

Statement of

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before the

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1. Preface.

Mr. Chairman and Members of the Committee:

I appreciate the opportunity to clarify the paper 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, 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/m^2). For example, all the human-made greenhouse gases now cause a forcing of more than $2 \text{ W}/\text{m}^2$. 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 (CO_2) and less methane (CH_4), 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 300 feet lower. These changes, as summarized in Figure 1, caused a negative climate forcing of about $6\frac{1}{2} \text{ W}/\text{m}^2$. That forcing maintained a planet that was 5°C colder than today. This empirical information implies that climate sensitivity is about $\frac{3}{4}^\circ\text{C}$ per watt 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). The greenhouse gases, on the left, have a positive forcing, which would tend to cause warming. CO_2 has the largest forcing, but CH_4 , when its indirect effect on other gases is included, causes a forcing half as large as that of CO_2 . CO_2 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 $1.7 \text{ W}/\text{m}^2$ since the Industrial Revolution began [the error bars, in some cases subjective, yield an uncertainty in the net forcing of $1 \text{ W}/\text{m}^2$]. The equilibrium warming from a forcing of $1.7 \text{ W}/\text{m}^2$ is $1.2\text{-}1.3^\circ\text{C}$. However, because of the ocean's long response time, we would expect a global warming to date of only about $\frac{3}{4}^\circ\text{C}$. An energy imbalance of $0.7 \text{ W}/\text{m}^2$ remains with that much more energy coming into the planet than going out. This means there is another $\frac{1}{2}^\circ\text{C}$ 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 0.7 W/m². This, as mentioned above, implies that there is about 0.5°C 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/m² 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 3°C for doubled CO₂, but actual sensitivity could be as small as 2°C or as large as 4°C for doubled CO₂), the climate forcing scenario (aerosol 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 1.7 ± 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.

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 1.5°C 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 climate stabilization 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/m^2 in the next 50 years.

The alternative scenario results in an additional global warming in the next 50 years of about $\frac{3}{4}^\circ\text{C}$, 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 $\frac{1}{4} \text{ W/m}^2$ in the alternative scenario, compared with almost 1 W/m^2 in the business-as-usual scenario. In other words, our children will leave their children a debt ($\frac{3}{4}^\circ\text{C}$ additional warming in the pipeline) that is only slightly more than the amount of unrealized warming ($\frac{1}{2}^\circ\text{C}$) hanging over our heads now.

Figure 6 is a cartoon summarizing the two parts of the alternative scenario. First, the scenario keeps the added CO_2 forcing at about 1 W/m^2 , which requires that annual increases in atmospheric CO_2 concentrations be similar to those in the past decade. The precise scenario that we employ has the CO_2 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- CO_2 forcings. Principally, that means to halt, or even better reverse, the growth of black carbon (soot), tropospheric ozone (O_3) and methane (CH_4). These can loosely be described as air pollution, although in dilute amounts methane is not harmful to health. Black carbon, with adsorbed organic carbon, nitrates and sulfates, and tropospheric ozone are principal ingredients in air pollution.

Black carbon (soot). Black carbon aerosols, except in the extreme 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 Indian children 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 and cleaner more efficient coal burning at utilities. 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, despite oratory about possible climate change and expectations that the developing world would be the source of increasing emissions.

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 rates 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, we must make the case that 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.

- (1) *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.
- (2) *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).
- (3) *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. The trend of CO₂ emissions by the United States is particularly important for the reasons discussed above. 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, despite much rhetoric about global warming in the 1990s, 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 Earth has warmed in the past century is well established, and there is a high degree of confidence that humans have been a major 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, especially since countries such as the United States have made only modest efforts at conservation. 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.

Global warming is a long-term problem. 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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Ice Age Climate Forcings (W/m^2)

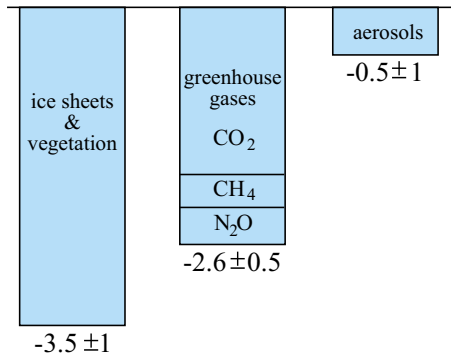


Figure 1. Climate forcing during the Ice Age 20,000 years ago relative to the current interglacial period. This forcing of $-6.6 \pm 1.5 W/m^2$ and the $5^\circ C$ cooling of the Ice Age imply a climate sensitivity of $0.75^\circ C$ per $1 W/m^2$.

Forcing $\sim 6.6 \pm 1.5 W/m^2$
Observed $\Delta T \sim 5^\circ C$
 $\rightarrow \frac{3}{4}^\circ C$ per W/m^2

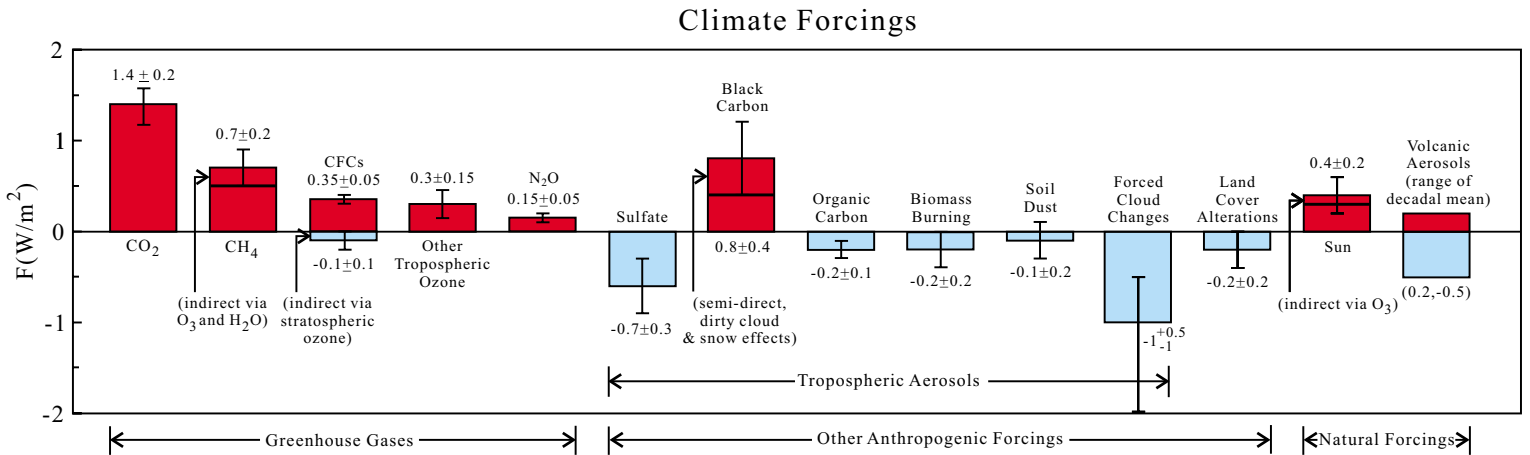


Figure 2. Estimated change of climate forcings between 1850 and 2000, based on (1) with five principal aerosols delineated.

