Committee on
GOVERNMENTAL AFFAIRS
The United States Senate

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TESTIMONY

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before the
Committee on Governmental Affairs
United States Senate

1. Preface.

Mr. Chairman and Members of the Committee:

I appreciate the opportunity to provide information relevant to your considerations of a strategy to address climate change. Specifically, I would like to clarify and expand upon a paper that I co-authored with four other scientists on climate change in the 21st century, published in Proceedings of the National Academy of Sciences (1). In that paper, we define an "alternative scenario" for the forcing agents that cause climate change. The alternative scenario gives equal emphasis to reducing air pollution and to a continued slow downtrend in CO2 emissions. This scenario produces only a moderate climate change in the next 50 years. We suggest that the climate forcings in this scenario can be achieved via pragmatic actions that make good sense for a variety of reasons. Collateral benefits include improvements in human health, agricultural productivity, and greater energy self-sufficiency. Our alternative scenario differs markedly from the "business as usual" scenarios of the Intergovernmental Panel on Climate Change (IPCC), which have received the greatest attention among the plethora of IPCC scenarios. However, I emphasize that our paper is not a criticism of IPCC. The IPCC reports (2), produced by hundreds of outstanding scientists, provide an invaluable assessment of the status of scientific understanding of climate change.

Although our research has relevance to public issues, including your present consideration of strategies for long-term stabilization of climate forcings, it is not our job to suggest policies. Our objective is to provide scientific information that the public and their representatives can use to help choose wise policies. Thus our aim is to provide relevant information on the forcing agents that drive climate change that is as quantitative and as clear as the data permit.

2. Introduction: Basic Concepts.

The Earth's climate fluctuates from year to year and century to century, just as the weather fluctuates from day to day. It is a chaotic system, so changes occur without any forcing, but the chaotic changes are limited in magnitude. The climate also responds to forcings. If the sun brightens, a natural forcing, the Earth becomes warmer. If a large volcano spews aerosols into the stratosphere, these small particles reflect sunlight away and the Earth tends to cool. There are also human-made forcings.

We measure forcings in watts per square meter (W/m2). For example, all the human-made greenhouse gases now cause a forcing of more than 2 W/m2. It is as if we have placed two miniature Christmas tree bulbs over every square meter of the Earth 's surface. That is equivalent to increasing the brightness of the sun by about 1 percent.

We understand reasonably well how sensitive the Earth's climate is to a forcing. Our most reliable measure comes from the history of the Earth. We can compare the current warm period, which has existed several thousand years, to the previous ice age, about 20,000 years ago (3, 4, 5). We know the composition of the atmosphere during the ice age from bubbles of air that were trapped as the ice sheets on Greenland and Antarctica built up from snowfall. There was less carbon dioxide (CO2) and less methane (CH4), but more dust in the air. The surface was different then, with ice sheets covering Canada and parts of Europe, different distributions of vegetation, even the coast-lines differed because sea level was about 400 feet lower. These changes, as summarized in Figure 1, caused a negative climate forcing of about 6½ W/m2. That forcing maintained a planet that was 5C colder than today. This empirical information implies that climate sensitivity is about ¾C per W/m2 of forcing. Climate models have about the same sensitivity, which provides encouraging agreement between the real world and the complex computer models that we use to predict how climate may change in the future.

There is another important concept to understand. The climate cannot respond immediately to a forcing, because of the long time needed to warm the ocean. It takes a few decades to achieve just half of the equilibrium climate response to a forcing. Even in 100 years the response may be only 60-90 percent complete (5). This long response time complicates the problem for policy-makers. It means that we can put into the pipeline climate change that will only emerge during the lives of our children and grandchildren. Therefore we must be alert to detect and understand climate change early on, so that the most appropriate policies can be adopted.

3. Past Climate Forcings and Climate Change.

The climate forcings that exist today are summarized in Figure 2 (1, 6). The greenhouse gases, on the left, have a positive forcing, which would tend to cause warming. CO2 has the largest forcing, but CH4, when its indirect effect on other gases is included, causes a forcing half as large as that of CO2. CO2 is likely to be increasingly dominant in the future, but the other forcings are not negligible.

