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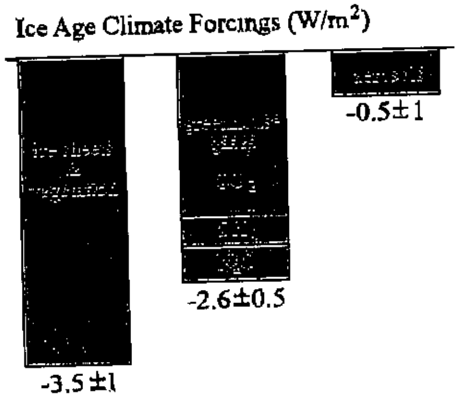

Figure 1. Climate forcing during the Ice Age 20,000 years ago relative to the current interglacial period. This forcing of -6.6 ± 1.5 W/m² and the 5°C cooling of the Ice Age imply a climate sensitivity of 0.75°C per 1 W/m².

Forcing $\sim 6.6 \pm 1.5$ *W/m²*

Observed $\Delta T \sim 5$ °C

$\rightarrow \frac{3}{4}$ °C *per W/m²*

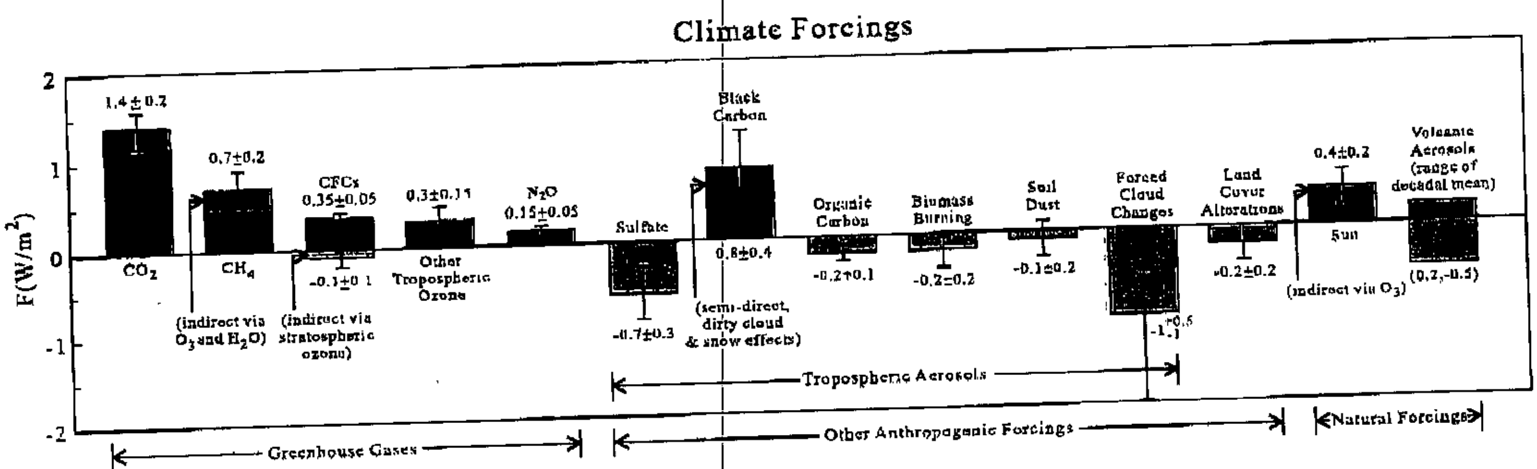

Figure 2. Estimated change of climate forcings between 1850 and 2000.