Sum $\sim 1.7 W/m^2$
Sensitivity $\frac{3}{4}^\circ C$ per $W/m^2 \rightarrow 1.2 - 1.3^\circ C$ warming at equilibrium
Today: $\frac{3}{4}^\circ C$ warming + $0.7 W/m^2$ remaining imbalance

Radiative Forcings

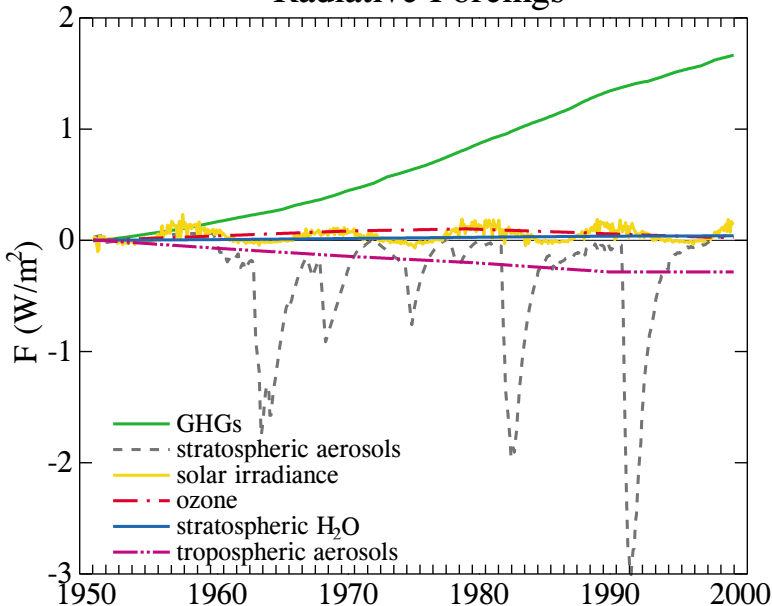


Figure 3. Climate forcings in the past 50 years, relative to 1950, due to six mechanisms (6). The first five forcings are based mainly on observations, with stratospheric H₂O including only the source due to CH₄ oxidation. GHGs include the well-mixed greenhouse gases, but not O₃ and H₂O. The tropospheric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

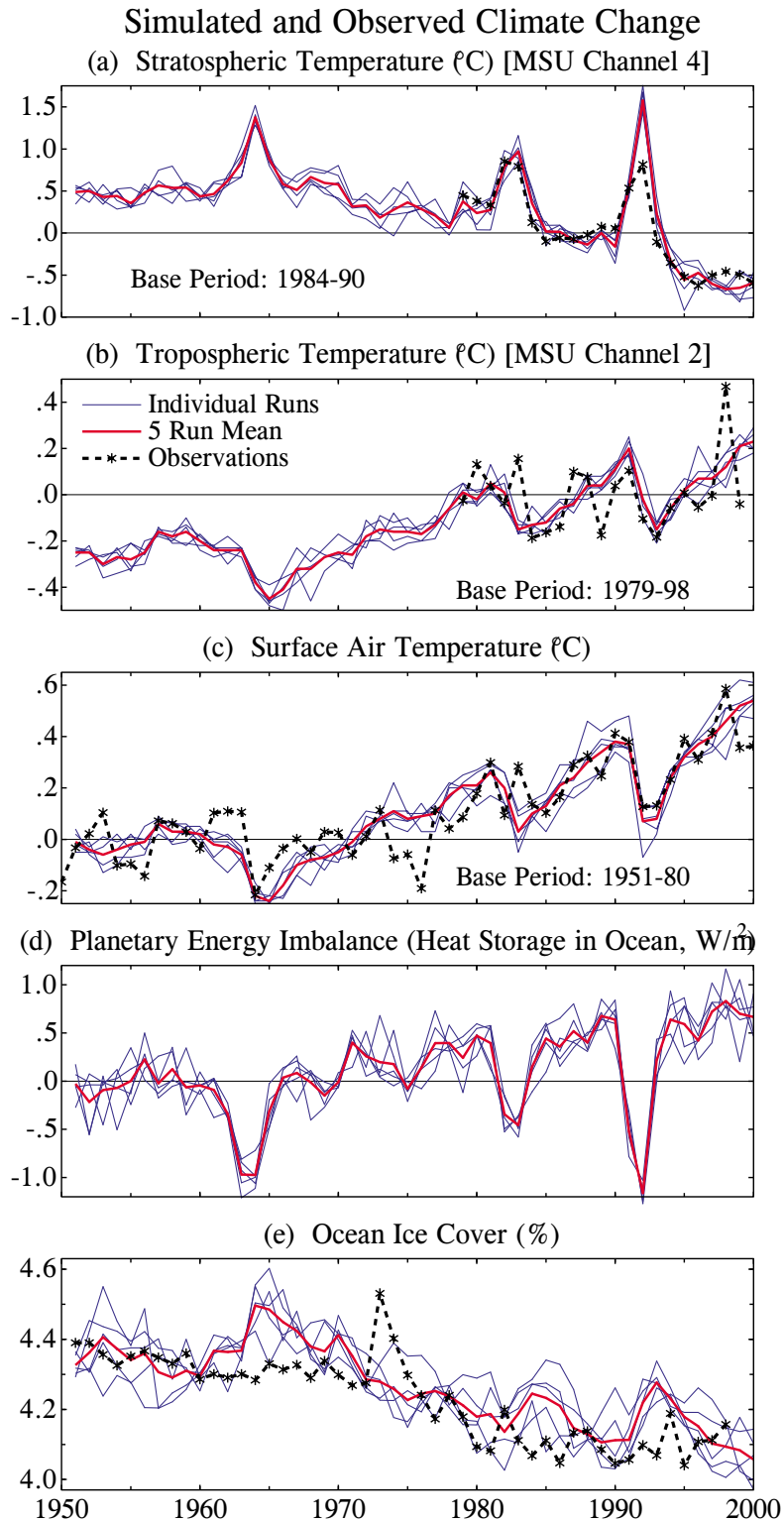


Figure 4. Simulated and observed climate change for 1950-2000 (6). These simulations with GISS climate model (3) employ empirical mixing rates and fixed horizontal heat transports in the ocean (5). Climate forcings are those of Figure 3.

