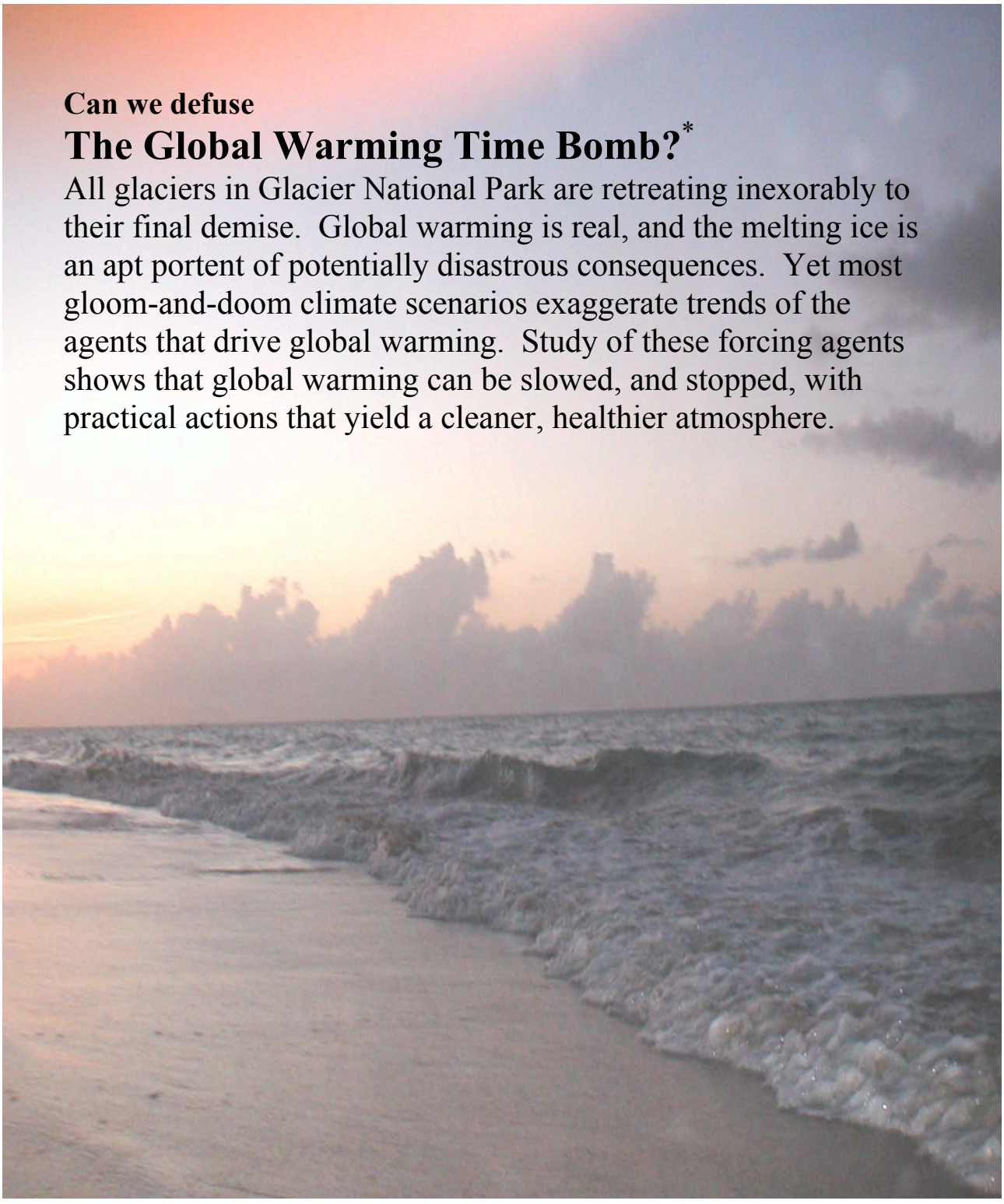

Figure 1. Wind and tides mix the ocean to great depths. Thus, because of the thermal inertia of this ocean water, it requires at least several decades for the ocean temperature to respond fully to a climate forcing.

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* Edited presentation of James Hansen to the Council on Environmental Quality, June 12, 2003.

A paradox in the notion of human-made global warming became strikingly apparent to me one summer afternoon in 1976 on Jones Beach, Long Island. Arriving at midday, my wife, son and I found a spot near the water to avoid the scorching hot sand. As the sun sank in the late afternoon, a brisk wind from the ocean whipped up whitecaps. My son and I had goose bumps as we ran along the foamy shoreline and watched the churning waves.

It was well known by then that human-made "greenhouse gases," especially carbon dioxide (CO_2) and chlorofluorocarbons (CFCs), were accumulating in the atmosphere. These gases are a climate "forcing," because they alter the energy budget of the planet (see Box 1). Like a blanket, they absorb infrared (heat) radiation that would otherwise escape from the Earth's surface and atmosphere to space.

In the summer of 1976, Andy Lacis and I, along with other colleagues at the NASA Goddard Institute for Space Studies, calculated that these human-made gases were heating the Earth's surface at a rate of almost 2 W/m^2. A miniature Christmas tree bulb dissipates about 1 W, mostly in the form of heat. So it was as if humans had placed two of these tiny bulbs over every square meter of the Earth's surface, burning night and day.

The paradox that this result presented was the contrast between the awesome forces of nature and the tiny light bulbs. Surely their feeble heating could not command the wind and waves or smooth our goose bumps. Even their imperceptible heating of the ocean surface must be quickly dissipated to great depths, so it must take many years, perhaps centuries, for the ultimate surface warming to be achieved (Figure 1).

This seeming paradox in the notion of human-made global warming has now been largely resolved through study of the history of the Earth's climate, which reveals that small forces, maintained long enough, can cause large climate change. And, consistent with the historical evidence, the Earth has begun to warm in recent decades, at a rate predicted by climate models that take account of the atmospheric accumulation of human-made greenhouse gases. The warming is having noticeable impacts as glaciers are retreating worldwide, Arctic sea ice has thinned, and spring, defined by the cyclical behavior of organisms, the average temperature and the breakup of winter ice, comes about one week earlier than when I grew up in the 1950s.

Yet many issues remain unresolved. How much will climate change in coming decades? What will be the practical consequences? What, if anything, should we do about it? The debate over these questions is highly charged because of the economic stakes inherent in any attempts to slow the warming.

Objective analysis of global warming requires quantitative knowledge of (1) the sensitivity of the climate system to forcings, (2) the forcings that humans are introducing, and (3) the time required for climate to respond. All of these issues can be studied with global climate models, which are numerical simulations on computers. But our most accurate knowledge about climate sensitivity, at least so far, is based on empirical data from the Earth's history.

The Lessons of History

Over the past few million years the Earth's climate has swung repeatedly between ice ages and warm interglacial periods. Twenty thousand years ago an ice sheet covered Canada, reaching as far south as Seattle, Iowa and New York City. More than a mile thick, the ice sheet, should it return, would tower over and crush to dust the tallest buildings in its path.

A 400,000 year record of temperature is preserved in the Antarctic ice sheet, which, except for coastal fringes, escaped melting even in the warmest interglacial periods. H_2O isotopes (deuterium and ^{18}O) in the annual snow layers reveal the temperature at which the snow formed. This record (Figure 2) suggests that the present interglacial period (the Holocene), now about 12,000 years old, is already long of tooth. Absent humans, the Earth might "soon" (in thousands of years) be headed into its next ice age.The next ice age will never come, however, unless humans desert the planet. As we shall see, the small forces that drove millennial climate changes are now overwhelmed by human forcings. A small fraction of the gases that civilization emits is sufficient to avert global cooling. The problem is now the opposite: human forcings are driving the planet toward a warmer climate. Our best guide for how much the Earth's climate will change is provided by the record of how the Earth responded to past forcings.

The natural millennial climate changes are associated with slow variations of the Earth's orbit induced by gravitational torque by other planets, mainly Jupiter and Saturn (because they are so heavy) and Venus (because it comes so close). These torques cause the Earth's spin axis, now tilted 23 degrees from perpendicular to the plane of the Earth's orbit, to wobble more than one degree (about 40,000 year periodicity), the season at which the Earth is closest to the sun to move slowly through the year (about 20,000 year periodicity), and the Earth's orbit to vary from near circular to elliptical with as much as 7 percent elongation (no regular periodicity, but large changes on 100,000 year and longer time scales).

These perturbations hardly affect the annual mean solar energy striking the Earth, but they alter the geographical and seasonal distribution of insolation as much as 10-20 percent. The insolation changes, over long periods, affect the building and melting of ice sheets. Today, for example, the Earth is nearest the sun in January and farthest away in July. This orbital configuration increases winter atmospheric moisture and snowfall and slows summer melting in the Northern Hemisphere, thus, other things being equal, favoring buildup of glaciers. Insolation and climate changes also affect uptake and release of CO_2 and CH_4 by plants, soil and the ocean, as shown by changes of atmospheric CO_2 and CH_4 that are nearly synchronous with the climate changes (Figure 2).

When the temperature, CO_2 and CH_4 curves are carefully compared, it is found that the temperature changes usually precede the CO_2 and CH_4 changes, on average by 500-1000 years. This indicates that climate change causes CO_2 and CH_4 changes. However, these greenhouse gas changes are a positive feedback that contributes to the large magnitude of the climate swings.

Climatologists are still developing a quantitative understanding of the mechanisms by which the ocean and land release CO_2 and CH_4 as the Earth warms, but the paleoclimate data are already a goldmine of information. The most critical insight that the ice age climate swings provide is an empirical measure of climate sensitivity.

The composition of the ice age atmosphere is known precisely from air bubbles trapped as the Antarctic and Greenland ice sheets and numerous mountain glaciers built up from annual snowfall. The geographical distributions of the ice sheets, vegetation cover, and coastlines during the ice age are well mapped. From these data we know that the change of climate forcing between the ice age and today was about $6^1/_2$ W/m^2 (Figure 3). This forcing maintains a global temperature change of 5°C, implying a climate sensitivity of $^3/_4 \pm {}^1/_4$ °C per W/m^2. Climate models yield a similar climate sensitivity. However, the empirical result is more precise and reliable because it includes all the processes operating in the real world, even those we have not yet been smart enough to include in the models.

The paleo data provide another important insight. Changes of the Earth's orbit are an instigator of climate change, but they operate by altering atmosphere and surface properties and thus the planetary energy balance. These atmosphere and surface properties are now influenced more by humans than by our planet's orbital variations. Greenhouse gases are increasing today and glaciers and ice sheets are melting back. The old maxim, that the Earth is heading toward a new ice age, has been rendered void by the power of modern technology.

Box 1: Climate Forcings, Sensitivity, Response Time and Feedbacks.

A *climate forcing* is an imposed perturbation of the Earth's energy balance. If the sun brightens, that is a positive forcing that warms the Earth. Aerosols (fine particles) blasted by a volcano into the upper atmosphere reflect sunlight to space, causing a negative forcing that cools the Earth's surface. These are natural forcings. Human-made gases and aerosols are also important forcings.

