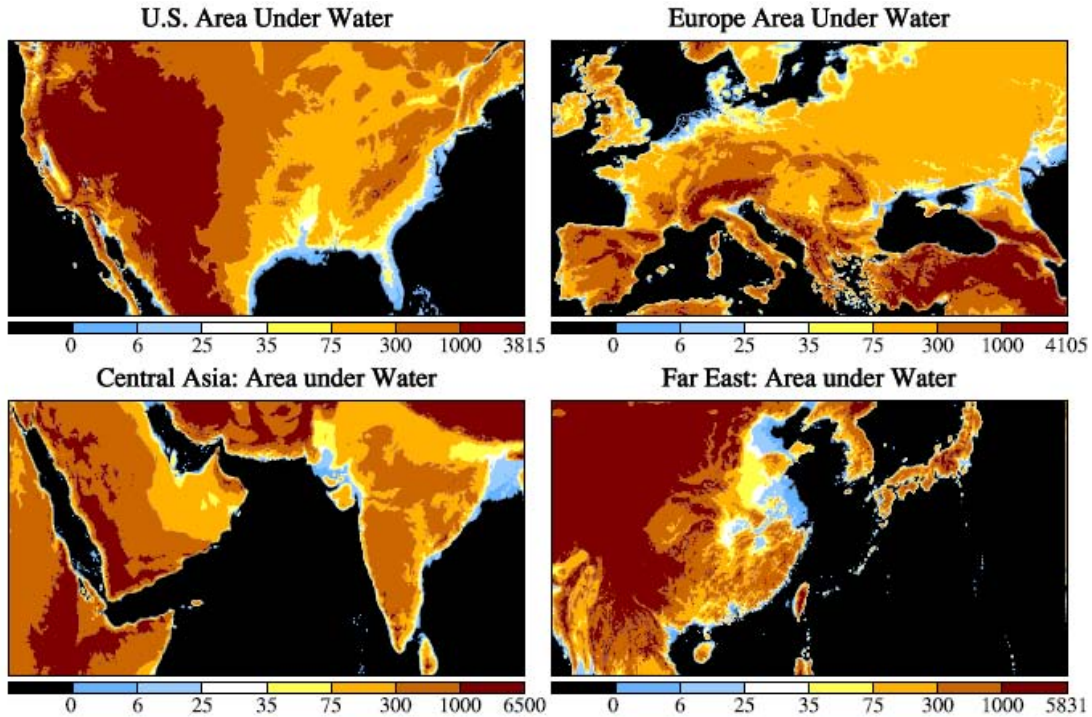


Figure 4. Areas under water for specified sea level increases. Blue regions would be expected to eventually be under water with global warming as great as that of the middle Pliocene (2-3°C).

Sea level change has received less attention in the past than it warrants, because of a common presumption that ice sheets had an inertia preventing substantial changes on time scales shorter than millennia. Closer inspection of paleoclimate data calls that assumption into question, and increasingly rapid changes on West Antarctica and Greenland, observed by satellite and in the field during the past few years, are truly alarming. West Antarctica is of particular concern, because, as a marine based ice sheet, global warming attacks it from both below and above.

Sea level is already raising at a rate of 3.5 cm per decade (more than one foot per century) and the rate is accelerating. It is impossible to say at exactly what level of global warming cold accelerate to meters per century, because ice sheet disintegration is a very non-linear process in which changes can occur suddenly. But paleoclimate data suggests that we are not far from such a level of global warming.

B. Extermination of Species

Climate change is emerging while the state of the wild is stressed by other forces. Pressures include destruction of habitat, hunting and resource use, pollution, and introduction of exotic competing species. Climate effects are magnified by these stresses, including human-caused fragmentation of ecosystems. As a result, continued business-as-usual greenhouse gas emissions threaten many ecosystems and their species, which together form the fabric of life on Earth and provide a wide range of services to humanity.