Aerosols, in the middle of the figure, are fine particles in the air. Some of these, such as sulfate, which comes from the sulfur released in coal and oil burning, are white, so they scatter sunlight and cause a cooling. Black carbon (soot) is a product of incomplete combustion, especially of diesel fuel and coal. Soot absorbs sunlight and thus warms the planet. Aerosols tend to increase the number of cloud droplets, thus making the clouds brighter and longer-lived. All of the aerosol effects have large uncertainty bars, because our measurements are inadequate and our understanding of aerosol processes is limited.

If we accepted these estimates at face value, despite their large uncertainties, we would conclude that, climate forcing has increased by 1.6 W/m2 since the Industrial Revolution began [the error bars, in some cases subjective, yield an uncertainty in the net forcing of 1 W/m2]. The equilibrium warming from a forcing of 1.6 W/m2 is 1.2C. However, because of the ocean’s long response time, we would expect a global warming to date of only about ¾ C. An energy imbalance of 0.6 W/m2 remains, with that much more energy coming into the planet than going out. This means there is another ½C global warming already in the pipeline - it will occur even if atmospheric composition remains fixed at today’ s values.

The climate forcings are known more precisely for the past 50 years, especially during the past 25 years of satellite measurements. Our best estimates are shown in Figure 3. The history of the tropospheric aerosol forcing, which involves partial cancellation of positive and negative forcings, is uncertain because of the absence of measurements. However, the GHG and stratospheric aerosol forcings, which are large forcings during this period, are known accurately.

When we use these forcings in a global climate model (3) to calculate the climate change (6), the results are consistent with observations (Figure 4). We make five model runs, because of the chaos in the climate system. The red curve is the average of the five runs. The black dots are observations. The Earth's stratosphere cools as a result of ozone depletion and CO2 increase, but it warms after volcanic eruptions. The troposphere and the surface warm because of the predominantly positive forcing by increases of greenhouse gases, in reasonably good agreement with observations.

The fourth panel in Figure 4 is important. It shows that the simulated planet has an increasing energy imbalance with space. There is more energy coming into the planet, from the sun, than there is energy going out. The calculated imbalance today is about 0.6 W/m2. This, as mentioned above, implies that there is about 0.5C additional global warming already in the pipeline, even if the atmospheric composition does not change further. An important confirmation of this energy imbalance has occurred recently with the discovery that the deep ocean is warming. That study (7) shows that the ocean took up heat at an average rate of 0.3 W/m 2 during the past 50 years, which is reasonably consistent with the predictions from climate models. Observed global sea ice cover has also decreased as the models predict.

There are many sources of uncertainty in the climate simulations and their interpretation. Principal among the uncertainties are climate sensitivity (the Goddard Institute for Space Studies model sensitivity is 3C for doubled CO2, but actual sensitivity could be as small as 2C or as large as 4C for doubled CO 2), the climate forcing scenario (aerosols and tropospheric ozone changes are very poorly measured), and the simulated heat storage in the ocean (which depends upon the realism of the ocean circulation and mixing). It is possible to find other combinations of these "parameters" that yield satisfactory agreement with observed climate change.

Nevertheless, the observed positive heat storage in the ocean is consistent with and provides some confirmation of the estimated climate forcing of 1.6 ± 1 W/m2. Because these parameters in our model are obtained from first principles and are consistent with our understanding of the real world, we believe that it is meaningful to extend the simulations into the future, as we do in the following section. Such projections will become more reliable and precise in the future if we obtain better measurements and understanding of the climate forcings, more accurate and complete measures of climate change, especially heat storage in the ocean, and as we employ more realistic climate models, especially of ocean circulation and the upper atmosphere.

4. Scenarios for 2000-2050.

We extend our climate model simulations into the future for two climate forcing scenarios shown in Figure 5. In the popular "business-as-usual" scenario, which the media focuses upon, the climate forcing increases by almost 3 W/m2 in the next 50 years. This leads to additional global warming of about 1.5C by 2050 and several degrees by 2100. Such a scenario, with exponential growth of the greenhouse forcing, leads to predictions of dramatic climate change and serious impacts on society.