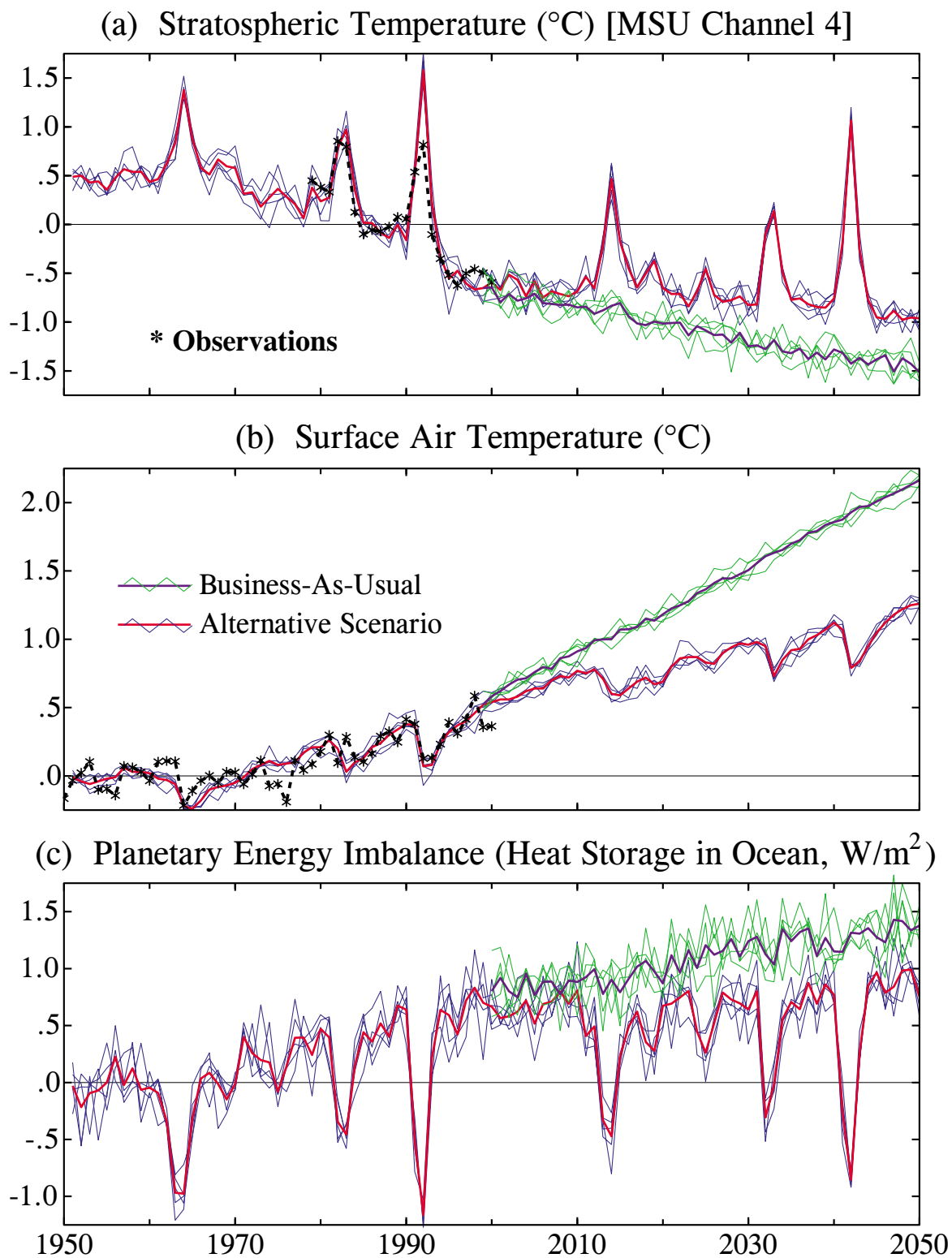


Figure 5. Simulated temperatures and planetary energy imbalance for the forcings in Figure 3 (6). The business-as-usual (1% CO_2/year) adds $2.9 \text{ W}/\text{m}^2$ forcing in 2001-2050. The alternative scenario adds a greenhouse gas forcing of $1.1 \text{ W}/\text{m}^2$ in that period and includes volcanoes similar to those during 1951-2000.

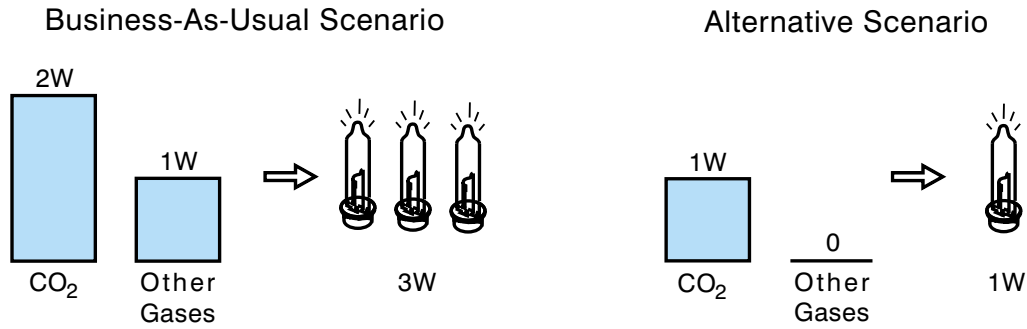


Figure 6. Cartoon depicting approximate added climate forcings between in an extreme “business-as-usual” scenario and the “alternative” scenario.