Animals and plants migrate as climate changes, but their potential escape routes may be limited by geography or human-made obstacles. Polar species can be pushed off the planet, as they have no place else to go. In Antarctica, Adelie and emperor penguins are in decline, as shrinking sea ice has reduced the abundance of krill, the penguins shrimp-like food source (Gross, As the Antarctic ice pack recedes, a fragile ecosystem hangs in the balance, *PLoS Biol.* 3(4):e127).

Arctic polar bears are also feeling the pressure of melting sea ice. Polar bears hunt seals on the sea ice and fast in the summer, when the ice retreats from shore. As ice is receding earlier, populations of bears in Canada have declined about 20%, with the weight of females and the number of surviving cubs decreasing a similar amount.



Figure 5. Polar bear numbers are in decline. In some populations the weight of females and the number of cubs have decreased about 20 percent. (Image Credit: Paul Burke, First People)

The apparent good news is that the U.S. Fish and Wildlife Service is considering whether it will protect polar bears under the Endangered Species Act (Pennisi, U.S. weighs protection for polar bears, *Science* **315**, 25, 2007). I say apparent, because the announcement was made only after the Fish and Wildlife Service was taken to court for failure to act. And connection of polar bear plight to greenhouse gas emissions has been drawn only by those bringing suit, not by the government.

Life in alpine regions, including the biologically diverse slopes leading to the mountains, is similarly in danger of being pushed off the planet. As a given temperature range moves up the mountain the area with those climatic conditions becomes smaller and rockier, and the air thinner. The resulting struggle for life is already becoming apparent in the southwest United States, where the effects are hastened by intensifying drought and fire.

The Mount Graham red squirrel survives now on a single Arizona mountain, one of the 'islands in the sky' in the American Southwest. These 'islands' are green regions scattered on mountains in the desert. Stresses on this species include introduction of a grey squirrel that raids the food middens built by the red squirrel. Classified as endangered, the Graham red squirrel population rebounded to over 500 by 1999 (Jordan, Computers may help save Mount Graham red squirrel, *Univ. Arizona News*, April 27, 2006), but has since declined to between 100 and 200 (Egan, Heat invades cool heights over Arizona desert, *New York Times*, 27 March 2007). Loss of the red squirrel will alter the forest, as its middens are a source of food and habitat for chipmunks, voles and mice.



Figure 6. Mount Graham Red Squirrel survives on a single mountain in Arizona, one of dozens of ‘islands in the sky’, green regions surrounded by desert. Green islands and squirrels are pushed higher as temperature rises and will be pushed off the planet if global warming continues. (Credits: PHOTOSMITH, 2004, Claire Zugmeyer and Bruce Walsh, University of Arizona.)

The new stress driving down Graham red squirrel numbers, perhaps toward extinction, is climatic: increased heat, drought and fires. Heat-stressed forests are vulnerable to prolonged beetle infestation and catastrophic fires. Rainfall still occurs, and when it does it can be substantial because warmer air holds more water. But dry periods are more intense and resulting forest fires burn hotter, thus leaving an almost-lifeless ‘scorched earth’ so devastated that lower reaches of the forest cannot recover, becoming part of the desert below.

Might the Graham red squirrel be ‘saved’ by transplantation to a higher mountain, where it could compete for a niche? One difficulty would be the ‘tangled bank’ of interactions that has evolved among species (Montoya et al., Ecological networks and their fragility, *Nature* **442**, 259-264, 2006). What is the prospect that humans can understand, let alone reproduce, all the complex interactions that create ecological stability? ‘Assisted migration’ thus poses threats to other species (Zimmer, A radical step to preserve a species: assisted migration, *New York Times*, 23 January 2007), as well as uncertain prospects for those that are transported.

The underlying cause of the climatic threat to the Graham Red Squirrel, and millions of other species, is continued ‘business-as-usual’ increase of fossil fuel use. The best chance for all species, including humans, is a conscious choice by the latter species to pursue an alternative energy scenario, one leading to stabilization of climate.