The "alternative scenario" assumes that global use of fossil fuels will continue at about today's rate, with an increase of 75 ppm in airborne CO2 by 2050. Depending on the rate of CO2 uptake by the ocean and biosphere this may require a small downtrend in CO2 emissions, which would be a helpful trend for obtaining stabilization of greenhouse gases later in the century. The alternative scenario also assumes that there will be no net growth of the other forcings: in somewhat over-simplified terminology, "air pollution" is not allowed to get any worse that it is today. The added climate forcing in the alternative scenario is just over 1 W/m2 in the next 50 years.

The alternative scenario results in an additional global warming in the next 50 years of about ¾C, much less than for the business-as-usual scenario. In addition, the rate of stratospheric cooling declines in the alternative scenario (top panel of Figure 5), and in fact the lower stratospheric temperature would probably level out because of expected stratospheric ozone recovery (not included in this simulation). The planetary energy imbalance increases by only about ¼ W/m2 in the alternative scenario, compared with almost 1 W/m2 in the business-as-usual scenario. In other words, our children will leave their children a debt (¾C additional warming in the pipeline) that is only slightly more than the amount of unrealized warming (½C) hanging over our heads now.

Figure 6 is a cartoon summarizing the two parts of the alternative scenario. First, the scenario keeps the added CO2 forcing at about 1 W/m2, which requires that annual increases in atmospheric CO2 concentrations be similar to those in the past decade. The precise scenario that we employ has the CO2 growth rate declining slowly during these 50 years, thus making it more feasible to achieve still lower growth rates in the second half of the century and an eventual "soft landing" for climate change. Second, the net growth of other climate forcings is assumed to cease. The most important of these "other" forcings are methane, tropospheric ozone, and black carbon aerosols. Specific trace gas scenarios used in our global climate model simulations are shown in Figure 7.

In the following two sections we provide data that helps provide an indication of how difficult or easy it may be to achieve the elements of the alternative scenario.

5. Alternative Scenario: Air Pollution.

One of the two requirements for achieving the alternative scenario is to stop the growth of non-CO2 forcings. Principally, that means to halt, or even better reverse, the growth of black carbon (soot), tropospheric ozone (O3) and methane (CH4). These can loosely be described as air pollution, although in dilute amounts methane is not harmful to health. Black carbon, with absorbed organic carbon, nitrates and sulfates, and tropospheric ozone are principal ingredients in air pollution.

***Black carbon (soot)*.** Black carbon aerosols, except in the extr eme case of exhaust puffs from very dirty diesel trucks or buses, are invisibly small particles. They are like tiny sponges that soak up toxic organic material that is also a product of fossil fuel combustion. The aerosols are so small that they penetrate human tissue deeply when breathed into the lungs, and some of the tiniest particles enter the blood stream.

Particulate air pollution, including black carbon aerosol, has been increasingly implicated in respiratory and cardiac problems. A recent study in Europe (8) estimated that air pollution caused annually 40,000 deaths, 25,000 new cases of chronic bronchitis, 290,000 episodes of bronchitis in children, and 500,000 asthma attacks in France, Switzerland and Austria alone, with a net cost from the human health impacts equal to 1.6 percent of their gross domestic product. Pollution levels and health effects in the United States are at a comparable level. Primary sources of black carbon in the West are diesel fuels and coal burning.

The human costs of particulate air pollution in the developing world are staggering. A study recently published (9) concluded that about 270,000 children in India under the age of five die per year from acute respiratory infections arising from particulate air pollution. In this case the air pollution is caused mainly by low temperature inefficient burning of field residue, cow dung, biomass and coal within households for the purpose of cooking and heating. Pollution levels in China are comparably bad, but in China residential coal use is the largest source, followed by residential use of biofuels (10).

Referring back to Figure 2, note that there are several aerosols that cause cooling, in addition to black carbon that causes warming. There are ongoing efforts to slow the growth of sulfur emissions or reduce emissions absolutely, for the purpose of reducing acid rain. In our alternative scenario for climate forcings, it is assumed that any reduced sulfate cooling will be at least matched by reduced black carbon heating. Principal opportunities in the West are for cleaner more efficient diesel motors, cleaner more efficient coal burning at utilities, and substitution of alternative energy sources that produce less or no black carbon. Opportunities in the developing world include use of biogas in place of solid fuels for household use, and eventually use of electrical energy produced at central power plants.