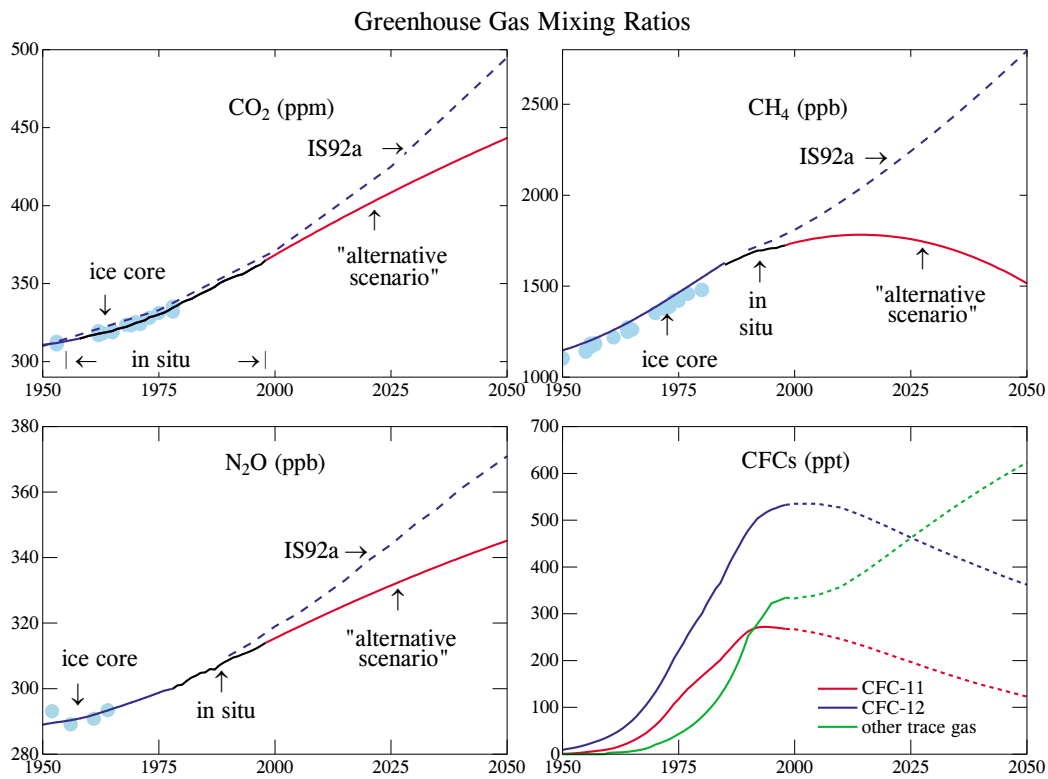


Figure 7. Measured greenhouse gas amounts and "alternative scenario" extensions to 2050. IS92a scenarios of IPCC (2) for CO₂, CH₄ and N₂O are illustrated for comparison. The sum of CFC and “other trace gas” forcings is constant after 2000 in the alternative scenario.

United States Fossil-Fuel CO₂ Emissions

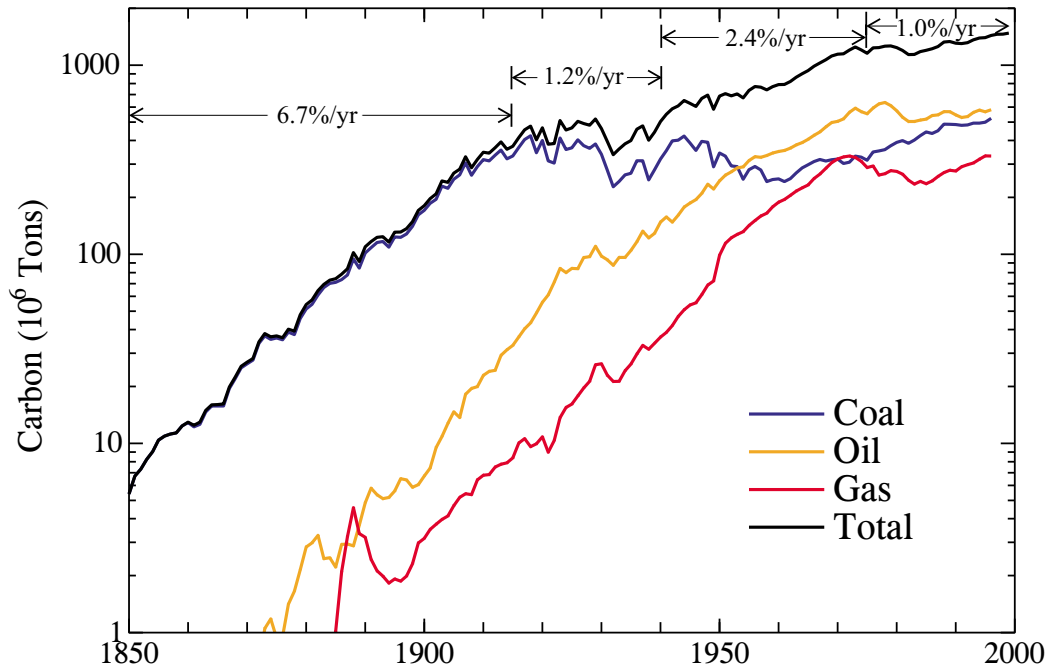


Figure 8. Annual emissions of CO₂ from fossil fuels in the United States (principal data source: Oak Ridge National Laboratory, Department of Energy)

Global Fossil-Fuel CO₂ Emissions

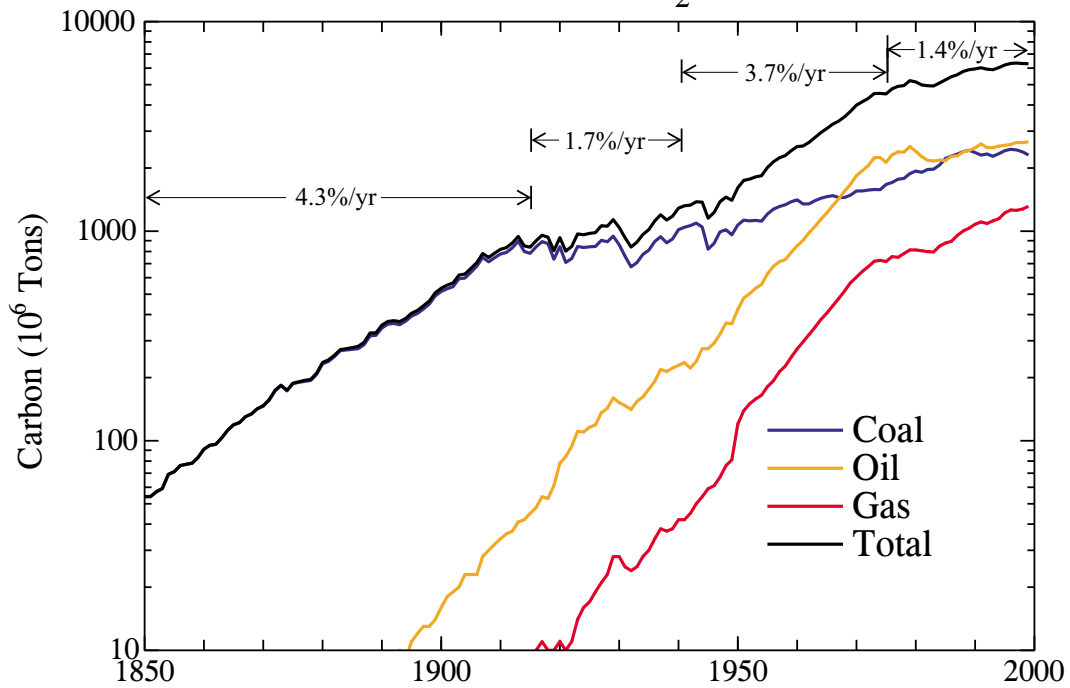


Figure 9. Annual emissions of CO₂ from fossil fuels in the world (principal data source: Oak Ridge National Laboratory, Department of Energy)