C. Regional Climate Change

Regional climate changes due to global warming may have the greatest impact on humans in the near-term. Changes of the hydrologic cycle are of special concern. An expansion and intensification of subtropical dry conditions occurs consistently in climate model simulations of global warming. Practical impacts include increased drought and forest fires in regions such as the Western United States, Mediterranean, Australia, and parts of Africa. Paleoclimate data provide further evidence of increased drought in the Western United States accompanying warmer climate.

It is difficult to specify a precise threshold for ‘dangerous’ based on regional effects, but there is already evidence that some of these impacts are beginning to be detectable. Thus regional climate change, as well as sea level and species, would be protected by stabilizing global warming near its current level.

5. Four-Point Strategy to Stabilize Climate

The evidence we have presented is no reason for gloom and doom. Instead, we must resolve to move rapidly to the next phase of the industrial revolution. In doing so, we can help restore wonders of the natural world, of creation, while maintaining and expanding benefits of advanced technology.

Actions that are needed become apparent upon review of basic fossil fuel facts. Figure 7a shows estimated amounts of CO₂ in each fossil fuel reservoir: oil, gas, coal and unconventional fossil fuels (tar sands, tar shale, heavy oil, methane hydrates). A significant fraction of oil and gas has already been used (dark portion of bar graph). Proven and anticipated reserves are based on Energy Information Administration estimates. Other experts estimate higher or lower reserves, but the uncertainties do not alter our conclusions.