Sum ~ 1.7 *W/m²*

Sensitivity $\frac{3}{4}$ °C *per W/m²* $\rightarrow$ 1.2 - 1.3 °C *warming at equilibrium*

Today: $\frac{3}{4}$ °C *warming* + 0.7 *W/m² remaining imbalance*

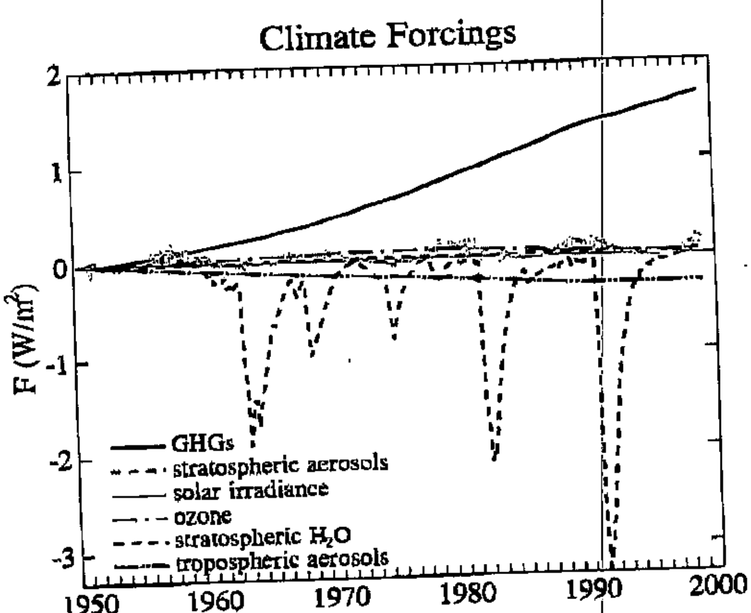

Figure 3. Climate forcings in the past 50 years due to six mechanisms, relative to 1950. The first five forcings are based mainly on observations, with stratospheric H_2O including only the source due to CH_4 oxidation. GHGs include the well-mixed greenhouse gases, i.e., it excludes O_3 and H_2O. The tropospheric aerosol forcing is uncertain in both its magnitude and time dependence.