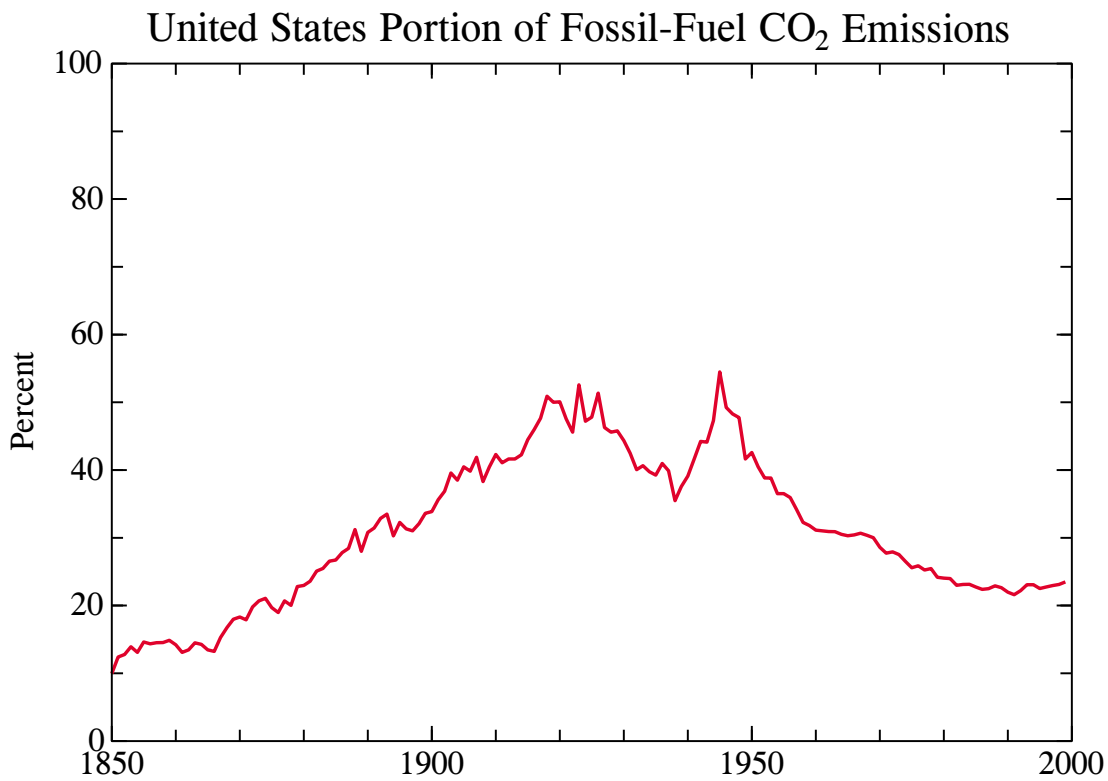


Figure 10. Percentage of world fossil-fuel CO₂ emissions produced in the United States.

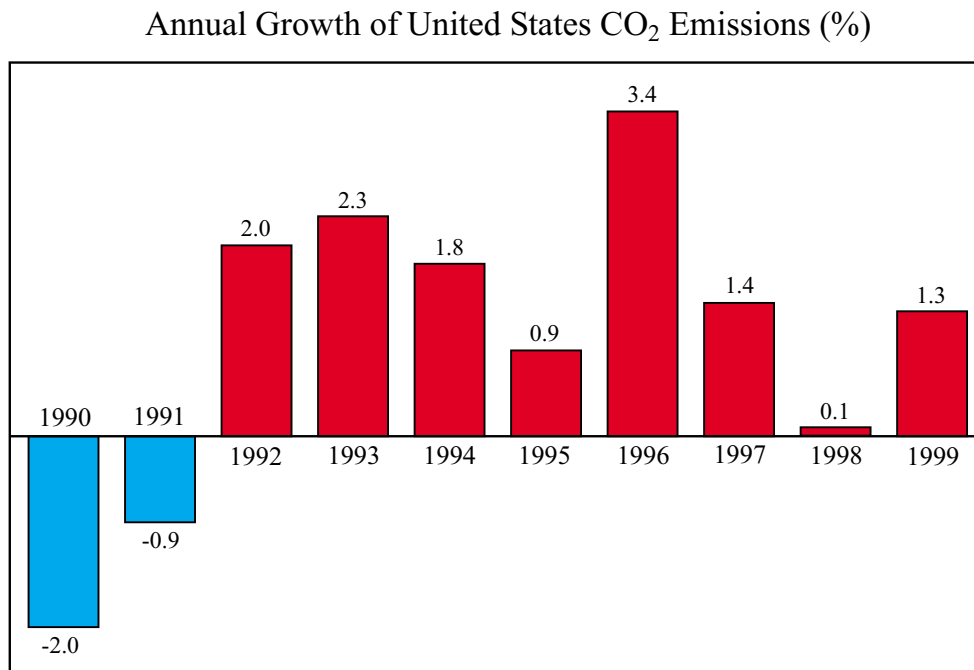


Figure 11. Annual change of United States fossil-fuel CO₂ emissions.

A Brighter Future

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Contrary to Wuebbles' thesis, most of the media did not misunderstand the thrust of our recent paper (Hansen et al., 2000). We do indeed assert that a scenario is feasible in which the rate of global warming declines. We also posit that, with an understanding of the significant climate forcings, it is possible to achieve such a climatically brighter path with actions that are not "economically wrenching", indeed, actions that make economic sense independent of global warming.