Climate sensitivity is the response to a specified forcing, after climate has time to reach a new equilibrium, including effects of fast feedbacks. A common measure of climate sensitivity is the global warming for doubled atmospheric CO_2. Climate models suggest that doubled CO_2 would cause 3ºC global warming, with an uncertainty of at least 50%. Doubled CO_2 is a forcing of about 4 W/m^2, implying that global climate sensitivity is about $^3/_4$ºC per W/m^2 of forcing.

Climate response time is the time needed to achieve most of the climate response to an imposed forcing, including the effects of fast feedbacks. The response time of the Earth's climate is long, at least several decades, because of the thermal inertia of the ocean and the rapid mixing of waters within the upper few hundred meters of the ocean.

Climate sensitivity and response time depend upon c*limate feedbacks*, which are changes of the planetary energy balance induced by the climate change that can magnify or diminish climate response. Feedbacks do not occur immediately in response to a climate forcing; rather they develop as the climate changes.

Fast feedbacks come into play quickly as temperature changes. For example, the air holds more water vapor as temperature rises, which is a positive feedback magnifying the climate response, because water vapor is a greenhouse gas. Other fast feedbacks include changes of clouds, snow cover, and sea ice. It is uncertain whether the cloud feedback is positive or negative, because clouds can increase or decrease in response to climate change. Snow and ice are positive feedbacks, because as they melt the darker ocean and land absorb more sunlight.

Slow feedbacks, such as ice sheet growth and decay, amplify millennial climate changes. Ice sheet changes can be treated as forcings in evaluating climate sensitivity on decade to century time scales.

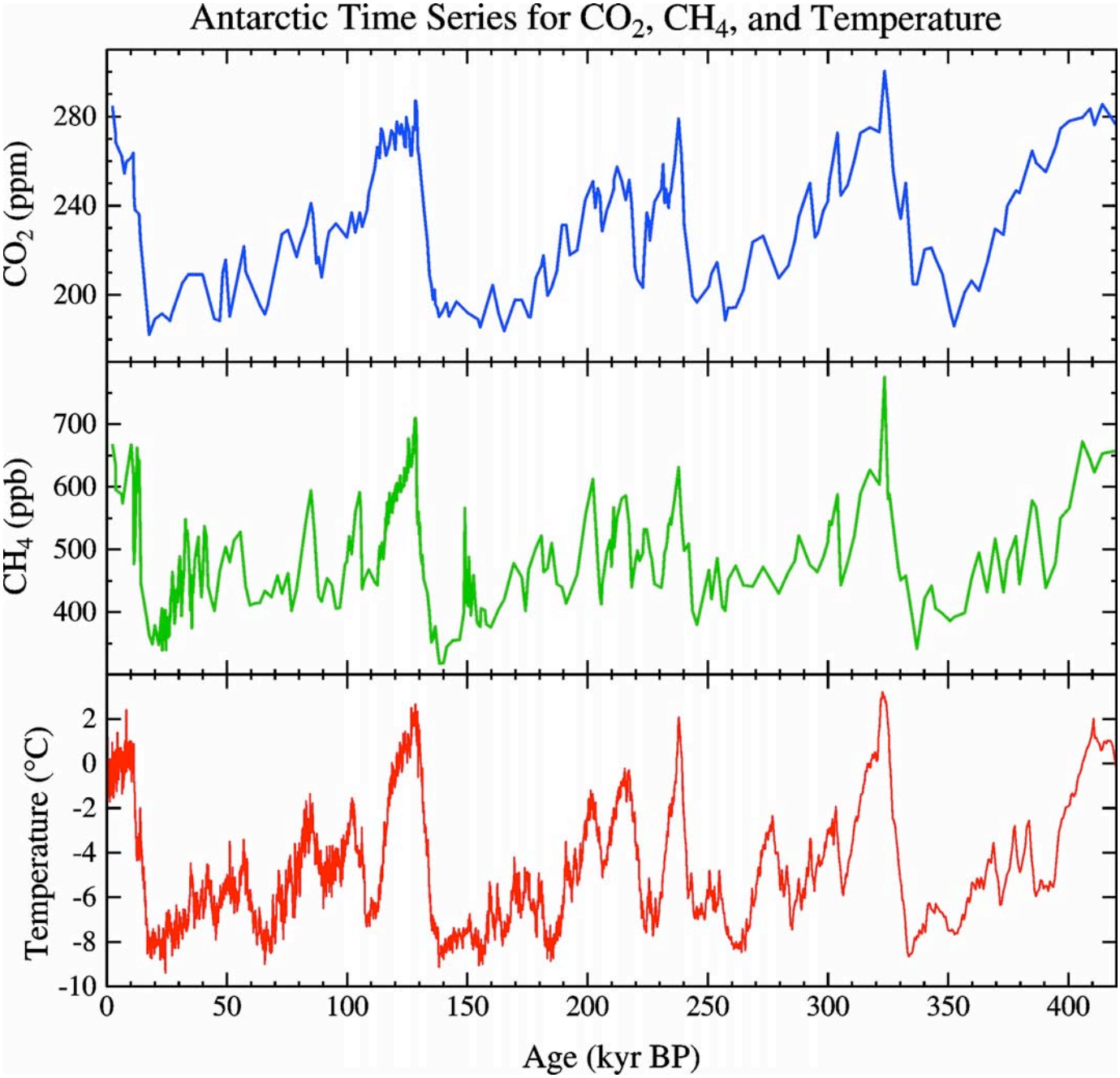

Figure 2. Record of atmospheric temperature, CO_2 and CH_4 extracted from Antarctic ice core by Petit et al. (Nature, **399**, 429, 1999)

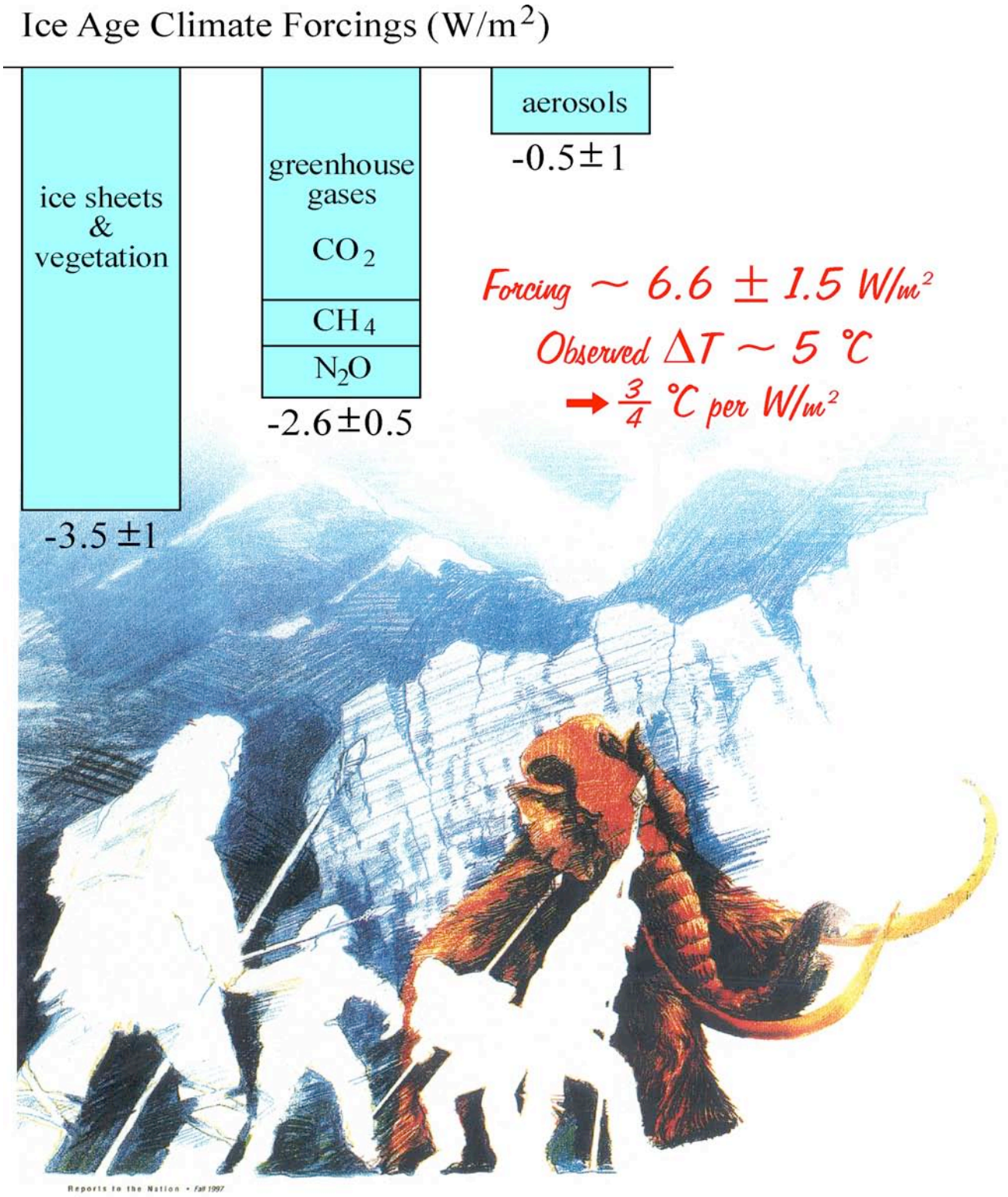

Figure 3. Climate was dramatically different than today during the last ice age, which peaked 20,000 years ago. Global climate forcing was about $6^1/_2$ W/m^2 less than in the current inter-glacial period. This forcing maintained a planet 5°C colder than today. [Drawing from *Reports to the Nation,* Fall, 1997.]

Box 2: But What About…

"Last winter was so cold! I don't notice any global warming!" Global warming is ubiquitous, but its magnitude so far is only about 1°F. Day-to-day weather fluctuations are of order 10°F. Even averaged over a season this natural (year-to-year) variability is about 2°F, so global warming does not make every season warmer than a few decades ago. However, global warming already makes the probability of a warmer than "normal" season about 60%, rather than the 30% that prevailed in 1950-1980 [Plate XV in *Carl Sagan's Universe*, Cambridge Univ. Press, 282 pp., 1997].

"I read that satellites measure global cooling, not warming." That was the story a few years ago, but as the satellite record has lengthened and been studied more carefully it has shifted to warming. The discrepancy with surface measurements is disappearing. The primary issue now is: "how fast is the warming?"

"The surface warming is mainly urban 'heat island' effects near weather stations." Not so. As predicted, the largest warming is found in remote regions such as central Asia and Alaska. The largest areas of surface warming are over the ocean, far from urban locations [see maps at http://www.giss.nasa.gov/data/update/gistemp]. Temperature profiles in the solid earth, at hundreds of boreholes around the world, imply a warming of the continental surfaces between 0.5 and 1°C in the past century.

"The warming of the past century is just a natural 'rebound' from the 'little ice age'." Any rebound from the European little ice age, which peaked in 1650-1750, would have been largely complete by the 20th century. Indeed, the natural long-term climate trend is to a colder climate.

"Isn't human-made global warming saving us from the next ice age?" Yes, but the gases that we have added to the atmosphere are already far more than needed for that purpose.

"Climate variations are mainly due to solar variability." The sun does flicker and the 'little ice age' may have been caused, at least in part, by reduced solar output. Best estimates are that the sun contributed about one quarter of global warming between 1850 and 2000. Climate forcing by greenhouse gases is now larger than that by the sun, and the greenhouse forcing is increasing monotonically while no significant long-term trend is expected for the sun. The sun may contribute to future climate change, but it is no longer the dominant player.