***Ozone (O3)*.** Chemical emissions that lead to tropospheric ozone formation are volatile organic compounds and nitrogen oxides (carbon monoxide and methane also contribute). Primary sources of these chemicals are transportation vehicles, power plants and industrial processes.

High levels of ozone have adverse health and ecosystem effects. Annual costs of the impacts on human health and crop productivity are each estimated to be on the order of $10 billion per year in the United States alone.

Ozone in the free troposphere can have a lifetime of weeks, and thus tropospheric ozone is at least a hemispheric if not a global problem. Emissions in Asia are projected to have a small effect on air quality in the United States (11). Closer neighbors can have larger effects, for example, recent ozone increases in Japan are thought to be due in large part to combustion products from China, Korea and Japan (12). A coordinated reduction of those chemical emissions that lead to the formation of low level ozone would be beneficial to developing and developed countries.

Our alternative scenario assumes that it will be possible, at minimum, to stop further growth of tropospheric ozone. Recent evidence suggests that tropospheric ozone is decreasing downwind of regions such as Western Europe (13), where nitrogen oxide and carbon monoxide emissions are now controlled, but increasing downwind of East Asia (12). Global warming may aggravate summer time ozone production, but this feedback effect would be reduced with the small warming in the alternative scenario. The evidence suggests that cleaner energy sources and improved combustion technology could achieve an overall ozone reduction.

Methane (CH4). Methane today causes a climate forcing half as large as that of CO2, if its indirect effects on stratospheric H2O and tropospheric O3 are included. The atmospheric lifetime of CH4 is moderate, only 8-10, years, so if its sources were reduced, the atmospheric amount would decline rather quickly. Therefore it offers a great opportunity for a greenhouse gas success story. It would be possible to stabilize atmospheric CH4 by reducing the sources by about 10%, and larger reductions could bring an absolute decrease of atmospheric CH4 amount.

The primary natural source of methane is microbial decay of organic matter under anoxic conditions in wetlands. Anthropogenic sources, which in sum may be twice as great as the natural source, include rice cultivation, domestic ruminants, bacterial decay in landfills and sewage, leakage during the mining of fossil fuels, leakage from natural gas pipelines, and biomass burning.

There are a number of actions that could be taken to reduce

CH4 emissions: (1) capture of methane in coal mining, landfills, and waste management, (2) reduction of pipeline leakage, especially from antiquated systems such as in the former Soviet Union, (3) reduction of methane from ruminants and rice growing, as the farmers' objectives are to produce meat, milk and power from the animals, not methane, and food and fiber from the fields, not methane.

The economic benefits of such methane reductions are not so great that they are likely to happen automatically. Methane reduction probably requires international cooperation, including developing countries. Although the task is nontrivial, it represents an opportunity for a success story. In some sense, methane in climate change is analogous to the role of methyl-chloroform in ozone depletion. Although the growth of long-lived chlorofluorocarbons has only begun to flatten out, stratospheric chlorine is already declining in amount because of reductions in the sources of short-lived methyl-chloroform.

6. Alternative Scenario: Carbon Dioxide

CO2 is the largest single human-made climate forcing agent today, and its proportion of the total human-made climate forcing can be anticipated to increase in the future. It is not practical to stop the growth of atmospheric CO2 in the next several decades. However, it is possible to slow the growth rate of CO2 emissions via actions that make good economic and strategic sense.

Scenarios for CO2 are commonly constructed by making assumptions about population growth, standard of living increases, fuel choices, and technology. This procedure yields a huge range of possibilities with little guidance as to what is likely. An alternative approach is to examine historical and current rates of change of CO2 emissions, estimate the changes that are needed to keep the climate change moderate, and consider actions that could produce such rates of change. That is the procedure we explore here.

***Fossil-fuel CO2 emissions*.** Figures 8 and 9 show U.S. and global CO2 emissions. Emissions in the U.S. grew faster in the 1800s than in the rest of the world, as the U.S. itself was still growing and had rapid immigration. Growth of U.S. emissions was slower than in the rest of the world during the second half of the 20th century, when other parts of the world were industrializing.

The important period for the present discussion is the past 25 years, and the past decade. The U.S. growth rate was 1%/year over the past 25 years, as we largely succeeded in decoupling economic and energy use growth rates. The global growth rate was moderately higher, 1.4%, as there was faster growth in developing nations. However, in the past decade the growth rate of U.S. CO2 emissions has been higher than in the world as a whole (1%/year in the U.S. vs. 0.6%/year in the world).