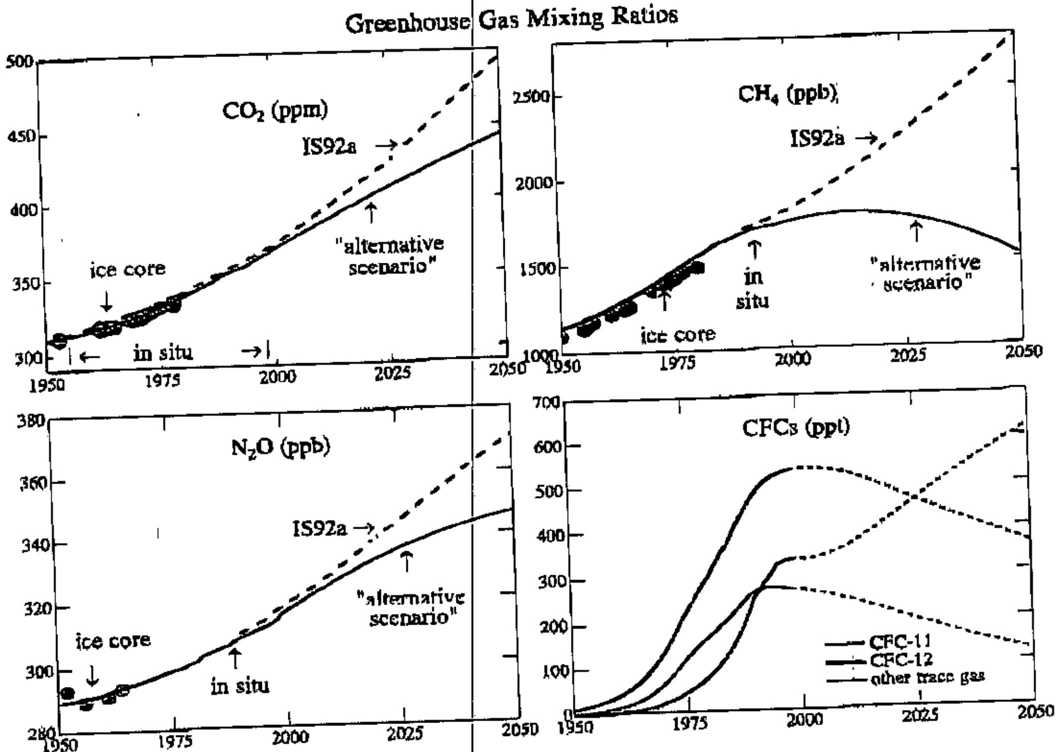

Figure 7. Measured greenhouse gas amounts and an extension to 2050 based on the "alternative scenario" of Hansen et al. [2000]. IS92a scenarios for CO_2, CH_4 and N_2O [IPCC, 1992] are illustrated for comparison. The sum of CFC and "other trace gas" forcings is constant after 2000 in the alternative scenario.

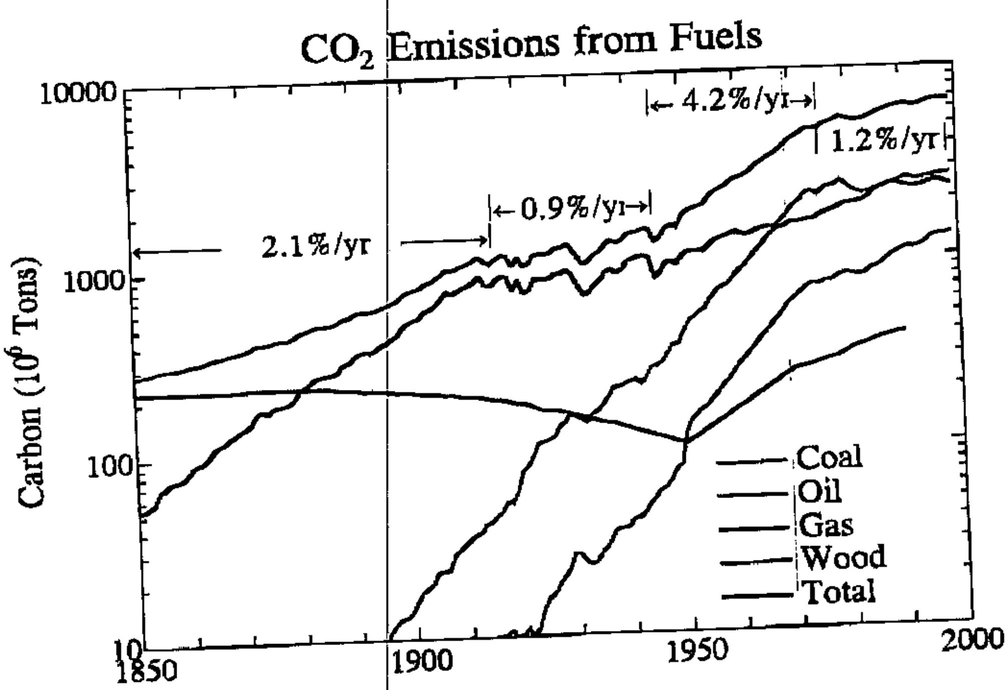

Figure 8. CO_2 emissions from fuel use [Marland and Boden, 1998]; estimate for wood by N. Makarova, Rockefeller University.