"Global warming will be negligible if the "iris effect", suggested by Richard Lindzen, is valid." This proposed negative climate feedback (in which it is supposed that tropical clouds adjust to allow more heat radiation to escape to space when the Earth gets warmer) has been discredited in specific tests against in situ and satellite data. More generally, any feedbacks that exist in the real world are included in the empirical measures of climate sensitivity provided by the history of the Earth. This history shows that the Earth's climate is sensitive to forcings, with a sensitivity similar to that of climate models.

Climate Forcing Agents Today

The largest change of climate forcings in recent centuries is caused by human-made greenhouse gases. These gases absorb the Earth's infrared (heat) radiation. Because they make the atmosphere more opaque in the infrared region, the Earth's radiation to space emerges from a higher level in the atmosphere where it is colder. The energy radiated to space is thus reduced, causing a temporary planetary energy imbalance, with the Earth absorbing more energy from the sun than it radiates to space. Thus the Earth gradually warms, but it requires about a century to return most of the way to equilibrium, because of the large heat capacity of the oceans. In the meantime, before it achieves equilibrium, more forcings may be added.

The single most important human-made greenhouse gas is CO_2, which comes mainly from burning of fossil fuels (coal, oil and gas). However, the combined effect of the other human-made gases is comparable to that of CO_2. These other gases, especially tropospheric ozone (O_3) and its precursors including methane (CH_4), are ingredients in atmospheric smog that damages human health and agricultural productivity.

Aerosols (fine particles in the air) are, besides greenhouse gases, the other main human-made climate forcing. Aerosols cause a more complex climate forcing than that by greenhouse gases. Some aerosols, such as sulfates arising from sulfur in fossil fuels, are highly reflective (white) and thus reduce solar heating of the Earth. However, black carbon (soot), a product of incomplete combustion of fossil fuels, biofuels and outdoor biomass burning, absorbs sunlight and thus heats the atmosphere.

This aerosol direct climate forcing is uncertain by at least 50%, in part because aerosol amounts are not well measured. In addition, the black carbon effect is complex. In regions of heavy soot, such as India and China, sunlight at the surface is reduced, causing a local surface cooling. However, the heating of the air at higher levels results in surface warming on global average, through its influence on atmospheric stability and cloud cover. These effects must be computed with global climate models, and their magnitude differs from one model to another.

Aerosols also cause an indirect climate forcing by altering the properties of cloud drops. Human-made aerosols increase the number of condensation nuclei for cloud drops, thus causing the average size of the cloud drops to be smaller. The larger number of smaller drops makes the clouds slightly brighter. Smaller drops also make it more difficult for the clouds to produce rain, thus increasing average cloud lifetime. Brighter long-lived clouds reduce the amount of sunlight absorbed by the Earth, so the indirect effect of aerosols is a negative forcing that causes cooling.

Other human-made climate forcings include replacement of forests by cropland. Forests are dark even with snow on the ground, so their removal reduces solar heating.

Natural forcings, such as volcanic eruptions and fluctuations of the sun's brightness, probably have little trend on a time scale of 1000 years. However, evidence of a small solar brightening over the past 150 years implies a climate forcing of a few tenths of 1 W/m^2.

The net value of the forcings added since 1850 is 1.6 ± 1.0 W/m^2. Despite the large uncertainties, there is evidence that this estimated net forcing is approximately correct. One piece of evidence is the close agreement of observed global temperature during the past several decades with climate models driven by these forcings. More fundamentally, the observed heat gain by the world ocean in the past 50 years is consistent with the estimated net climate forcing, as discussed below.

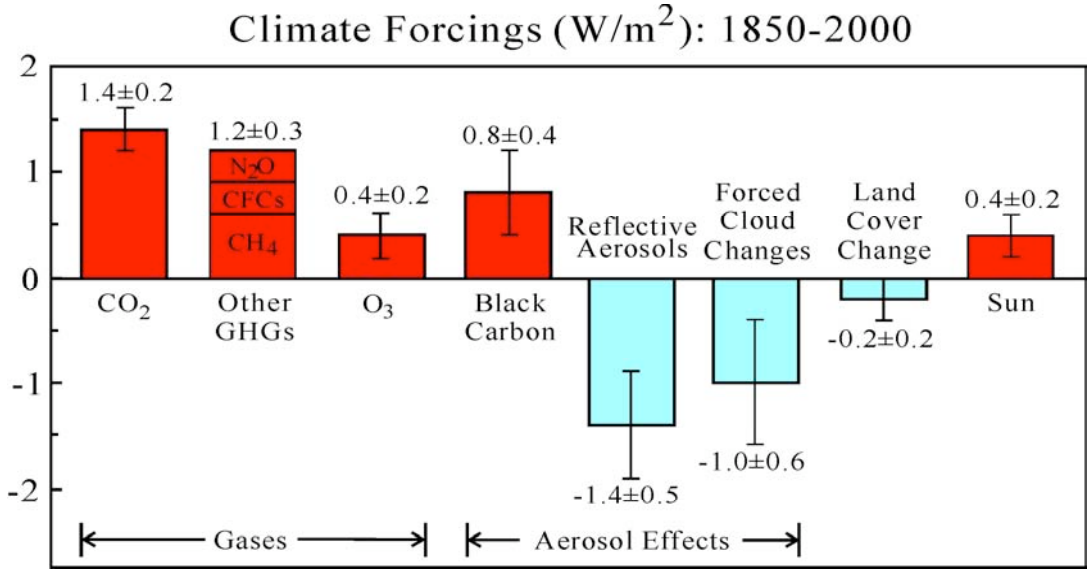

Figure 4. Climate forcing agents in the industrial era. Error bars are partly subjective 1 (standard deviation) uncertainties.

- Increases of well-mixed greenhouse gases (excludes O_3) are known accurately from in situ observations and bubbles of air trapped in ice sheets. For example, the increase of CO_2 from 285 parts per million (ppm) in 1850 to 368 ppm in 2000 is accurate to about 5 ppm. The conversion of this gas change to a climate forcing (1.4 W/m^2), from calculation of the infrared opacity, adds about 10% to the uncertainty.
- The CH_4 increase since 1850, including its effect on stratospheric H_2O and tropospheric O_3, causes a climate forcing half as large as that by CO_2. Principal anthropogenic sources of CH_4 are landfills, coal mining, leaky natural gas lines, increasing ruminant population, rice cultivation, and anaerobic waste management lagoons. In the last decade the growth rate of CH_4 has slowed, suggesting that the growth of sources is slowing.
- Tropospheric O_3 is increasing partly because CH_4 is increasing, but the primary cause is other human-made emissions, especially carbon monoxide, nitrogen oxides, and volatile organic compounds. Air quality regulations in the U.S. and Europe reduced O_3 precursor emissions in recent years, but not quite enough to balance increased emissions in the developing world.
- Black carbon ("soot"), a product of incomplete combustion, can be seen in the exhaust of diesel-fueled trucks and buses. It is also produced by biofuels and outdoor biomass burning. Black carbon aerosols per se are not well measured, but their climate forcing is estimated from wide-spread multi-spectral measurements of total aerosol absorption. The estimated forcing includes the effect of soot in reducing the reflectance of snow and ice.
- The reflective human-made aerosols are mainly sulfates, nitrates, organic carbon, and soil dust. Sources include fossil fuel burning and agricultural activities. Sources of the abundant sulfates are known reasonably well, but the 1 uncertainty in the net forcing by reflective aerosols is at least 35%.
- The indirect effects of aerosols on cloud properties are difficult to compute accurately, but recent satellite measurements of the correlation of aerosol and cloud properties are consistent with the estimated net forcing of –1 W/m^2. The uncertainty is at least 50%.
- Land cover effects are estimated in a global climate model by replacing crops with natural vegetation. The primary effect is in snowy regions, where snow-covered fields are brighter than forests.
- Long-term measurements of sunspots and faculae on the sun, and their empirical relationship with solar brightness during the satellite era, suggest a small solar brightening over the past 150 years. The estimated climate forcing, including associated ozone change, is a few tenths of 1 W/m^2.

Global Warming

Global average surface temperature has increased about $^{3}/_{4}$°C (1.35°F) during the period of extensive instrumental measurements, i.e., since the late 1800s. Most of the warming, about $^{1}/_{2}$°C (0.9°F), occurred after 1950. The causes of observed warming can be investigated best for the past 50 years, because most climate forcings were observed then, especially since satellite measurements of the sun, stratospheric aerosols and ozone began in the 1970s. Furthermore, 70% of the anthropogenic increase of greenhouse gases occurred after 1950.

Changes of known climate forcings since 1950 are shown in Figure 5. Largest forcings are the positive forcing by greenhouse gases and negative forcing by aerosols. Stratospheric aerosols, which are sulfates from occasional volcanic eruptions, are well-measured. However, human-made aerosols, which have multiple sources and compositions, are poorly measured.

These forcings have been used to drive climate simulations for 1951-1998 with the NASA Goddard Institute for Space Studies SI2000 climate model [Reference 1b]. This model has sensitivity $^{3}/_{4}$°C per W/m^2, consistent with paleoclimate data and typical of other climate models. The largest suspected flaws in the simulations are omission of poorly understood aerosol effects on cloud drops and probable underestimate of black carbon changes. The first of these is a negative forcing and the second is positive, so these flaws should be partially compensating in their effect on global temperature.

Simulated climate changes are compared with observations in Figure 6. The five model runs differ only because of unforced ("chaotic" or "weather") variability, which is an inherent characteristic of complex coupled dynamical systems. The stratosphere in the model cools, mainly due to ozone depletion, but it warms after volcanoes as the aerosols absorb thermal radiation. The troposphere and surface warm due to increasing greenhouse gases, with brief cooling intervals caused by large volcanoes. These changes are in accord with observations, as illustrated. However, it would be a mistake to take this agreement as quantitative confirmation of the principal model parameters and assumptions. A larger (smaller) value for the net climate forcing could yield comparable agreement with the observations, if it were combined with a smaller (larger) value of climate sensitivity. Also, unforced (chaotic) variability in this specific version of the GISS model is probably less than unforced variability of real world climate.

The most important quantity is the planetary energy imbalance (Figure 6d). This imbalance is a consequence of the long time that it takes the ocean to warm. We conclude that the Earth is now out of balance by something between 0.5 and 1 W/m^2, i.e. there is that much more solar radiation being absorbed by Earth than heat being emitted to space. One implication of this imbalance is that, even if atmospheric composition does not change further, the Earth's surface will eventually warm another 0.4-0.7°C.

The Earth's energy imbalance is a vital statistic, because it is the residual climate forcing that the planet has not yet responded to. It is too small to be measured directly, but we can verify its value because the only place that the energy can be going is into melting ice or heating the air, land and ocean. It is worth examining simple calculations of these energy sinks, because, as we show in the next section, this provides insight about prospects for future global changes.