Figure 10 provides a useful summary. The U.S. portion of global fossil fuel CO2 emissions increased from 10% in 1850 to 50% in 1920. Since then the U.S. portion has declined to 23% as other parts of the world industrialized. The temporary spike beginning in 1940 is associated with World War II, including vigorous exertion of U.S. industry to supply the war effort. In the 1990s the U.S. portion of global emissions increased.

Growth rate required for "alternative scenario". A small change in the CO2 emissions growth rate yields large changes in emissions several decades in the future. A 1%/year growth yields a 64% growth of emissions in 50 years, compared with constant emissions (0%/year growth rate). A growth rate of

-0.5%/year yields a -22% change of emissions in 50 years. Thus CO2 emissions in 50 years are more than twice as large in a 1%/year scenario than in a -0.5%/year scenario.

Incomplete understanding of the Earth’s "carbon cycle" creates some uncertainty, but to a good approximation the increase in atmospheric CO2 is commensurate with the CO2 emission rate. Therefore full achievement of the "alternative scenario" probably requires the global CO2 emissions growth rate to be approximately zero or slightly negative over the next 50 years.

Even if the United States achieves a zero or slightly negative growth rate for CO2 emissions, there is no guarantee that the rest of the world will follow suit. However, the economic and strategic advantages of a more energy efficient economy are sufficient to make this path attractive to most countries. It is likely that the shape of the U.S. and global CO2 emissions curves will continue to be fundamentally congruent. In any case, any strategy for achieving a climate change "soft landing", whether pursued unilaterally or otherwise, surely requires that the downward change in the U.S. CO2 emission growth rate be at least comparable to the change needed in the global average. There are many reasons for the United States to aggressively pursue the technology needed to achieve reduced CO2 emissions, including potential economic benefit and reduced dependence on foreign energy sources.

It is not our task to suggest specific policies. However, there are options for achieving the slower CO2 growth rate. Otherwise, the alternative scenario is not viable.

In the short-term, a case can be made that pent-up slack in energy efficiency (14), if pursued aggressively, can help achieve a zero or slightly negative CO2 emissions growth rate. Renewable energy sources, even though their output is relatively small, also can contribute to slowing the growth rate of emissions. There has been resistance of some industries to higher efficiency requirements. In that regard, the experience with chlorofluorocarbons is worth noting. Chemical manufacturers initially fought restrictions on CFC production, but once they changed their position and aggressively pursued alternatives they made more profits than ever. Similarly, if substantially improved efficiencies are developed (for air conditioners, appliances, etc.), such that there is a significant gap between operating costs of installed infrastructure and available technologies, that could facilitate increased turnover. Perhaps government or utility actions to encourage turnover also might be considered. Corporations will eventually reap large profits from clean air technologies, energy efficiency, and alternative energies, so it is important for our industry to establish a leadership position.

In the long-term, many energy analysts believe it is unlikely that energy efficiency and alternative energy sources can long sustain a global downtrend in CO2 emissions. Lovins (15) argues otherwise, pointing out the cost competitiveness of efficient energy end-use, gas-fired cogeneration and trigeneration at diverse scales, wind power and other renewable sources. Certainly it makes sense to give priority to extracting the full potential from efficiency and renewable energy sources. Holdren (16) concludes that meeting the energy challenge requires that we maximize the capabilities and minimize the liabilities in the full array of energy options.

Many (my impression is, most) energy analysts believe that the requirement of a flat-to-downward trend of CO2 emissions probably would require increasing penetration of a major energy source that produces little or no CO2. Our task is only to argue that such possibilities exist. It will be up to the public, through their representatives, to weigh their benefits and liabilities. We mention three possibilities.

Nuclear power: if its liabilities, including high cost and public concern about safety, waste disposal and nuclear weapons proliferation, can be overcome, it could provide a major no-CO2 energy source. Advocates argue that a promising new generation of reactors is on the verge of overcoming these obstacles (17). There does not seem to be agreement on its potential cost competitiveness.

Clean coal: improved energy efficiency and better scrubbing of particulate emissions present an argument for replacing old coal-fired power plants with modern designs. However, CO2 emissions are still high, so an increasing long-term role for coal depends on development of the "zero emissions" plant, which involves CO2 capture and sequestration (18).