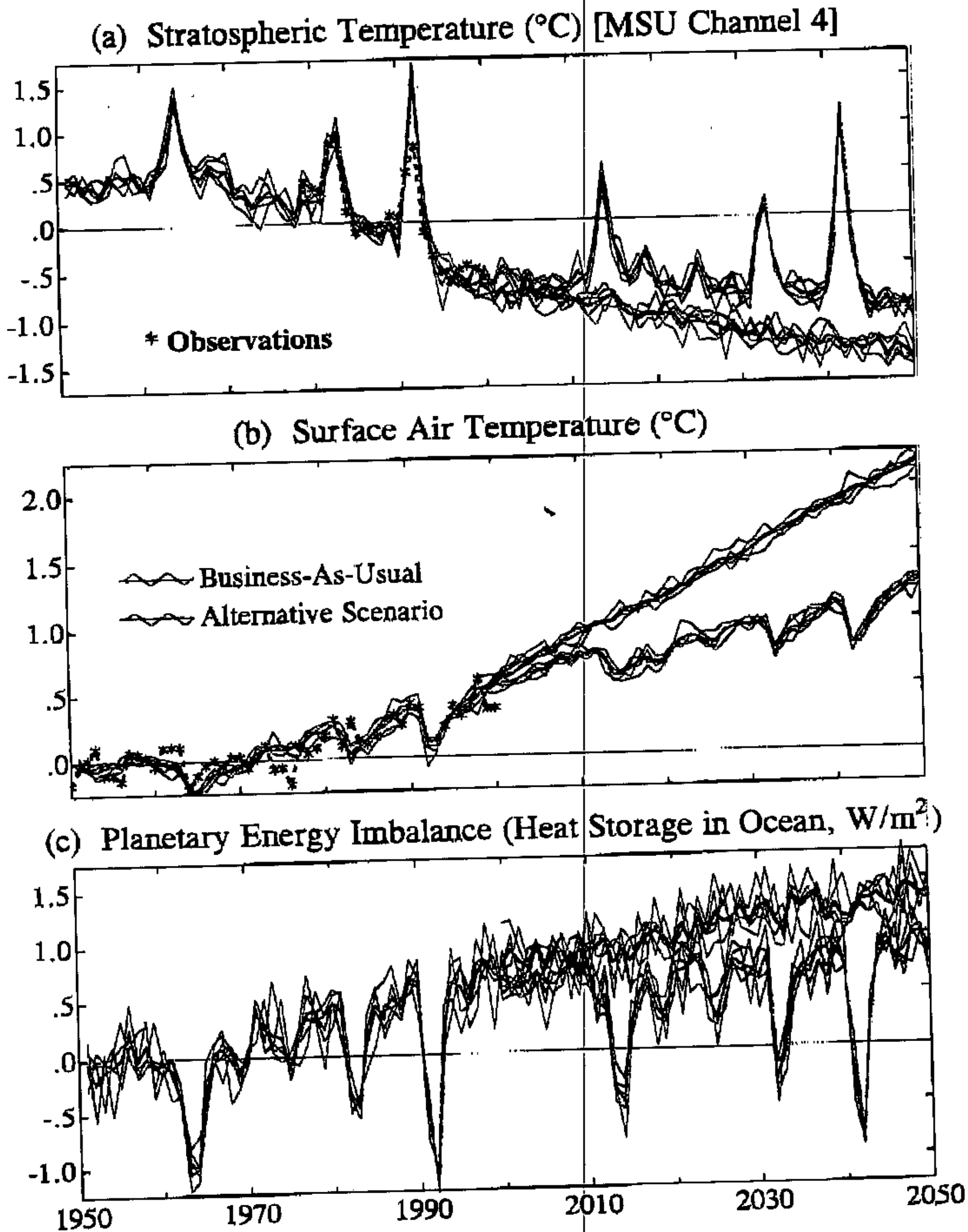

Figure 5. Simulated temperatures and planetary energy imbalance for the six forcings in Figure 3 for 1950-1999 with two scenarios for 2000-2050, with business-as-usual (1% CO_2/year, 2.9 W/m^2) and the alternative scenario (Figure 7, 1.1 W/m^2).