As summarized in Box 4, most of the energy imbalance has been heat going into the ocean. Sydney Levitus has analyzed ocean temperature changes of the past 50 years, finding that the world ocean heat content increased about 10 W years/m^2 in the past 50 years, consistent with the time integral of the planetary energy imbalance. Levitus also finds that the rate of ocean heat storage in recent years is consistent with our estimate that the Earth is now out of energy balance by 0.5-1 W/m^2. Note that the amount of heat required to melt enough ice to raise sea level one

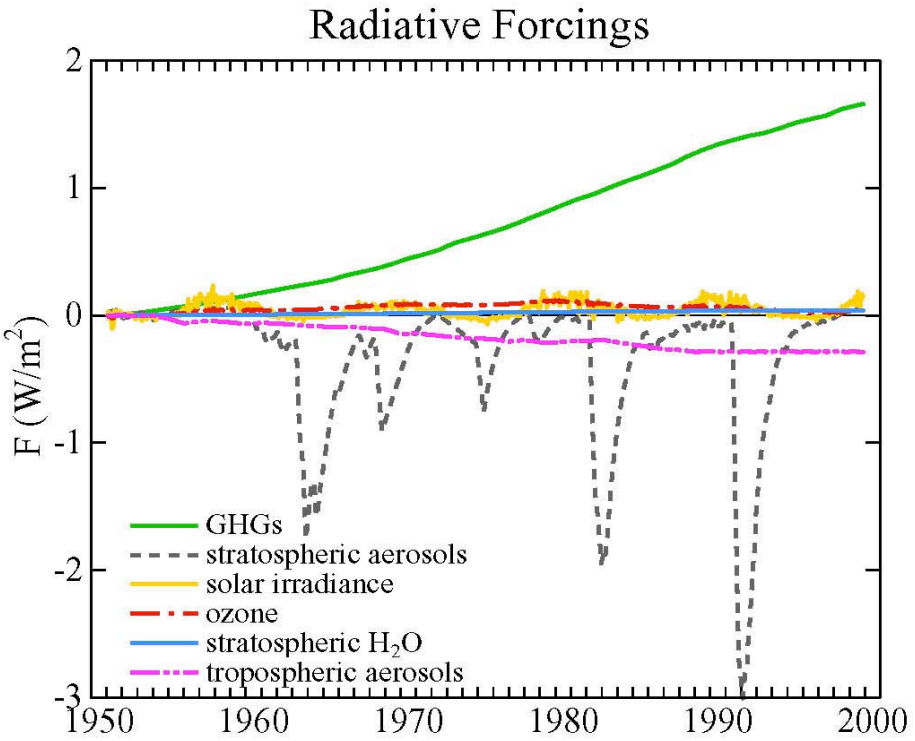

Figure 5. Climate forcing in the past 50 years due to six mechanisms (GHGs = long-lived greenhouse gases). The tropospheric aerosol forcing is very uncertain [Reference 1b].

Box 4: Planetary Heat Storage: Ice, Air, Land and Ocean.

Estimates of the energy used to melt ice and warm the air, land and ocean in the past 50 years.[1]

Ice melting: assume that the 10 cm sea level rise between 1950 and 2000 was from melting ice (thermal expansion of warming ocean water contributes about half the rise, but this error is partly balanced by melting sea ice and ice shelves, which do not raise sea level). If the melted ice started at –10°C and ended at the mean ocean surface temperature, +15°C, the energy used is 125 cal/g (100 cal/g for melting). The heat storage is thus $10 g/cm^2 \times 125 cal/g \times 4.19$ joules/cal × area Earth × 0.71 ~1.9×10^{22} joules ~ **1.2 watt-years**.

Air warming: 0.5°C warming, atmospheric mass ~ 10 m of water, heat capacity air ~ 0.24 cal/g/°C, yields heat storage in the air: $0.5°C \times 1000 g/cm^2 \times 0.24$ cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26×10^{22} joules ~ **0.16 watt-years.**

Land warming: The mean depth of penetration of a thermal wave into the Earth's crust in 50 years, weighted by ΔT, is about 20 m. With a density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage of Earth, the land heat storage is 2×10^3 cm × 3 g/cm^3 × 0.2 cal/g/°C × 0.5°C × 4.19 joules/cal × area Earth × 0.29 ~ 0.37×10^{22} joules ~ **0.23 watt-years**.

Ocean warming: Levitus finds a mean ocean warming of 0.035°C in the upper 3 km of the ocean. The heat storage is thus: $0.035°C \times 3 \times 10^5 g/cm^2$ × 1 cal/g × 4.19 joules/cal × area Earth × 0.71 ~ 16×10^{22} joules ~ **10 watt-years**.

[1]Note that 1 watt-sec = 1 joule, # sec/year ~ $\pi \times 10^7$, area Earth ~ 5.1×10^{18} cm^2, 1 watt-yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.71, 1 calorie ~ 4.19 joules.

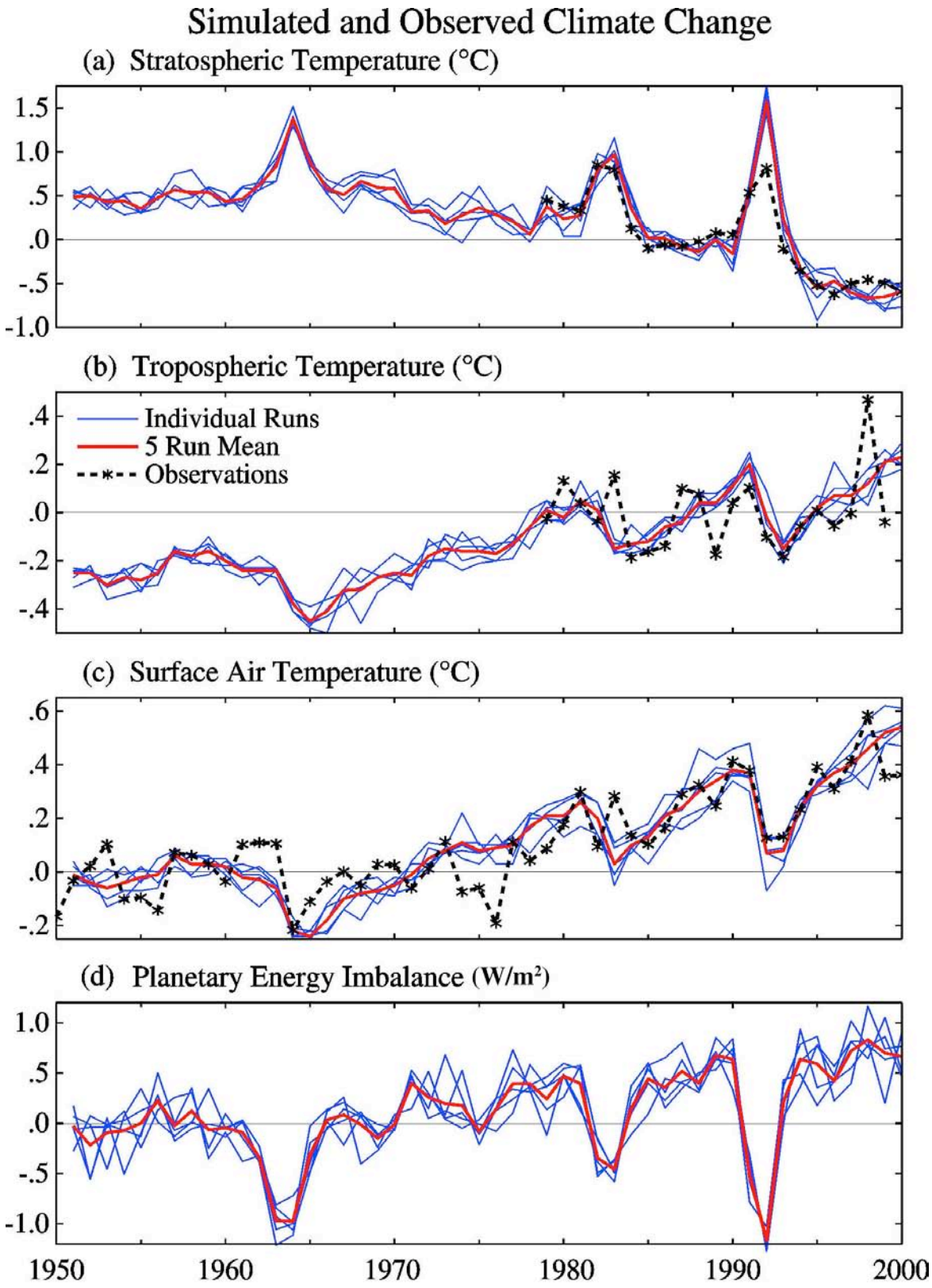

Figure 6. Simulated and observerd global temperature change for 1951-2000 and simulated planetary energy imbalance [Reference 1b].

meter is about 12 watt-years (averaged over the planet), energy that could be accumulated in 12 years if the planet is out of balance by 1 W/m^2.

The agreement with observations, for both the modeled temperature change and ocean heat storage, leaves no doubt that observed global climate change is being driven by (natural and anthropogenic) forcings. The current rate of ocean heat storage is a critical planetary metric, because it determines the amount of additional global warming that is already "in the pipeline". It is important for a second, related, reason: it equals the reduction in climate forcings that we would need to make if we wished to stabilize the Earth's present climate.

The Time Bomb

The goal of the United Nations Framework Convention on Climate Change, produced in Rio de Janeiro in 1992, is to stabilize atmospheric composition to "prevent dangerous anthropogenic interference with the climate system" and achieve that in ways that do not disrupt the global economy. The United States was the first developed country to sign the convention, which has since been ratified by practically all countries. Defining the level of warming that constitutes "dangerous anthropogenic interference" (DAI) is thus a crucial but difficult part of the global warming problem.

The United Nations established an Intergovernmental Panel on Climate Change (IPCC) with responsibility for analysis of global warming. IPCC has defined climate forcing scenarios, used these for simulations of 21st century climate, and estimated the impact of temperature and precipitation changes on agriculture, natural ecosystems, wildlife and other matters [Reference 12a]. Significant effects are found, but even with warming of several degrees there are winners and losers. IPCC estimates sea level change as large as several tens of centimeters in 100 years, if global warming reaches several degrees Celsius. Their calculated sea level change is due mainly to thermal expansion of ocean water, with little change in ice sheet volume.

These moderate climate effects, even with rapidly increasing greenhouse gases, leave the impression that we are not close to DAI. The IPCC analysis also abets the emphasis on adaptation to climate change, as opposed to mitigation, in recent international discussions. Adaptation is required, to be sure, because climate change is already underway. However, I will argue that we are much closer to DAI than is generally realized, and thus the emphasis should be on mitigation.

The dominant issue in global warming, in my opinion, is sea level change and the question of how fast ice sheets can disintegrate. A large portion of the world's people live within a few meters of sea level, with trillions of dollars of infrastructure. The need to preserve global coast lines, I suggest, sets a low ceiling on the level of global warming that would constitute DAI.

The history of the Earth, and the present human-made planetary energy imbalance, together paint a disturbing picture about prospects for sea level change. To appreciate this situation we must consider how today's global temperature compares with peak temperatures in the current and previous interglacial periods, how long-term sea level change relates to global temperature, and the time required for ice sheets to respond to climate change.