Our paper does not denigrate the "business-as-usual" (BAU) scenario that has been popular in global climate model simulations. The BAU scenario provides a valuable warning of potential climate change if the world follows a path with climate forcings growing more and more rapidly. Our aim was to present a companion scenario that stimulates discussion of actions that help avoid a gloom and doom scenario. I tried to clarify our objectives in an "Open Letter", which is made available in this issue of *Climatic Change*. I summarize here key points of discussion.

Black Carbon (BC). One of our assertions is that BC (soot) plays a greater role in climate change than has been appreciated. We believe that the forcing due to BC is of the order of 1 W/m^2 , rather than of the order of 0.1 W/m^2 , as assumed by IPCC (1996).

My present estimate for global climate forcings caused by BC is: (1) $0.4 \pm 0.2 \text{ W/m}^2$ direct effect, (2) $0.3 \pm 0.15 \text{ W/m}^2$ semi-direct effect (reduction of low-level clouds due to BC heating; Hansen et al., 1997), (3) $0.1 \pm 0.05 \text{ W/m}^2$ "dirty clouds" due to BC droplet nuclei, (4) $0.2 \pm 0.1 \text{ W/m}^2$ snow and ice darkening due to BC deposition. These estimates will be discussed in a paper in preparation. The uncertainty estimates are subjective. The net BC forcing implied is $1 \pm 0.3 \text{ W/m}^2$.

Air Pollution. Aerosols and tropospheric ozone (O_3) are not addressed by the Kyoto protocol. They should be. A reason proffered for excluding ozone is that its chemistry is so complex that "most scientists' eyes glaze over" (Revkin, 2000). Perhaps the latter assertion is true. But it is not adequate reason to exclude air pollution from international climate negotiations. Our estimated anthropogenic global climate forcing due to BC (1 W/m^2) and O_3 (0.4 W/m^2) is comparable to the CO_2 forcing (1.4 W/m^2). One thesis in our paper is that halting the growth of air pollution can make a significant contribution to slowing global warming.

Effects of air pollution on humans are large in the developed world and staggering in the developing world. A recent study (Kunzli et al., 2000) estimates that particulate air pollution in France, Austria and Switzerland takes 40,000 lives annually with health costs equal to 1.6% of the gross national products. An example for the developing world is the estimate (Smith, 2000) that 270,000 Indian children under 5 years old die annually from acute respiratory infections caused by air pollution. Most of the pollution in this latter case arises from indoor combustion for cooking and heating, a primary source of the cloud of pollutants now mushrooming from India and China. Aerosols and ozone also reduce agricultural productivity with costs of many billions of dollars.

Practical benefits of air pollution reduction accrue immediately, not in 100 years. We assert in our paper that this offers an opportunity to reduce the climate problem with a cooperative approach that has immediate clear benefits to both developing and developed countries.

Methane. We conclude that climate forcing by CH_4 is 0.7 W/m^2 , fully half as large as the forcing by CO_2 . Observed growth of CH_4 is not accelerating, contrary to assumptions in many climate scenarios. Indeed, the growth rate has declined by two-thirds in the past 20 years. However, future trends are uncertain.

The task of understanding CH_4 should be jumped on, like a chicken on a June bug. Yet research support has been minuscule. We need quantitative understanding of CH_4 sources and sinks to define optimum policies. It may be possible to find practices that reduce methane emissions while saving money. Farmers want cows and beasts of burden to produce milk, meat, and power, not methane. Rice growers seek food and fiber, not methane, but we must also compare impacts of altered practices on N_2O

production. There is much potential for methane capture via improved mining and waste management practices.

Scenarios. Science works via iterative comparison of theory and observations. Differences found are not a problem - on the contrary, only by discovering and investigating these can our understanding advance. One problem with the IPCC reports is that each report produces new (and more numerous) greenhouse gas scenarios with little attempt to discuss what went wrong with the previous ones. As a result, dramatic changes that have occurred since the 1980s in prospects for future climate forcings receive inadequate attention.

Figure 1 shows climate forcing scenarios used for climate simulations in the 1980s (Hansen et al., 1988). The actual climate forcing in 2000 is close to that of scenario B, and the derivative (growth rate) is less than that of scenario B. Further slowdown is needed to achieve the path of the “alternative scenario”. The fact that the real world does not now *seem to be* following a path toward the median of the greenhouse gas amounts projected by Ramanathan et al. (1985) for 2030 in no way detracts from that paper, which, in my opinion, was one of the most stimulating papers in atmospheric sciences during recent decades. Indeed, to at least a small extent, one might credit the slowdown in climate forcing growth rates to the warning implicit in this and related papers.

Why have growth-rates fallen below BAU scenarios? One clear reason: the Montreal Protocol, which forced a phase-out of CFCs. That is an example of what we propose: actions useful for other reasons that also help to slow climate change. Reasons for the decline in the CH₄ growth rate need to be understood better. The apparent flattening of the CO₂ growth rate is probably due in part to an increased CO₂ sink, which may (or may not) be a temporary phenomenon.

CO₂ scenarios are the most critical. Our approach, characterized as naïve by Wuebbles, emphasizes observations. We note that the growth rate of CO₂ (fossil fuel) emissions has declined from about 4%/year to 1%/year in recent decades. It is noteworthy that the current IPCC (2001) scenarios have a growth rate in the 1990s that is almost double the observed rate of 0.8%/year (linear trend fit to 5-year running mean), but it is consistent with their failure to emphasize data. I will not characterize the IPCC approach defended by Wuebbles, but I note in my open letter the difficulty inherent in multiplying assumptions about population, economic development, and technology 50 or 100 years in the future. In my letter I specifically discuss their population estimates, which already appear to be unduly pessimistic.

Media and the Public. Wuebbles claims that the press misunderstood our paper. I believe that he fails to see the forest for the trees. The media do not always get technical details correct, as scientists know well. Moreover, media often have editorial positions and put their own spin on news stories. I complain in my open letter about an exceptional case in which *Nature* disguised their editorial position as a “news” article in which they report only criticisms of our paper. However, overall the media deserve credit for correctly conveying the thrust of our perspective on climate change. Indeed, the *Washington Post* editorial discussed in my open letter is, in my opinion, 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.

Sure, 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.

The suggestion that BC causes a forcing of about 1 W/m² is a possible example. Observations required to verify the forcing are extensive, because it is the sum of several effects. Perhaps recognition of the BC forcing will allow IPCC to include fully the negative direct and indirect forcings of sulfate and organic aerosols, something that they have been reluctant to do. There is still much to be learned.

In my letter 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. I am curious, for example, whether the IPCC

(1996) conclusion that fossil fuel CO₂ emissions must be cut by more than 80% to stabilize atmospheric CO₂ at 550 ppm will be supported by empirical data on the carbon cycle as it accumulates.