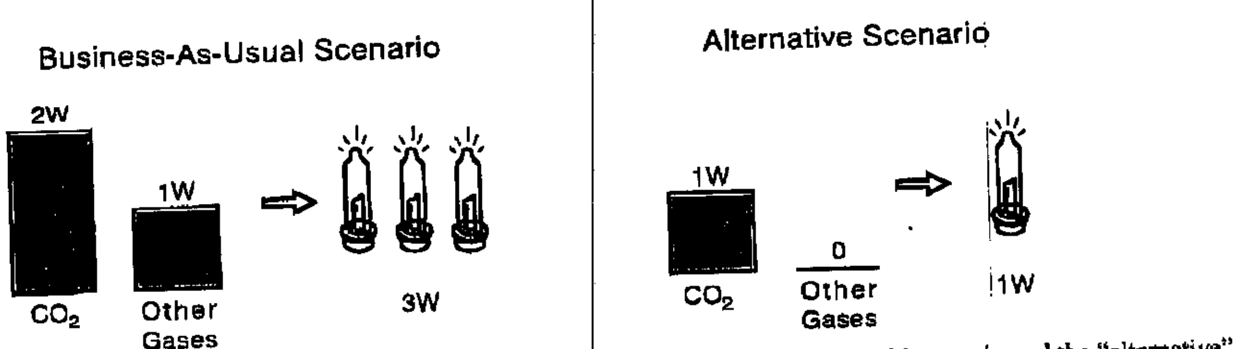

Figure 6. Added climate forcings between 2000 and 2050 in a "business-as-usual" scenario and the "alternative" scenario.