Warmth in the Holocene peaked between 6000 and 10,000 years ago, but subsequent cooling was slight. As shown by the Antarctic temperature record (Figure 2), the polar temperature during the Holocene peak was about 1°C warmer than it was in the mid 20th century. During the previous (Eemian) interglacial period polar temperatures were perhaps another 2°C warmer. However, both paleoclimate data and climate models show that polar temperature change is about a factor of two larger than global mean temperature change. [The ice core temperature anomalies at the pole refer to the inversion level, where the snow is formed; surface air anomalies are slightly larger (Reference 2d).]

This means that, with the 0.5°C global warming of the past few decades, *the Earth's average temperature is just now passing through the peak Holocene temperature level*. Furthermore, the current planetary energy imbalance of about $^3/_4$ W/m^2 implies that global warming already "in the pipeline", about another 0.5°C, will take us about halfway to the global temperature that existed at the peak of the Eemian period.

Sea level during the Eemian is estimated to have been 5-6 meters (16-20 feet) higher than it is today. Although the geographical distribution of climate change influences the effect of global warming on ice sheets, paleoclimate history suggests that global temperature is a good predictor of eventual sea level change. The main issue is: how fast will ice sheets respond to global warming?

IPCC calculates only a slight change in the ice sheets in 100 years. However, the IPCC calculations include only the gradual effects of changes in snowfall, sublimation and melting. In the real world, ice sheet disintegration is driven by highly nonlinear processes and feedbacks. The peak rate of deglaciation following the last ice age was a sustained rate of melting of more than 14,000 km^3/year, about one meter of sea level rise every 20 years, which was maintained for several centuries. This period of most rapid melt, meltwater pulse 1A, coincided, as well as can be measured, with the time of most rapid warming (Reference 2d).

Given the present unusual global warming rate on an already warm planet, we can anticipate that areas with summer melt and rain will expand over larger areas of Greenland (Figure 7) and fringes of Antarctica. This will darken the ice surface in the season when the sun is high, promote freeze-thaw ice breakup, and, via ice crevasses, provide lubrication for ice sheet movement. Rising sea level itself tends to lift marine ice shelves that buttress land ice, unhinging them from anchor points. As ice shelves break up, this accelerates movement of land ice to the ocean.

This qualitative picture of nonlinear processes and feedbacks is supported by the asymmetric nature of glacial cycles (Figure 3) and the high rate of sea level rise associated with rapid warming. Although building of glaciers is slow, limited by annual snowfall rates, once an ice sheet begins to collapse its demise can be spectacularly rapid.

This natural melting process will be accelerated by the human-induced planetary energy imbalance. This imbalance provides an ample supply of energy for melting ice (Box 4), which can be delivered to the ice via ocean currents, atmospheric winds, and rainfall, as well as by icebergs drifting to lower latitudes. Furthermore, this energy source is supplemented by increased absorption of sunlight by ice sheets darkened by black carbon aerosols, as discussed below, and the positive feedback process as melt-water darkens the ice surface.

These considerations do not mean that we should expect large sea level change in the next few years. Preconditioning of ice sheets for accelerated break-up may require a long time, perhaps many centuries. However, I suspect that significant sea level rise could begin within decades, if the planetary energy imbalance continues to increase. Whatever that preconditioning period is, it seems clear that global warming beyond some limit will create a legacy of large sea level change for future generations. And once large-scale ice sheet breakup is underway, it will be impractical to stop. The same inertia of the ice sheets, which discourages rapid change, is a threat for the future. It will not be possible to build walls around Greenland and Antarctica. Dykes may protect limited regions, such as Manhattan and the Netherlands, but most of the global coastlines will be inundated.

I argue that the level of DAI is likely to be set by the global temperature and planetary radiation imbalance at which substantial deglaciation becomes practically impossible to avoid. Based on the paleoclimate evidence discussed above, I suggest that the highest prudent level of additional global warming is not more than about 1°C. In turn, given the existing planetary energy imbalance, this means that additional climate forcing should not exceed about 1 W/m^2.

Figure 7. Surface melt on the Greenland ice sheet descending into a moulin. The moulin is a nearly vertical shaft, worn in the glacier by the surface water, that carries the water to the base of the ice sheet. [Photo courtesy of Roger Braithwaite and Jay Zwally.]

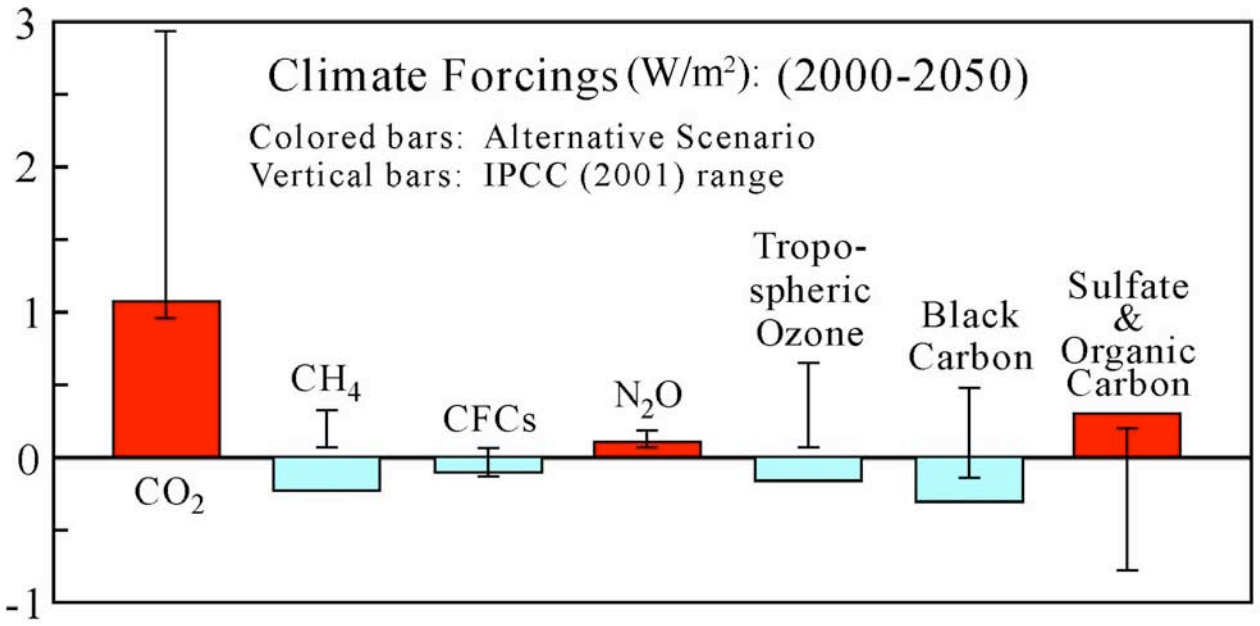

Figure 8. Climate forcing scenario for 2000-2050 that yields a forcing of 0.85 W/m^2 (colored bars) [Reference 1a].

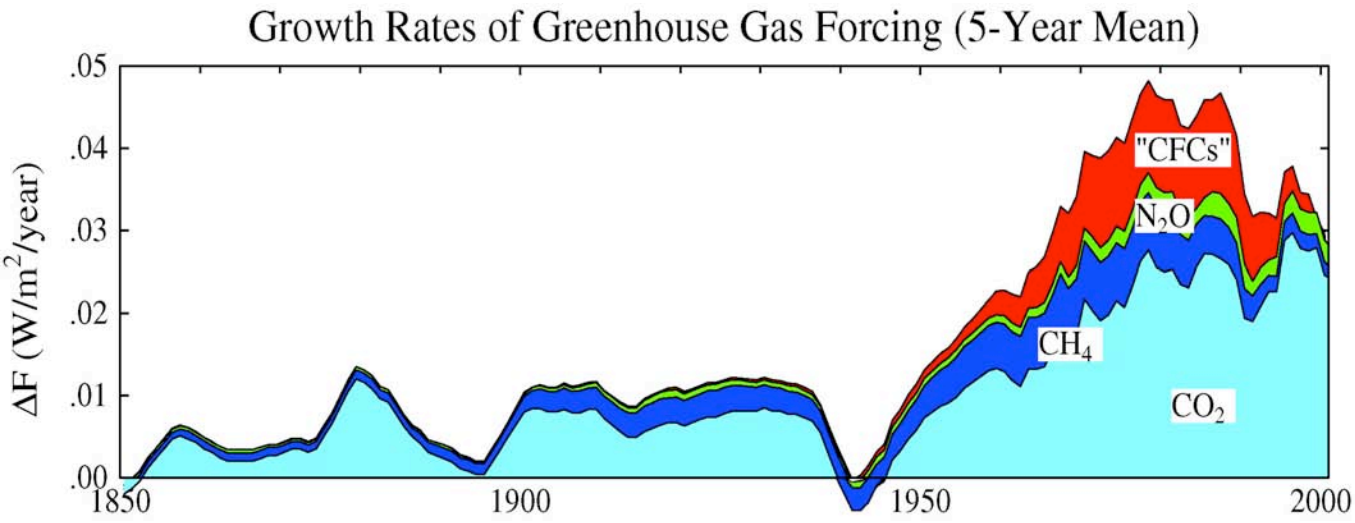

Figure 9. Growth rate of climate forcing by well-mixed greenhouse gases (5-year mean), O_3 and stratospheric H_2O, which were not well measured, are not included [Reference 1a].

Detection of early signs of accelerating ice sheet breakup, and analysis of the processes involved, may be provided by the satellite IceSat recently launched by NASA. IceSat will use lidar and radar to precisely monitor ice sheet topography and dynamics. We may soon be able to investigate whether or not the ice sheet time bomb is approaching detonation.

Climate Forcing Scenarios

The IPCC defines many climate forcing scenarios for the 21st century based on multifarious "story lines" for population growth, economic development, and energy sources. The scenarios lead to a wide range for added climate forcings in the next 50 years (vertical bars in Figure 8).

The IPCC added climate forcing in the next 50 years is 1-3 W/m^2 for CO_2 and 2-4 W/m^2 with other gases and aerosols included. Even their minimum added forcing, 2 W/m^2, would cause DAI with the climate system, based on our criterion. Further, IPCC studies suggest that the Kyoto Protocol, designed to reduce greenhouse gas emissions from developed countries, would reduce global warming by only several percent. Gloom and doom seem unavoidable.

However, are the IPCC scenarios necessary or even plausible? There are reasons to believe that the IPCC scenarios are unduly pessimistic. First, they ignore changes in emissions, some already underway, due to concerns about global warming. Second, they assume that true air pollution will continue to get worse, with O_3, CH_4 and BC all greater in 2050 than in 2000. Third, they give short shrift to technology advances that can reduce emissions in the next 50 years.

An alternative way to define scenarios is to examine current trends of climate forcing agents, to ask why they are changing as observed, and to try to understand whether there are reasonable actions that could encourage further changes in the growth rates. Precise data are available for trends of the long-lived greenhouse gases (GHGs) that are well-mixed in the atmosphere, i.e., CO_2, CH_4, N_2O and CFCs (chlorofluorocarbons).

The growth rate of the GHG climate forcing peaked in the early 1980s at a rate of almost 0.5 W/m^2 per decade, but declined by the 1990s to about 0.3 W/m^2 per decade (Figure 9). The primary reason for the decline was reduced emissions of CFCs, whose production was phased out because of the destructive effect of CFCs on stratospheric ozone.