Strategic Considerations. Wuebbles states that our scenario can not be “used in any sense as a strategy, particularly given the inhomogeneities in the aerosol distribution and radiative forcing.” We do not try to specify a detailed strategy for dealing with global warming (nor does Wuebbles or IPCC). However, we do present an outline of a strategy and argue 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, especially since countries such as the United States have made only modest efforts at conservation. The potential economic and strategic gains from reduced energy imports themselves warrant the required efforts in energy conservation and development of alternative energy sources.

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.

Global warming is a long-term problem. 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 research and development that permits an objective assessment of the role of 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.

Finally, an amusing thing about Wuebbles’ criticism is the space devoted to noting that, even if there is some cancellation of global mean forcings by aerosols and gases, there may still be climate effects due to the geographical inhomogeneity of the net forcing. That’s right. However, he fails to recognize that reduction of particulate air pollution will reduce this inhomogeneity, not increase it.

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Climate Forcing

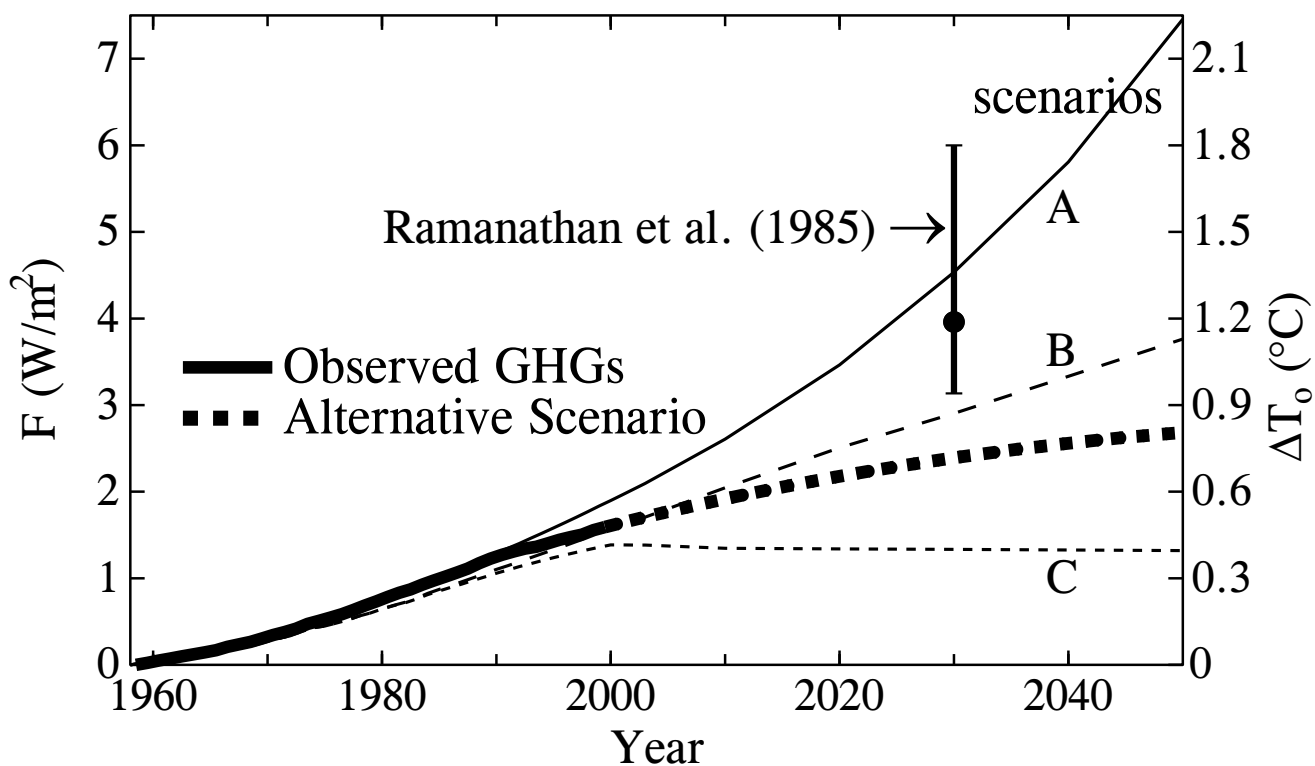


Figure 1. Greenhouse gas climate forcings for the scenarios A (“business as usual” or “fast growth”), B (“slow growth”) and C (“no growth”) of Hansen et al. (1988) and the “alternative scenario” of Hansen et al. (2000). Heavy solid curve shows actual climate forcing based on changes of CO_2 , CH_4 , N_2O , CFCs, stratospheric H_2O , and numerous trace gases. O_3 forcing is not included because of poor knowledge of changes and the expectation of partial cancellation between tropospheric increases and stratospheric decreases. Details are provided in a paper in preparation (“Climate forcings in the GISS SI2000 model”). The units for climate forcing employed by Hansen et al. (1988), ΔT_0 ($^\circ\text{C}$), the equilibrium global mean temperature change that would occur if there were no climate feedbacks, differ from the forcing in W/m^2 by the factor: ΔT_0 ($^\circ\text{C}$) = $0.3 F$ (W/m^2).

Hot News on Warming

Text from *The Washington Post*

Monday, August 28, 2000: Page A18

IF YOU'RE trying to decide whether to be an optimist or a pessimist on global warming, recent news is enough to leave you dizzy. An icebreaker found open water at the North Pole, prompting a new wave of attention to the thinning polar ice cap. That seemed like bad news, although some oceanographers said summertime cracks in Arctic ice aren't new, and this one shouldn't be over-interpreted. Texas, the state that produces the most greenhouse gas emissions, for the first time took steps to study the extent of those emissions and consider possible ways to reduce them. That was good news, although it doesn't guarantee state action. And Dr. James Hansen, a leader in drawing government attention to global warming, published a report suggesting that it may be "more practical to slow global warming than is sometimes assumed" by focusing in the short term on cutting heat-trapping gases other than carbon dioxide. That was surprising news, at least to those of us who have seen the climate-change fight centering on reducing carbon dioxide emissions.

It's long been known that carbon dioxide isn't the only gas that helps hold heat in the atmosphere. Six "greenhouse gases" were included in the Kyoto protocol, the international agreement that calls for cutting emissions by 2012. But carbon dioxide, the most abundant greenhouse gas, has dominated the public debate. It has been a subject of contention because it is a byproduct of burning fossil fuels, such as coal and gas, that drive modern industrial society. American opponents of the Kyoto protocol have argued that the reductions it requires could wreck the economy.