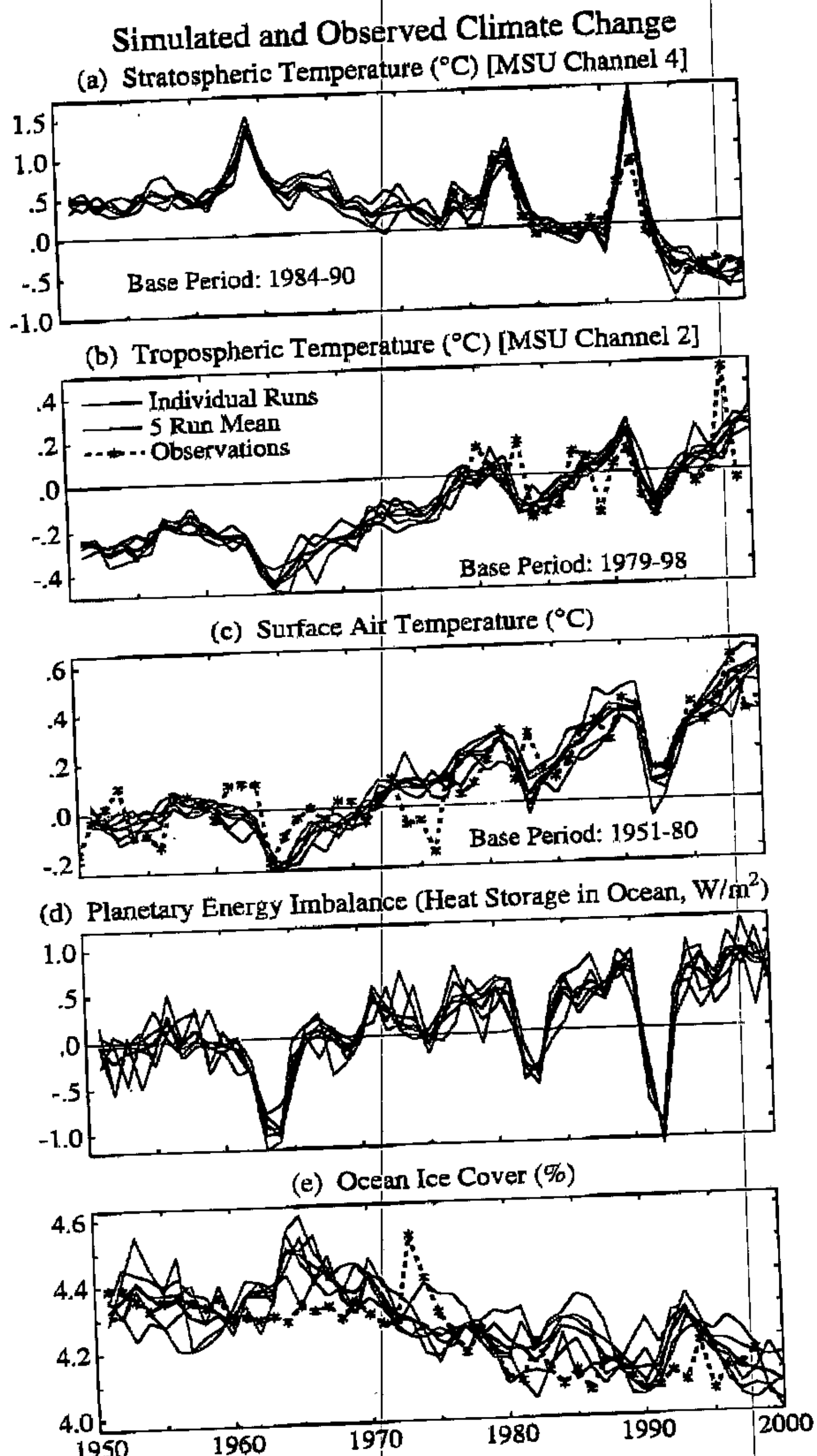

Figure 4. Simulated and observed climate change for 1950-2000. These simulations with GISS climate model employ empirical mixing rates in the ocean. Climate forcings are those of Figure 3.

The Forcing Agents Underlying Climate Change

Briefing for: Global Climate Change Working Group
Washington, DC
March 29, 2001

James E. Hansen, Head
NASA Goddard Institute for Space Studies

Good morning. Thank you for this opportunity to discuss climate change. I am director of the NASA Goddard Institute for Space Studies a division of Goddard Space Flight Center located at Columbia University in New York. We specialize in the study of planets, especially the Earth's climate - how it varies, and why it varies. One of our prime objectives is to provide scientific information that the public and their representatives can use to help make wise policies. It is not our job to suggest policies. Our aim is to provide information that is as quantitative and as clear as the data permit.

Permit me to first summarize a few 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 W/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. 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 6½ W/m^2. That forcing maintained a planet that was 5°C colder than today. This empirical information implies that climate sensitivity is about ¾°C per watt of forcing. Climate models have the same sensitivity, which shows an encouraging agreement between the real world and the complex computer models that we are using 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 75-90 percent complete. 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.

With that preamble, let's discuss the climate forcings summarized in Figure 2. The greenhouse gases, on the left, have a positive forcing, which would tend to cause warming. CO_2 has the largest forcing, but methane, when you include its indirect effect on other gases, 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, which is 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, in turn making the clouds brighter and longer-lived. All of the aerosol effects have large uncertainty bars, because our measurements are inadequate and our understanding 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 W/m^2 since the Industrial Revolution began [the error bars, in some cases subjective, yield an uncertainty in the net forcing of 1 W/m^2]. The equilibrium warming from a forcing of 1.7 W/m^2 is 1.2-1.3°C. However, because of the ocean's long response time, we would expect a global warming to date of only about 3/4°C. An energy imbalance of 0.7 W/m^2 remains, with that much more energy coming into the planet than going out. This means there is another 1/2°C global warming already in the pipeline - it will occur even if atmospheric composition remains fixed at today's values.

We know these climate forcings 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 very uncertain. 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 to calculate the climate change, as shown in Figure 4, the results are consistent with observations. [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 CO_2 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/m^2. 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, by Syd Levitus of NOAA, 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.

We extend these climate model simulations into the future for two climate forcing scenarios illustrated in Figure 5. In the popular "business-as-usual" scenario, which the newspapers love, the climate forcing increases by almost 3 W/m^2 in the next 50 years. This leads to additional global warming of about 1.5°C by 2050 and several degrees by 2100. In the "alternative scenario" fossil fuels continue to be used at about today's rate, with a slow trend toward less CO_2 emissions, but there is no further growth of the other forcings. In simple terms, 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 additional global warming in the next 50 years in the alternative scenario is about ¾ °C, much less than for the business-as-usual scenario. In addition, the rate of stratospheric cooling declines in the alternative scenario, and it may stop entirely if stratospheric ozone begins to recover. The planetary energy imbalance increases by only about ¼ W/m^2 in the alternative scenario, but by almost 1 W/m^2 in the business-as-usual scenario.