The two most important GHGs, with CFCs on the decline, are CO_2 and CH_4. The growth rate of CO_2, after surging between the end of World War II and the mid-1970s, has since almost flattened out to an average growth rate of about 1.6 ppm per year (Figure 10a). The CH_4 growth rate has declined dramatically in the past 20 years, by at least two-thirds (Figure 10b).

These growth rates are related to the rate of global fossil fuel use (Figure 11). Fossil fuel emissions increased by more than 4%/year from the end of World War II until 1975, but subsequently by only about 1%/year. The change in fossil fuel growth rate occurred after the oil embargo and price increases of the 1970s, with subsequent emphasis on energy efficiency. CH_4 growth has also been affected by other factors including changes in rice farming and increased efforts to capture CH_4 at landfills and in mining operations.

If recent growth rates of these GHGs continued, the added climate forcing in the next 50 years would be about 1.5 W/m^2. To this must be added the (positive or negative) change due to other forcings such as O_3 and aerosols. These forcings are not well-monitored globally, but it is known that they are increasing in some countries while decreasing in others. Their net effect should be small, but it could add as much as 0.5 W/m^2. Thus, if there is no slowing of emission rates, the human-made climate forcing could increase by 2 W/m^2 in the next 50 years.

This "current trends" growth rate of climate forcings, 2 W/m^2 in 50 years, is at the low

end of the IPCC range of 2-4 W/m^2. The IPCC 4 W/m^2 scenario requires 4%/year exponential growth of CO_2 emissions maintained for 50 years and large growth of air pollution. The 4 W/m^2 scenario yields dramatic climate change for the media to fixate upon, but it is implausible.

Although the "current trends" scenario of 2 W/m^2 in 50 years is at the low end of the IPCC range, it is larger than the 1 W/m^2 level that we suggested as our current best estimate for the level of DAI. This raises the question of whether there is a feasible scenario with still lower climate forcing.

A Brighter Future

I have discussed elsewhere [Reference 6] a specific "alternative scenario" that keeps added climate forcing in the next 50 years at about 1 W/m^2. Expected global warming by 2050 is between $^1/_2$°C and $^3/_4$°C, i.e., a warming of about 1°F [References 1b, 1c].

This alternative scenario has two components: (1) halt or reverse growth of air pollutants, specifically soot, O_3, and CH_4, (2) keep average fossil fuel CO_2 emissions in the next 50 years about the same as today. The CO_2 and non-CO_2 portions of the scenario are equally important. I argue that they are both feasible and make sense for other reasons, in addition to climate.

Air pollution. Is it realistic to stop the growth of air pollution, or even achieve some reduction? A million people die every year from air pollution, with large economic cost. Actions to improve air quality have been initiated already in the United States and Europe, and still stricter standards are likely. In developing countries, such as India and China, air pollution is already about as bad as can be tolerated. Discussions among scientists from developed and developing countries [Reference 3] suggest that cleaner air is practical, and achievement could be speeded if there were concerted efforts to develop and share cleaner technologies.

Emphasis should be placed, in addressing air pollution, on the constituents that contribute most to global warming. Methane, a precursor of O_3, offers a great opportunity to halt the growth of a substance that has been expected to contribute much to future global warming. If human sources of CH_4 are reduced, it may even be possible to get the atmospheric CH_4 amount to decline, thus providing a cooling that would partially offset the CO_2 increase. Reductions of black carbon (BC) aerosols would help counter the warming effect of reductions in sulfate aerosols. O_3 precursors, besides CH_4, especially nitrogen oxides and volatile organic compounds, must be reduced to decrease low-level O_3, the prime component of smog, which damages the human respiratory system and agricultural productivity.

Actions needed to reduce CH_4, such as methane capture at landfills, waste management facilities, and fossil fuel mining, have economic benefits that partially offset the costs. Prime sources of BC are diesel fuels and biofuels. These sources need to be dealt with for health reasons. The tiny BC aerosols spewed out in the burning of these fuels are microscopic sponges that soak up toxic organic carbon emitted in the same burning process. When these minuscule soot particles are breathed into the lungs they penetrate human tissue deeply. Some enter the bloodstream and are suspected of being the primary carcinogen in air pollution. Diesel could be burned more cleanly with improved technologies. However, there may be even better solutions, such as hydrogen fuel, which would eliminate ozone precursors as well as soot.

Carbon dioxide. CO_2 will be the dominant anthropogenic climate forcing in the future. Is the CO_2 portion of the alternative scenario feasible? It would require a near-term leveling off of fossil fuel CO_2 emissions and a decline of CO_2 emissions before mid-century, heading toward stabilization of atmospheric CO_2 by the end of the century. Near-term leveling of emissions

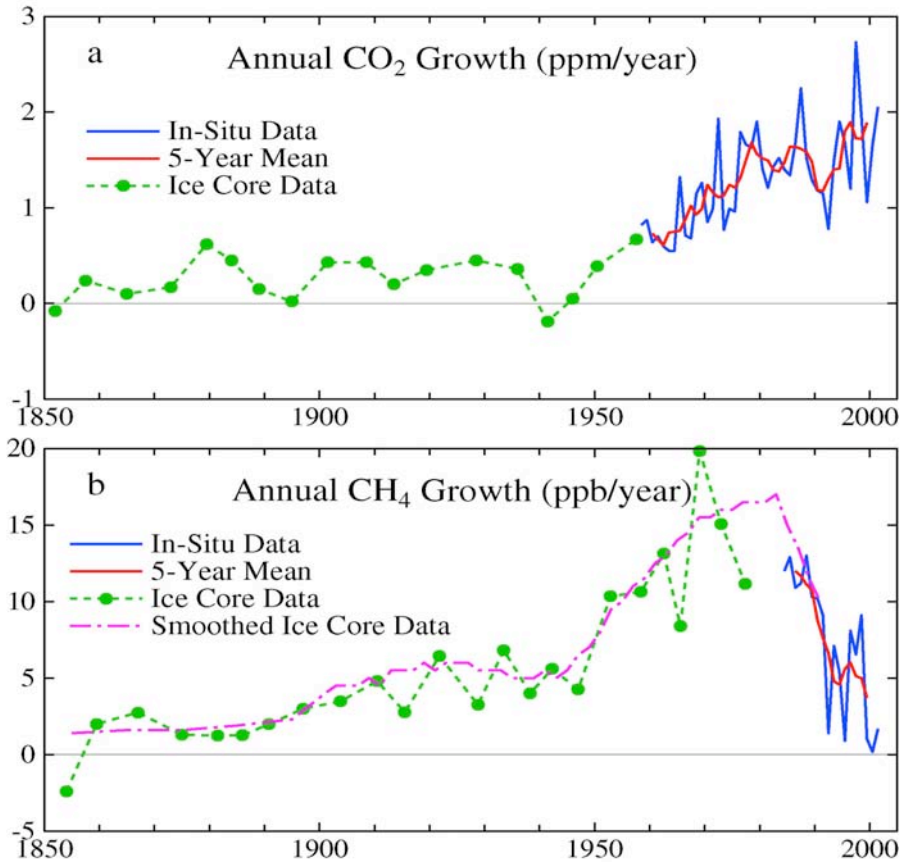

Figure 10. Growth rates of atmospheric CO_2 and CH_4 [Reference 1a; data update by Ed Dlugokencky and Tom Conway, NOAA Climate Monitoring and Diagnostics Laboratory].

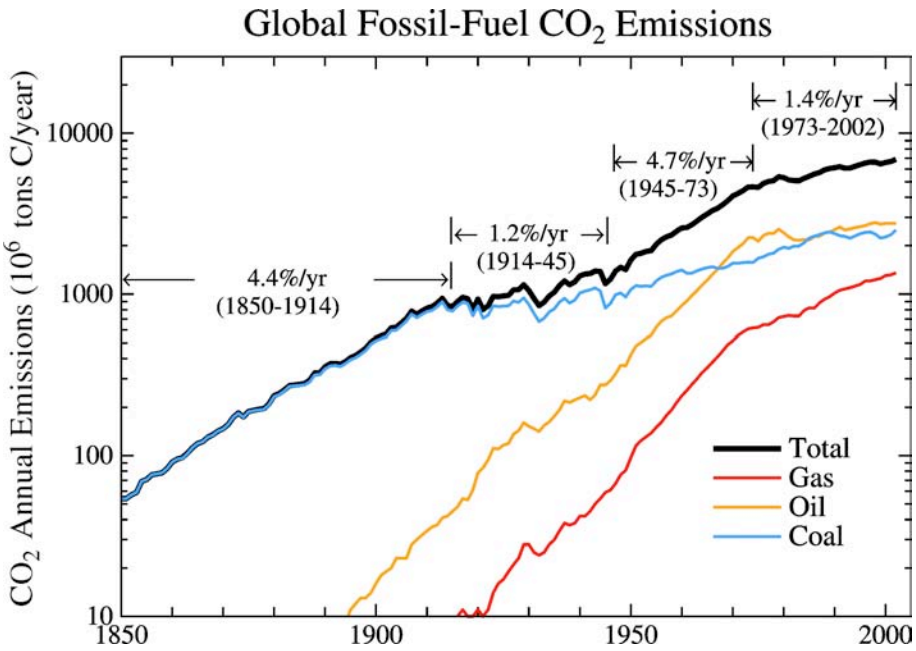

Figure 11. Global fossil fuel CO_2 emissions based on data of Marland and Boden [References 1a and 11]; 2001-2002 update based on Reference 11b.

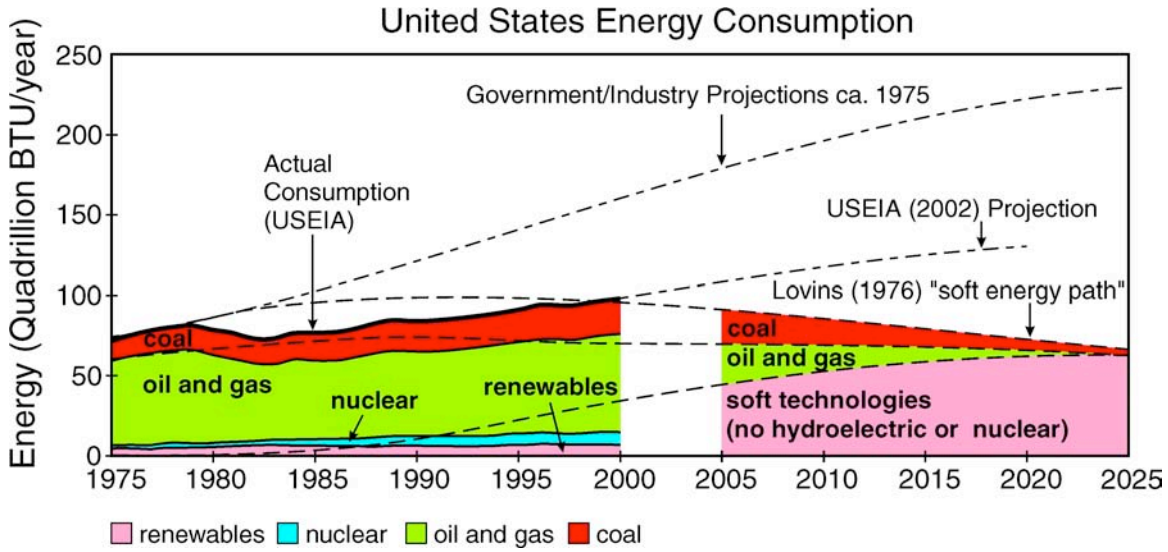

Figure 12. Projections of U.S. energy use made in the early 1970s compared with actual use. The growth of "soft" energy technologies (renewable energies, excluding large hydroelectric dams) advocated by Lovins has not occurred to a noticeable extent, but his projection of total energy use was quite accurate.