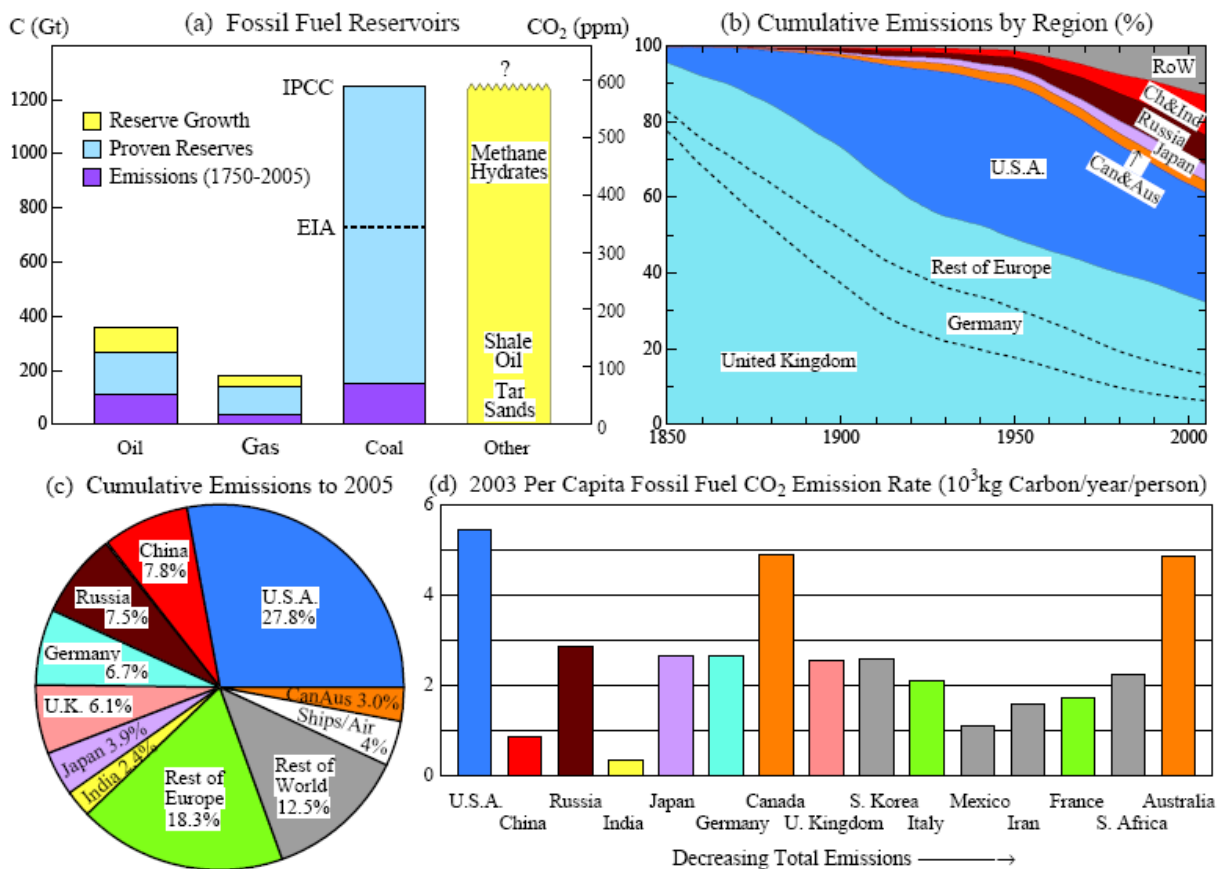


Figure 7. (a) Carbon dioxide contained in fossil fuel reservoirs, the dark areas being the portion already used, (b, c) Cumulative fossil fuel CO₂ emissions by different countries as a percent of global total, (d) Per capita emissions for the ten largest emitters of fossil fuel CO₂ (Marland, A *Compendium of Data on Global Change*, Oak Ridge Natl. Lab., 2006).

Data on fossil fuel reservoirs must be combined with knowledge about the ‘carbon cycle’. The ocean quickly takes up a fraction of fossil fuel CO₂ emissions, but uptake slows as CO₂ added to the ocean exerts a ‘back pressure’ on the atmosphere. Further uptake then depends upon mixing of CO₂ into the deep ocean and ultimately upon removal of CO₂ from the ocean via formation of carbonate sediments. As a result, one-third of fossil fuel CO₂ emission remains in the air after 100 years and one-quarter still remains after 500 years.

One conclusion from these fossil fuel facts is that readily available oil and gas resources alone will take atmospheric CO₂ to the neighborhood of 450 ppm. Coal and unconventional fossil fuels could take atmospheric CO₂ to far greater levels. These carbon reservoirs are an important boundary condition in framing solutions to the climate crisis.

A second boundary condition is the Earth's energy imbalance, which defines the 'momentum' of the climate system. Creation of 'a different planet', with an ice-free Arctic and eventual disintegration of ice sheets, can be averted only if planetary energy balance is restored at an acceptable global temperature, i.e., one that avoids these catastrophic changes. Estimates of permissible additional warming must be refined as knowledge advances and technology improves, but the upshot of crystallizing science is that the 'safe' global temperature level is, at most, about 1°C greater than year 2000 temperature. It may be less, indeed, I suspect that it is less, but that does not alter our conclusions.

A 1°C limit on added global warming implies a CO₂ ceiling of about 450 ppm (reference A). There is some 'play' in the CO₂ ceiling due to other human-made climate forcings that cause warming, especially methane, nitrous oxide, and 'black soot'. The 'alternative scenario' (Hansen et al., Proc. Natl. Acad. Sci., 97, 9875-9880, 2000), designed to keep additional warming under 1°C, has CO₂ peaking at 475 ppm via an assumed large reduction of CH₄. However, human-made sulfate aerosols, which have a cooling effect, are likely to decrease and tend to offset reductions of positive non-CO₂ forcings. Therefore 450 ppm is a good first estimate of the maximum allowable CO₂. Indeed, if recent mass loss in Antarctica is the beginning of a growing trend, it is likely that even 450 ppm is excessive and dangerous.

The low limit on allowable carbon dioxide has a bright side. Such a limit requires changes to our energy systems that would do more than solve the sea level problem. They would leave ice in the Arctic and avoid dramatic climate changes in other parts of the world. Air pollutants produced by fossil fuels, especially soot and low level ozone, also would be reduced, thus restoring a more pristine, healthy planet. Most species on the planet could survive.

An outline of the strategy that humanity must follow to avoid dangerous climate change emerges from the above boundary conditions. It is a four-point strategy (following tables).