Figure 6 is a cartoon emphasizing the two parts of the alternative scenario. First, we must keep the added CO_2 forcings at 1 W/m^2. This requires the rate of CO_2 increase in the next 50 years to be about the same as it has been in recent decades. More precisely, the scenario has a slow decline in the CO_2 growth rate during this 50 years, which would make it practical to further decrease growth rates in the second half of the century. Second, the growth of other climate forcings is assumed to cease. Principally that means methane, tropospheric ozone, and black carbon aerosols. [The specific trace gas scenarios used in the GCM simulations are shown in Figure 7.]

Carbon Dioxide. Is it realistic to keep the CO_2 growth rate from exceeding that of today? Figure 8 helps us to think about this. After World War II CO_2 emissions increased exponentially at more than 4%

per year, as economies and wealth expanded rapidly driven by fossil fuel energy. Since the oil price shock in the 1970s, the growth rate has been just over 1% per year. In the 1990s it was 0.8% per year. In the past three years it has been slightly negative. That may be a fluke - we have had other short periods with negative growth of CO_2 emissions. However, it is fair to say that the world is not far from having a flat emission rate of CO_2. This suggests that increased emphasis on energy efficiency and renewable energy sources can make the difference between increasing CO_2 emission rates and declining emission rates.

I do not want to inappropriately get into advocacy of specific policies. However, I do want to make clear that the alternative scenario is a practical scenario. It is doable on the basis of actions that make good economic and strategic sense. I am not suggesting that energy efficiency or renewable energy can alone solve current power shortage problems. Electrical power needs will continue to increase, as a larger and larger proportion of our and the world's energy use is electrical. Indeed, this is helpful for the sake of achieving the alternative scenario. It is more practical to reduce air pollution and increase energy efficiency at a modern power station than at local sources of fossil fuel burning.

At the risk of cluttering my main argument, I note that policy-makers should also be aware that it may be difficult to achieve the slowly declining CO_2 emissions in the alternative scenario if aging nuclear power plants are replaced by coal-fired plants, even using improved efficiency clean-coal plants. Leaving other issues aside, nuclear power is close to being a 'silver bullet' for the purpose of minimizing climate forcings. The public and their policy-making representatives should carefully contrast the merits of these different energy sources as they are each developed to their modern potentials. If clean-coal technology leads to an increasing role for coal in power generation, then achievement of the alternative scenario may require capture and sequestration of some of the coal-generated CO_2. Capture of CO_2 at power plants may in fact be practical, but methods of sequestration and the ultimate effects of sequestration need to be understood better.

<u>**Non-CO_2 Climate Forcings.**</u> The other requirement for achieving the alternative scenario, in addition to flattening the emissions rate of CO_2, 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 the 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 they are breathed into the lungs. Particulate air pollution has been increasingly implicated in respiratory and cardiac problems. A recent study in Europe [*Kunzil*, 2000] 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 GNP. Pollution levels and health effects in the U.S. are at a comparable level. Primary sources of black carbon in the West are coal burning and diesel fuels.

The human costs of particulate air pollution in the developing world are staggering. A study recently published in the Proceedings of the National Academy of Sciences [*Smith*, 2000] concluded that about 270,000 Indian children under the age of five died 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 there residential coal use is the largest source, followed by residential biofuel [*Streets*, 2001].

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 (O_3). 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. Because ozone in the free troposphere can have a lifetime of weeks, tropospheric ozone is a global problem, e.g., emissions in Asia are projected to have a significant effect on air quality in the United States. 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.