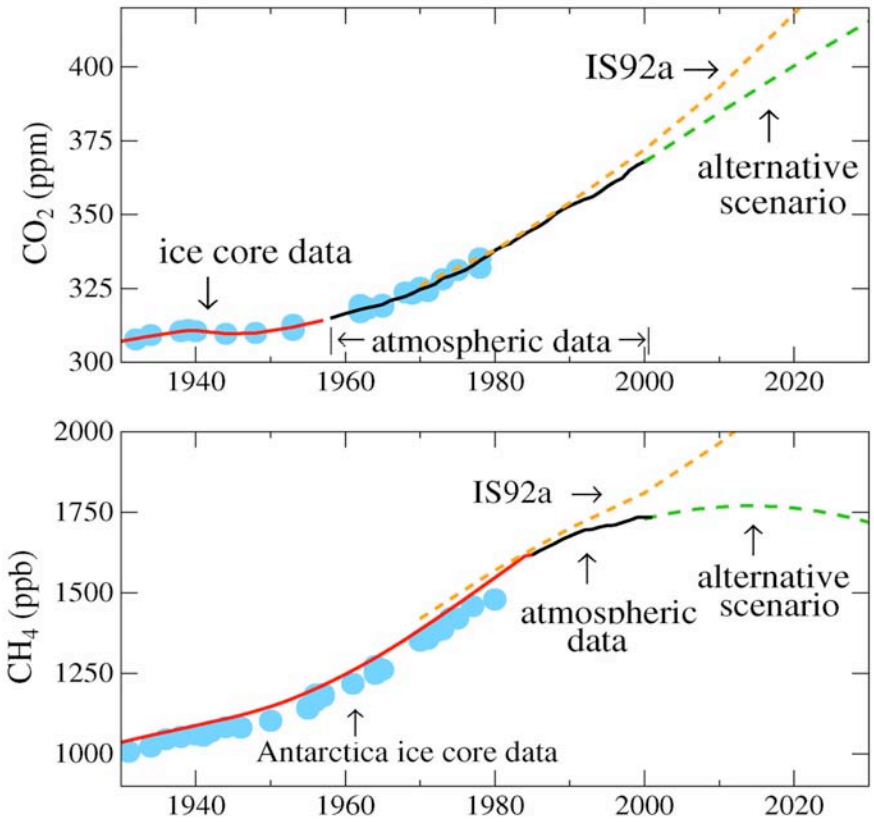

Figure 13. Observed CO_2 and CH_4 amounts, compared with the typical IPCC scenario and the "alternative scenario". The alternative scenario falls below all IPCC scenarios for both CH_4 and CO_2 (see Appendix). In situ observations are available from the NOAA Climate Monitoring and Diagnostics laboratory. CH_4 in Antarctica is less than global mean CH_4 because the CH_4 sources are primarily in the Northern Hemisphere [update of Reference 6a].

might be accomplished via improved energy efficiency and increased use of renewable energies, but a long-term decline of emissions will require development of energy technologies that produce little or no CO_2 or that capture and sequester CO_2.

The plausibility of flattening near-term CO_2 emissions is suggested by the history of emissions (Figure 11). The reduction from 4% annual growth to 1% was accomplished mainly via improved energy efficiency and without a concerted global scale effort. Current technologies provide great potential for more efficiency improvements (Reference 5). The growth rate of reported global fossil fuel CO_2 emissions in the 1990s was slightly less than 1%/year, despite robust economic growth in the United States, China, and the world as a whole (see Appendix). Concerted efforts at efficiencies and renewable energies have the potential to squeeze out an additional 1% in the near-term.

Long-term reduction of CO_2 emissions is a greater challenge, as energy use will continue to rise. Progress is needed across the board: continued efficiency improvements, more renewable energy, and new technologies. Next generation nuclear power, if acceptable to the public, could be an important contributor. There may be new technologies before 2050 that we have not imagined. A fallback, should greater fossil fuel use be necessary, is capture and sequestration of CO_2.

The impact of continual energy efficiency improvements must be recognized. Some analysts project a quadrupling of world energy needs by 2050 to 50 Terawatts (power use today is 10 Terawatts of fossil fuel energy and 2 Terawatts from other sources). These same persons have been projecting such energy growth rates for years without comparing their prior predictions with data.

As an informative example, we compare in Figure 12 projections of United States energy use made in the early 1970s with actual energy use. The data show that energy use increased about 1% per year over the past three decades, far below most projections. Only in the past few years has energy use crept above the level that Amory Lovins, an advocate of energy efficiencies, had projected, and then only because the trend toward improving mileage of passenger vehicles was reversed in the past decade. Note that a moderate 1% per year growth in energy use was achieved in a period when the real cost of (fossil fuel) energy was declining. The flat energy usage from the 1970s to the 1980s was aided by energy price increases in the 1970s.

The growth of "soft" energy technologies (renewable energies, excluding large hydroelectric dams) advocated by Lovins has not occurred to an extent sufficient to even show up in Figure 12. On the other hand, Lovins' projection of total energy use was accurate. Many opportunities exist for continuing improvements of energy efficiency, e,g,. in solid state lighting and in transportation. Thus it may be practical for total energy use in the U.S. to remain nearly flat for a substantial period. Furthermore, U.S. CO_2 emissions will increase less than energy use if renewable energy contributions are increased. Thus it seems feasible for U.S. CO_2 emissions to be flat or even decline.

Improvements of energy efficiency and moderation of energy growth rates are not limited to the U.S. Indeed, the U.S. fractions of global energy use and CO_2 emissions actually ***increased*** slightly in the past decade (Reference 1a). Realistic moderate global energy growth rates, coupled with near-term emphasis on renewable energies and long-term technology development, could keep global CO_2 emissions flat in the near-term and allow the possibility of long-term reductions, as may be required to avoid dangerous anthropogenic interference with climate. Quantitative CO_2 scenarios of this sort are presented in the Appendix.

Observed trends. Observed global CO_2 and CH_4 are shown in Figure 13. It is apparent

that the real world is beginning to deviate from the prototypical IPCC scenario, IS92a. It remains to be proven whether the smaller observed growth rates are a fluke, soon to return to IPCC rates, or are a meaningful difference. The concatenation of the alternative scenario with observations is not surprising, since that scenario was defined with observations in mind. However, in the two years since the alternative scenario was defined observations have continued on that path. Although I have shown that the IPCC scenarios are unrealistically pessimistic, I am not suggesting that the alternative scenario can be achieved without concerted efforts to reduce anthropogenic climate forcings.

The alternative scenario falls below all scenarios in IPCC (2001), as illustrated in the Appendix for CO_2. The same is true for the other major climate forcings that cause warming: CH_4, tropospheric O_3, and BC aerosols. It is likely that all these forcings are less than the IPCC pathways, but, unfortunately, except for CH_4 and CO_2, they are not being measured with an accuracy sufficient to define their rates of change.

Summary. *The strategy for dealing with climate change must evolve as the level of forcing that produces "DAI" is better defined and as climate forcings are better measured. Monitoring of the ice sheets, together with realistic ice sheet modeling, will help determine how close the ice sheets are to accelerating retreat. Precise monitoring of ocean heat content change, averaged over several years, will yield the sum of all current forcings. Measurements of individual climate forcing agents will help define the most effective ways to stop global warming.*

My Opinion: Scientific Uncertainties

The above assessment involves personal judgments, even though it is based on data and published papers. I included estimates of prime uncertainties, e.g., for climate sensitivity and climate forcings. However, there will surely be surprises as we obtain more information about climate forcings, observe actual climate change, and improve global climate models. In this section I discuss two areas of uncertainty that I believe deserve special attention.

Dangerous anthropogenic interference ("DAI"). Establishing the level of global warming that constitutes DAI deserves greater attention than it has received. I argue that DAI will be determined by the level of warming that threatens eventual large-scale disintegration of the ice sheets. That is probably a good assumption if, indeed, a global warming only of the order of 1-2°C is enough to initiate eventual removal of large portions of the Greenland or Antarctic ice sheets.

Why choose 1°C (relative to present global mean temperature) as a first estimate of the level of DAI? This is based in part on the assertion that global mean temperature at the peaks of the current (Holocene) and previous (Eemian) interglacial periods were only 0.5 and 1.5°C warmer, respectively, than the mid-twentieth century temperature, and the fact that the Earth has already warmed 0.5°C in the past 50 years. In presenting that argument, I used records of polar temperature and the assumption that polar temperature changes are amplified by at least a factor of two over global mean changes. However, in addition, global climate models driven by early Holocene and Eemian boundary conditions provide strong supporting evidence that global mean temperatures were not warmer than these estimated levels.

Michael Oppenheimer [Reference 2b] also has used ice sheet stability as a basis to infer the level of DAI, concluding that 2°C was his best estimate. His larger value is primarily a result of differing estimates for the global temperature in previous warm periods. I agree that the total uncertainties in the level of DAI, including those discussed below, encompass both the 1°C and 2°C estimates. Furthermore, other scientists will argue that the level of DAI could be even larger

than 2°C. Indeed, Wild et al. [Reference 2c], using one of the most sophisticated GCMs with 1° resolution, calculate that the Greenland and Antarctic ice sheets will ***grow*** with doubled CO_2, leaving only a modest sea level rise due mainly to thermal expansion of ocean water. In my opinion, the IPCC calculations, epitomized by the Wild et al. result, omit the most important physics, especially the non-linear effects of meltwater and secondarily the effects of black carbon. Clearly it is crucial to define DAI more accurately. For example, if there is now 0.5°C global warming "in the pipeline" then DAI = 2°C would permit three times as much additional anthropogenic climate forcing as would DAI = 1°C. The Wild et al. results predict an even higher DAI level.

The time required for ice sheets to respond to global warming, commonly assumed to be thousands of years, is another, related, aspect of the uncertainty in estimating DAI. IPCC presumes a negligible change of ice sheet dynamics in the 21st century. I doubt that assumption, because increased ice sheet movement surely must be driven by surface melt and percolation to the ice sheet base, rather than penetration of a thermal wave through the solid ice. Surface melt and summer precipitation associated with human-induced warming and planetary energy imbalance are likely to be unusual by paleoclimate standards, and even the paleoclimate record reveals instances of rapid ice sheet disintegration. The BØlling warming about 14 thousand years ago, for example, was accompanied almost simultaneously by sea level rise at a rate of 4-5 meters per century (Reference 2d).

Still another uncertainty is the magnitude of actual sea level rise during the Eemian period. This is uncertain because uneven motions of the Earth's crust make it difficult to determine mean sea level change from the data available for a small number of sites. If Eemian sea level was not much higher than that in the Holocene it would call into question our estimate for DAI. However, it would not eliminate concern about the possibility of large sea level rise due to the unique climate forcings in the budding "Anthropocene" era.