Outline of Solution

1. **Coal only in Powerplants w Sequestration**
Phase-out old technology. Timetable TBD
2. **Stretch Conventional Oil & Gas**
Via Incentives (Carbon tax) & Standards
Avoid Unconventional Fossil Fuels
3. **Reduce non-CO₂ Climate Forcings**
Methane, Black Soot, Nitrous Oxide
4. **Draw Down Atmospheric CO₂**
Improved Agricultural & Forestry Practices
Perhaps Biofuel-Powered Power-Plants

Methods to Reduce CO₂ Emissions

1. **Energy Efficiency & Conservation**
More Efficient Technology
Life Style Changes
2. **Renewable & CO₂-Free Energy**
Hydro
Solar, Wind, Geothermal
Nuclear
3. **CO₂ Capture & Sequestration**
→ **No Silver Bullet**
→ **All Three are Essential**

A. Coal and Unconventional Fossil Fuels

First, coal and unconventional fossil fuels must be used only with carbon capture and sequestration. Existing coal-fired power plants must be phased out over the next few decades. This is the primary requirement for avoiding 'a different planet'.

It is probably impractical to prevent use of most of the easily extractable oil and its use in small mobile sources. This makes it essential to use the huge coal resource in a way such that the CO₂ can be captured, and, indeed, the logical use of coal is in power plants. It is important to

recognize that a substantial fraction of the CO₂ emitted, if it is not captured, will remain in the air for an eternity.

Thus the most critical action for saving the planet at this time, I believe, is to prevent construction of additional coal-fired power plants without CO₂ capture capability. As governments around the world, not only in the United States, China and India, fail to appreciate this situation, it is important that citizens draw attention to the issue.

B. Stretching Oil and Gas with a Carbon Tax

Oil and gas must be ‘stretched’ so as to cover needs for mobile fuels during the transition period to the next phase of the industrial era ‘beyond petroleum’. This ‘stretching’, almost surely, can only be achieved if there is a continually rising price on carbon emissions. Innovations will be unleashed if industry realizes that this rising price is certain. Efficiency standards, for vehicles, buildings, appliances, and lighting are needed, as well as a carbon price. The carbon tax will also avert the threat of emissions from unconventional fossil fuels, such as tar shale.

C. Drawing Down Atmospheric CO₂

Because CO₂ is already near the dangerous level, steps must be taken to ‘draw down’ atmospheric CO₂. Farming and forestry practices that enhance carbon retention and storage in the soil and biosphere should be supported.

In addition, burning biofuels in power plants with carbon capture and sequestration could draw down atmospheric CO₂ (Hansen, *Political interference with government climate change science*, 19 March 2007 testimony to Committee on Oversight and Government Reform of the U.S. House of Representatives, <<http://www.columbia.edu/~jeh1>) in effect putting anthropogenic CO₂ back underground where it came from. CO₂ sequestered beneath ocean sediments is inherently stable (House et al., Permanent carbon dioxide storage in deep-sea sediments, *Proc. Natl. Acad. Sci.*, **103**, 12291-12295), and other safe geologic sites may also be available.

This use of biofuels in a power plant, which would draw down atmospheric CO₂, should be contrasted with use of corn-based ethanol to power vehicles. The latter process still results in large increases of atmospheric CO₂, increases food prices worldwide, and results in deforestation and poor agricultural practices as greater land area is pressed into service. In the use of biofuels for power plants, mentioned above, we would envisage use of cellulosic fibers and native grasses harvested with non-till practices. Limited land availability may make it difficult for biofuels to be the long-term solution for vehicle propulsion.

D. Non-CO₂ Climate Forcings

A reduction of non-CO₂ forcings can be a significant help in achieving the climate forcings needed to keep climate change within given bounds. Reduction of non-CO₂ forcings has benefits for human health and agriculture [West et al., 2005; *Air Pollution Workshop*, www.giss.nasa.gov/meetings/pollution2005], as well as for climate. Reduction of non-CO₂ forcings is especially effective in limiting Arctic climate change (reference A).