Dr. Hansen and a team of colleagues wrote that most of the global warming so far observed actually has come from other greenhouse gases such as methane, chlorofluorocarbons, and gases that combine to create ozone in smog. They suggested a strategy of focusing first on cutting those gases and black particles of soot that also trap heat. Some of the gases involved are already in decline because of other international restrictions; going after others amounts to an attack on air pollution, which the scientists argue should be attractive action in all parts of the world, independent of concerns about warming, because of the health benefits of cleaner air.

That optimistic scenario immediately caused some environmentalists to worry that the report would become a weapon for those who are skeptical about warming—who oppose any action. Dr. Hansen himself said it undoubtedly will be used that way, but that would be a misreading of the study. The new report does not challenge either the evidence that surface temperatures are going up or the growing consensus that human activities are contributing to the increase. It continues to cite the need for reductions in carbon dioxide emissions. There is no suggestion, nor should there be, that response to global warming should wait until the science is more certain.

What it does do is remind us that climate issues are complex, far from fully understood and open to a variety of approaches. It should serve as a caution to environmentalists so certain of their position that they're willing to advocate radical solutions, no matter what the economic cost. It suggests that the sensible course is to move ahead with a strong dose of realism and flexibility, focusing on approaches that are economically viable, that serve other useful purposes such as cutting dependence on foreign oil or improving public health, and that can help support international consensus for addressing climate change. If the Hansen report pushes the discussion in that direction, it will turn out to be good news indeed.

THURSDAY, NOVEMBER 16, 2000

INTERNATIONAL Herald Tribune

PUBLISHED WITH THE NEW YORK TIMES AND THE WASHINGTON POST

EDITORIALS/OPINION

Try a Commonsense Response to Global Warming

NEW YORK — Evidence continues to build that the world is slowly getting warmer. Almost all mountain glaciers are retreating. It was discovered this year that even the deep ocean is warming. On Earth's surface, where people live, the average warming is now about half a centigrade degree in the past 100 years.

Half a degree seems hardly noticeable. It is much less than weather fluctuations that occur every day. But it is a warning of possibly large climate changes as the 21st century progresses.

One worry is sea level, which will rise as glaciers melt and as ocean water expands from warming. A rise of a meter, a possibility this century, would submerge island nations such as the Maldives and the Marshall Islands, and it would be devastating to people living in Bangladesh and on the Nile Delta.

The greatest effect of global warming for most people may be an increase in extreme weather. Global warming is expected to cause more droughts and forest fires. It increases evaporation, which will lead, at other times and places, to heavier rainfall and floods.

□
The forces that drive global warming are no surprise. They are mainly the gases and fine particles that humans have been dumping into the atmosphere for many years. The gases, especially carbon dioxide and methane, absorb Earth's heat radiation and thus warm the surface, just as a blanket traps body heat. Fine particles of soot (black carbon) warm the air by absorbing sunlight.

Other human-made fine particles, especially sulfates, are nearly white. Sulfates come from sulfur in coal and

oil, which is released to the atmosphere when these fossil fuels are burned. Sulfates cool Earth by reflecting sunlight back to space.

The net effect of these human emissions is not accurately known, because the fine particles are not yet measured well. But it is estimated that the net heating is at least one watt, perhaps closer to two watts, per square meter. Such a human forcing of climate is comparable to increasing the brightness of the sun by 1 percent.

Earth responds slowly to such forcings. The thermal inertia of the ocean delays the response. It takes decades for most of the response to occur, and centuries for the full response.

The question we face today is how much more we should allow human climate forcing to grow. That question is being addressed now in The Hague by the world's nations.

These deliberations are guided by climate simulations carried out by the Intergovernmental Panel on Climate Change. The simulations focus on a gloomy scenario in which it is assumed that humans will burn coal, oil and gas at faster and faster rates.

This gloomy scenario leads to an additional forcing of three watts in the next 50 years. Such a forcing will almost surely lead to increases in climate extremes and a rising sea level.

Some increase in human climate forcing is inevitable. Fossil fuels are our primary source of energy. Because of the energy infrastructure, it requires decades to phase in new technologies that may produce less carbon dioxide.

However, we recently suggested a scenario that reduces the human forcing to only one watt in the next 50 years. This would yield a more moderate climate change, allowing time to understand climate change better and develop technologies and strategies to deal with it.

□
There are two elements in this commonsense solution to global warming. First we must stop the growth of air pollution. This would eliminate any added climate forcing by constituents other than carbon dioxide. Second we must burn fossil fuels, and thus emit carbon dioxide, no faster than we do today. That means that growing energy needs must be met by increased efficiency in current uses and by introducing technologies that produce little or no carbon dioxide.

Both elements are achievable but unlikely to happen by accident. Technologies that reduce air pollution have to be applied. Annual growth of carbon dioxide emissions, which has already slowed from 4 to 1 percent per year, must be slowed a bit further to zero growth or a small decrease.

Many actions could reduce both air pollution and carbon dioxide emissions. We need to develop clean fuels and renewable energy sources, and remove barriers to energy efficiency. Improved technology, perhaps including fuel cells and hydrogen power, can help reverse the trend to greater gas-guzzling vehicles. Utility profits should be designed to reward improved efficiency and decreased air pollution.

Improved energy efficiency, cleaner uses of fossil fuels and development of

renewable energy sources will have multiple benefits. In addition to slowing the growth of carbon dioxide, this will create jobs, improve economic competitiveness, reduce reliance on foreign sources of energy and improve public health.

Fine particles in air pollution, including soot, sulfates and organic aerosols, penetrate human tissue deeply, causing respiratory and cardiac problems. A recent study found that air pollution in France, Austria and Switzerland alone accounts for 500,000 asthma attacks and 40,000 deaths per year. Air pollution in developing countries, such as India and China, is even more severe.

□
International cooperation is needed, because emissions circulate worldwide. But benefits of progress, in climate stabilization and health, will be similarly widespread. Required cooperation, including technology transfer, can include incentives and economic opportunities for all parties.

The commonsense approach is to move forward by attacking air pollution, improving energy efficiency and developing renewable energy sources. This approach is economically sound and has collateral benefits. It should provide a meeting ground for persons from a wide spectrum of political viewpoints, all of whom wish to preserve the environment.

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The writer is director of the National Aeronautics and Space Administration's Goddard Institute for Space Studies. This comment was distributed by the Los Angeles Times Syndicate.