Our alternative scenario assumes that it will be possible to stop further growth of this pollutant. Recent evidence suggests that tropospheric ozone is decreasing downwind of regions such as Western Europe, where nitrogen oxide emissions are now controlled, but increasing downwind of East Asia. There is a clear potential for cleaner energy sources and improved combustion technology to achieve an ozone reduction.

Methane (CH_4). 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.

Our alternative scenario assumes that it will be possible to stop further growth of methane within 1-2 decades and bring about a small reduction in methane by 2050. There are economic benefits to reduction of methane loss from pipelines and during mining and to methane capture from landfills and waste management lagoons, as the methane can be used as a clean fuel. There is also an incentive and methods available for farmers to reduce methane production, as their goals are to produce meat, milk and power from the animals, not methane, and to produce food and fiber from the fields, not methane. However, these economic benefits are not so great that they are likely to happen automatically. The large climate forcing by methane, which is half as large as that by CO_2, warrants more attention being paid to this gas.

__Summary.__ CO_2 causes the single largest climate forcing, but several other forcings are important (Figure 2). To reduce global warming we must reduce the sum of these forcings. Figure 2 emphasizes that, in addition to CO_2, black carbon, tropospheric O_3, and CH_4 are important climate forcings. Indeed, their forcing, in sum, exceeds that of CO_2. Although it can be assumed that fossil fuel burning will continue in the foreseeable future, we suggest an alternative scenario (alternative to business-as-usual) that would result in relatively moderate climate change in the next 50 years and allow the possibility of a "soft landing" for climate change later in the century, as well as the possibility of stronger remedies in decades ahead if empirical evidence on climate change indicates such a necessity.

Alternative scenario. In this scenario the added climate forcing in the next 50 years is only 1 W/m^2. This requires only a small downtrend in CO_2 emissions, which could be achieved via improved energy efficiency and increased contributions from non-fossil fuel sources of energy. The other requirement in this scenario is stop the growth of non-CO_2 climate forcings, which implies a concerted attack on air pollution.

Opportunities - benefits. There are multiple benefits of the alternative climate forcing scenario, including improved public health in the United States and especially in the developing world, increased energy independence for the United States, and opportunities for business and technology. Indeed, the alternative scenario leads to economic benefits via improved human health and agricultural productivity. This scenario also has the advantage of putting the United States in a positive leadership role in a strategy that should be welcomed by the developing world, as well as the developed world.

Soft landing for climate change. The moderate increase of climate forcing in the alternative scenario results in a much smaller "planetary energy imbalance" than would be the case with business-as-usual. Thus we will be willing to our children and grandchildren a much lower chance of dramatic climate problems. In this scenario, with CO_2 emissions declining slowly toward 2050, it should be feasible to stabilize atmospheric composition later in the century with advanced energy technologies. In the worst case, if climate change accelerates unacceptably and should we fail to have developed non-fossil energy sources, it should be practical to capture CO_2 at power station and sequester it, as a larger and larger portion of energy generation will occur at central power stations.

Measurable progress. The alternative scenario provides benchmarks against which progress can be demonstrated. In the 1990s, despite extensive global warming rhetoric, United States and global CO_2 emissions increased, as did global air pollution. Fossil fuel use (and thus CO_2 emissions) are well tabulated and measurements of air pollution levels are improving. Thus there will be an open record that will allow comparison of emissions and air pollution levels during the next several years with the trends that occurred in the recent past.

Disclaimer. This specific discussion has not been submitted for Agency review. However, the NASA Administrator, Daniel Goldin, has encouraged me to speak my mind openly on the topic.

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Summary: Climate Forcings

1. Climate is being forced by human actions

2. It takes a long time for forcings to have their full effect

3. Reducing the net forcing is clearly desirable

4. CH_4, black carbon, and tropospheric O_3 are almost as important as CO_2 over the next 50 years

5. Aggressively targeting the non-CO_2 forcings will lead to slower growth in the net forcing than just tackling CO_2 would, while also leading to other benefits, especially for human health

6. CO_2 remains important, especially on longer time scales, and will have to be controlled at some point