Others: Oppenheimer and Boyle (19) suggest that solar power, which contributes very little of our power at present, could become a significant contributor if it were used to generate hydrogen. The hydrogen can be used to generate electricity in a fuel cell. Of course the other energy sources can also be used to generate hydrogen.

In Holdren’s (16) words: there are no silver bullets (in the array of energy options) nor are there any that we can be confident that we can do without. This suggests the need for balanced, increased public and private investment in research and development, including investments in generic technologies at the interface between energy supply and end use (20). The conclusion relevant to the alternative scenario is that, for the long-term, there are a number of possibilities for energy sources that produce no CO2.

7. Benchmarks.

The alternative scenario sets a target (1 W/m2 added climate forcing in 50 years) that is much more ambitious than IPCC business-as-usual scenarios. Achievement of this scenario requires halting the growth of non-CO2 climate forcings and slightly declining CO2 emissions. Climate change is a long-term issue and strategies surely must be adjusted as evidence accumulates and our understanding improves. For that purpose it will be important to have quantitative measures of the climate forcings.

Non-CO2 forcings. The reason commonly given for not including O3 and soot aerosols in the discussions about possible actions to slow climate change is the difficulty in quantifying their amounts and sources. That is a weak argument. These atmospheric constituents need to be measured in all countries for the sake of human health. The principal benchmark for these constituents would be their actual amounts. At the same time, we must develop improved understanding of all the sources of these gases and aerosols, which will help in devising the most cost-effective schemes for reducing the climate forcings and the health impacts.

Methane, with an atmospheric lifetime of several years, presents a case that is intermediate between short-lived air pollutants and CO2. Measurements of atmospheric amount provide a means of gauging overall progress toward halting its growth, but individual sources must be identified better to allow optimum strategies. Improved source identification is practical. In some cases quantification of sources can be improved by regional atmospheric measurements in conjunction with global tracer transport modeling.

Carbon Dioxide. Is it realistic to keep the CO2 growth rate from exceeding that of today? The single most important benchmark will be the annual change of CO2 emissions. Figure 11 shows the United States record in the 1990s. The requirement to achieve the "alternative scenario" for climate forcings is that these annual changes average zero or slightly negative. It is apparent that CO2 emissions grew at a rate that, if continued, would be inconsistent with the alternative scenario.

We suggest in the discussion above that it is realistic to aim for a lower emission rate that is consistent with the alternative scenario. This particular benchmark should receive much closer scrutiny than it has heretofore. The climate simulations and rationale presented above suggest that, if air pollution is controlled, the trend of this CO2 benchmark, more than any other single quantity, can help make the difference between large climate change and moderate climate change.

8. Communication.

Our paper on the alternative scenario (1) was reported with a variety of interpretations in the media. As I discuss in an open letter (21), this may be unavoidable, as the media often have editorial positions and put their own spin on news stories. Overall, the media correctly conveyed the thrust of our perspective on climate change. Furthermore, I suggest in my open letter that the *Washington Post* editorial on our paper (23) represented an astute assessment of the issues.

A basic problem is that we scientists have not informed the public well about the nature of research. There is no fixed "truth" delivered by some body of "experts". Doubt and uncertainty are the essential ingredient in science. They drive investigation and hypotheses, leading to predictions. Observations are the judge.

Of course, some things are known with higher confidence than others. Yet fundamental issues as well as details are continually questioned. The possibility of finding a new interpretation of data, which provides better insight into how something in nature works, is what makes science exciting. A new interpretation must satisfy all the data that the old theory fit, as well as make predictions that can be checked.

For example, the fact that the surface of the Earth has warmed in the past century is well established, and there is a high degree of confidence that humans have been a significant contributor to this warming. However, there are substantial uncertainties about the contributions of different forcings and how these will change in the future.

In my open letter (21) I note the potential educational value of keeping an annual public scorecard of measured changes of (1) fossil fuel CO2 emissions, (2) atmospheric CO2 amount, (3) human-made climate forcing, and (4) global temperature. These are well-defined quantities with hypothesized relationships. It is possible to make the science understandable, and it may aid the discussions that will need to occur as years and decades pass. It may help us scientists too.

9. Summary: A Brighter Future.

The "business-as-usual" scenarios for future climate change provide a useful warning of possible global climate change, if human-made climate forcings increase more and more rapidly. I assert not only that a climatically brighter path is feasible, but that it is achievable via actions that make good sense for other reasons (22, 24). The alternative scenario that we have presented does not include a detailed strategic plan for dealing with global warming. However, it does represent the outline of a strategy, and we have argued that its elements are feasible.

It is impractical to stop CO2 from increasing in the near term, as fossil fuels are the engine of the global economy. However, the decline of the growth rate of CO2 emissions from 4 to 1%/year suggests that further reduction to constant emissions is feasible. The potential economic and strategic gains from reduced energy imports themselves warrant the required efforts in energy conservation and development of alternative energy sources. It is worth noting that global CO2 emissions declined in 1998 and again in 1999, and I anticipate that the 2000 data will show a further decline. Although this trend may not be durable, it is consistent with the alternative scenario.

The other requirement in our alternative scenario is to stop the growth of non-CO2 forcings, which means, primarily, air pollution and methane. The required actions make practical sense, but they will not happen automatically and defining the optimum approach requires research.

A strategic advantage of halting the growth of non-CO2 forcings is that it will make it practical to stop the growth of climate forcings entirely, in the event that climate change approaches unacceptable levels. The rationale for that claim is that an ever-growing fraction of energy use is in the form of clean electrical energy distributed by electrical grids. If improved energy efficiency and non-fossil energy sources prove inadequate to slow climate change, we may choose to capture CO2 at power plants for sequestration.

Climate change is a long-term issue. Strategies will need to be adjusted as we go along. However, it is important to start now with common-sense economically sound steps that slow emissions of greenhouse gases, including CO2, and air pollution. Early emphasis on air pollution has multiple immediate benefits, including the potential to unite interests of developed and developing countries. Barriers to energy efficiency need to be removed. Research and development of alternative energies should be supported, including a hard look at next generation nuclear power. Ultimately strategic decisions rest with the public and their representatives, but for that reason we need to make the science and alternative scenarios clearer.

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Figures

Figure 1. Climate forcing during the Ice Age 20,000 years ago relative to the current interglacial period. This forcing of -6.6 1.5 W/m2 and the 5C cooling of the Ice Age imply a climate sensitivity of 0.75C per W/m2.

Figure 2. Estimated change of climate forcings between 1950 and 2000, based on (1) with five principal aerosols delineated.

Figure 3. Climate forcings in the past 50 years, relative to 1950, due to six mechanisms (6). The first five forcings are based mainly on observations, with stratospheric H2O including only the source due to CH4 oxidation. GHGs include the well-mixed greenhouse gases but not O3 and H2O. The tropospheric aerosol forcing is uncertain in both its magnitude and time dependence.

Figure 4. Simulated and observed climate change for 1950-2000 (6). These simulations with the GISS climate model (3) employ empirical mixing rates and fixed horizontal heat transports in the ocean (5). Climate forcings are those in Figure 3.

Figure 5. Simulated temperatures and planetary energy imbalance for the forcings in Figure 3 (6). The business-as-usual scenario (1% CO2/year) adds 2.9 W/m2 forcing in 2001-2050. The alternative scenario adds a greenhouse gas forcing of 1.1 W/m2 in that period and includes volcanoes similar to those during 1951-2000.

Figure 6. Cartoon depicting approximate added climate forcings in an extreme "business-as-usual" scenario and the "alternative" scenario (8).

Figure 7. Measured greenhouse gas amounts and "alternative scenario" extensions to 2050. IS92a scenarios of IPCC (2) for CO2, CH4 and N2O are illustrated for comparison. The sum of CFC and "other trace gas" forcings is constant after 2000 in the alternative scenario.

Figure 8. Annual emissions of CO2 from fossil fuels in the United States (principal data source: Oak Ridge National Laboratory, Department of Energy).

Figure 9. Annual emissions of CO2 from fossil fuels in the world (principal data source: Oak Ridge National Laboratory, Department of Energy).

Figure 10. Percentage of world fossil-fuel CO2 emissions produced in the Untied States.

Figure 11. Annual change of United States fossil-fuel emissions.

Charts and Figures

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