There are additional interesting issues that could alter the ice sheet response to human forcings. As discussed below, surface melt may be abetted by a slight aerosol darkening of the ice sheet surface, which becomes especially effective in the warm season. Another curiosity is that Antarctica (except the Antarctic Peninsula) and Greenland may have been "protected" in recent decades by amplification of the polar vortices, i.e., a strengthening of the zonal winds that has limited the warming in Greenland and Antarctica. To the extent that these enhanced zonal winds are driven by ozone depletion, this "protection" may decrease in coming decades as the Earth's ozone layer recovers.

It is apparent that there is considerable uncertainly about the level of global warming that will constitute DAI. This should be an area of focused research in coming years, especially since precise monitoring of ice sheet behavior is now possible. The NASA IceSat mission, monitoring ice sheet topography with centimeter scale precision, should be used to revitalize glaciological studies and test ice sheet modeling capabilities.

Carbonaceous aerosols. Climate modelers should be puzzled by the large negative forcings that aerosol scientists estimate as the direct and indirect effects of human-made fine particles in the air. If these forcings were included in full in global climate models, the models would tend to have cooling at middle latitudes in the Northern Hemisphere where the aerosols are most abundant, as has been stressed by Peter Stone and associates (Reference 7). In reality, moderate warming has been observed there.

It is possible that the negative aerosol forcings have been overestimated. Certainly better measurements are needed. However, we suggested (References 1a, 1b, 6) an alternative

interpretation: positive human-made climate forcings (in the same regions) have been underestimated, especially black carbon aerosols. Recent analyses of measurements by a global network of sun-photometers (Reference 8) provide partial confirmation of this interpretation, revealing that BC aerosols absorb about twice as much sunlight as in previous estimates.

There is another, indirect, forcing of BC aerosols that seems to have been overlooked by IPCC: the effect of BC aerosols on the albedo (reflectivity) of snow and ice. This effect is no surprise to a number of researchers (Reference 9) who have pointed out that the amount of absorbing aerosols in snow determines its maximum albedo. Snow albedos in the Arctic are seldom found to be much more than 90% at visible wavelengths, even though pure snow should have a visible albedo of at least 98%. Soil dust provides some of the aerosol absorption, but BC is believed to be the primary source of absorption.

We estimate, using the radiative transfer theory of Steve Warren, Warren Wiscombe, Petr Chylek and associates (References 9a,b) that this indirect BC climate forcing is about 0.5 W/m^2 in the Northern Hemisphere and about 0.3 W/m^2 globally. Probably two-thirds of this, 0.2 W/m^2, is anthropogenic. This positive forcing not only adds to global warming, it also contributes to (1) thinning of Northern Hemisphere sea ice and reduction of sea ice cover, (2) softening and loss of permafrost, (3) melting of alpine glaciers, (4) enhancement and expansion of the summer melt season on the Greenland ice sheet.

The BC forcing of snow and ice is seasonally dependent. BC has little effect on fresh snow, but as the snow ages and partially melts, BC remains as crud on the surface, noticeably decreasing the albedo of snow and ice. As a result, spring snowmelt is completed earlier, summer melt of glaciers is increased, and sea ice is thinned and reduced in area. I believe that these effects partially account for several otherwise puzzling phenomena: (1) alpine glaciers have retreated faster than expected for the magnitude of global warming, (2) Arctic sea ice has thinned in the past 50 years and decreased in area, while Southern Hemisphere sea ice has changed little, (3) spring in the Northern Hemisphere is coming noticeably earlier in recent decades, while fall has not been extended by an equal amount.

Unlike well-mixed greenhouse gases, the efficacy of BC as a climate forcing probably depends a good deal on the mechanism producing the BC. Tropical outdoor biomass burning, e.g, produces a lot of BC but even much more OC (organic carbon). The biomass burning lofts these aerosols into the middle troposphere where their effect on surface temperature is small, or even a slight cooling. In contrast, diesel fuels and biofuels produce a greater proportion of BC that remains mainly in the planetary boundary layer (the lowest mile or two), where it has a direct warming effect and an indirect warming effect after deposition on snow and ice surfaces.

"Die ganze welt erstickt im russ" (the whole world is suffocating in soot) was a headline of a local newspaper during an international conference on black carbon held in Austria in 1983. However, climate science has never fully investigated the role of BC in climate change. Global measurements of aerosols, including their effects on snow and ice albedos and their effects on clouds, and realistic modeling of all these phenomena are needed. It will not be possible to optimize strategies for dealing with global warming until all important climate forcings, including carbonaceous aerosols, have been well quantified.

My Opinion: Practical Matters

Science and politics don't mix. I believe that active researchers should offer objective assessment of the science problem and leave it to others to extract policy implications. The complication is that the scenarios for climate forcings and climate change are a function of

people's actions. Unless we make clear the relation between those actions and climate change, policy makers will not have the information they need.

Perhaps the best way to handle this situation is to point out the positive aspects in the positions of all three of the relevant parties in the climate change discussion: the Kyoto parties, the United States, and the developing countries. It turns out that each of the three parties is in a position to make unique contributions to reducing climate forcings, and, furthermore, the sum of these is what is needed to achieve a stable atmospheric composition and a stable climate, as universally agreed upon with the Framework Convention on Climate Change.

Let's start with the Kyoto parties. These countries have agreed to cut their greenhouse gas (GHG) emissions to a level several percent below their 1990 level. This will not be easy but it is achievable, based in part on fortuitous happenings: discovery of North Sea gas that allowed Britain to close coal mines, German reunification with closing of inefficient East German industry, collapse of the Soviet Union that reduced Russian CO_2 emissions 30%, and a stagnant Japanese economy that slowed their CO_2 emission growth. Adherence to the Kyoto Protocol by its signatories will engender improvement of energy efficiencies and development of renewable energies. The implied technological developments will have world-wide applications, reducing GHGs by more than the emission reductions within Kyoto party countries themselves.

The United States cannot practically meet proposed Kyoto Protocol GHG emission targets (which are based on 1990 emission levels) given the rapid growth of its economy and CO_2 emissions in the 1990s. Because of that growth, it is estimated that two-thirds of the cost of the Kyoto targets, if they were extended to the U.S., would be borne by the U.S., so there is no expectation that the U.S. will join that accord. However, President Bush indicated in a June 2001 "Rose Garden" speech that the U.S. would take a leadership role in addressing global climate change. He said that the United States would work aggressively on energy efficiencies, renewable energies, and longer-term technologies including fuel cells and hydrogen, next generation nuclear power, and CO_2 sequestration. In an advance beyond Kyoto, he recognized the importance of reducing air pollution climate forcings, specifically mentioning black soot, ozone, and its precursors. He said: "Our approach must be consistent with the long-term goal of stabilizing greenhouse gas concentrations in the atmosphere." And: "We will act, learn, and act again, adjusting our approach as science advances and technology evolves." This approach, together with the planned actions of the Kyoto parties, comprise essential ingredients needed for the "alternative scenario" to be achieved.

Developing countries, located primarily at low latitudes, stand to suffer the most if climate is not stabilized, and they already have punishing air pollution. The common presumption that their CO_2 emissions will soon explode ignores the fact that developing countries will wish to pursue high efficiency clean technologies for their own good. The experience with chlorofluorocarbons, in which India and China agreed to limit production in exchange for assistance with replacement technology, illustrates that such cooperation is possible. Climate mitigation and pollution reduction will benefit developing countries most of all, so attainment of their cooperation must be achievable. How to carry out these discussions and cooperation is a matter for policy makers and beyond the scope of this paper.

We note, however, that cooperation of developed and developing countries will be needed on CO_2 emissions as well as air pollution. Figure 14 shows that the Far East (defined as Japan, Korea, China, Taiwan, Mongolia) and the Rest of Asia (includes the Middle East) have had the fastest growing CO_2 emissions in recent decades and are now near the same level of emissions as the United States. Future global CO_2 emissions depend upon the path of Asian

emissions, yet the U.S. emissions (blue curve in Figure 14) remain critical for defining the global emissions curve.

Figure 14 also reveals a period of flat emissions in the U.S. during the 1970s and 1980s, which was mainly a consequence of energy efficiencies engendered by an oil supply disruption that caused a large increase of energy prices. Economists agree that the most efficient way to slow emissions growth would be an increasing cost for energy, but the cost growth should be slow and steady to avoid economic disruption and social hardships.

Limitations on global supplies of oil and gas, especially if environmental pressures restrict regions of exploration, might themselves tend to increase energy costs. However, improving technologies are likely to increase accessible hydrocarbon resources, and shortages that occur are usually in irregular disruptive bursts that create hardships and are less effective for improving energy efficiency. Governments could alleviate these problems via flexible assessments that yield a smooth growth of energy costs.

Coal is both the principal root of the CO_2 climate problem and the potential solution. Even if all accessible oil and gas is utilized, atmospheric CO_2 growth can be kept within the 2°C or even the "alternative" (1°C) scenarios, provided that CO_2 emissions from coal are limited. Coal produces more CO_2 per unit energy than oil or gas, and the CO_2 in coal resources is ten times greater than the CO_2 in oil resources (Reference 13), enough to cause global warming of several degrees Celsius and certain devastation of the ice sheets. Note that updating Table 2 in Reference 13 to 2002 indicates that the 86 ppm increase of atmospheric CO_2 since 1850 is composed of 40 ppm from coal, 34 ppm from oil and 12 ppm from gas.

A flattening of CO_2 emissions and a decline as the 21st century progresses thus could be obtained by requiring that new uses of coal be permitted only in cases where the resulting CO_2 is sequestered. This approach would make good economic sense, as the costs of sequestration would be attached to coal use, with coal then permitted to compete with other energy sources.

The largest reservoirs of coal are in the United States, China and Russia, although significant amounts exist in other countries. The international community may need to supply technological assistance to developing countries for sequestration capabilities, as it provided assistance for CFC replacements. International cooperation on coal use and sequestration is probably the most important action needed to stabilize atmospheric composition and climate.

Although coal is the key to solving the CO_2 problem, this does not mean that other actions are unneeded. Halting the growth of the non-CO_2 forcings is essential for staying beneath the most plausible levels of dangerous anthropogenic interference with the climate system, as are concerted efforts to improve energy efficiencies, increase use of renewable energies, and develop energy technologies that produce little or no CO_2.

The bottom line. How can I be optimistic if, as I have argued, climate is now in the hands of humans and it is closer to the level of "dangerous anthropogenic interference" than has been realized? If we compare the situation today to that 10-15 years ago, we realize that the main elements required to halt climate change, as summarized above, have come into being with remarkable rapidity. I realize that it will not be easy to stabilize greenhouse gas concentrations, but I am optimistic because I expect empirical evidence for climate change and its impacts to continue to accumulate, and that this will influence the public, public interest groups, industry, and governments at various levels. The question is: will we act soon enough. It is a matter of time.

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Appendix: Climate Forcing Scenarios

IPCC (2001) uses a "storyline" approach to produce a useful plethora of scenarios with a broad range of forcings. However, this approach does not show how much current emission trends must be modified in order to stay below an estimated level for dangerous anthropogenic interference. Also the IPCC predilection for exaggerated growth rates of population, energy intensity, and pollution calls into question the realism of their results. Let's try an alternative approach that begins with observed rates of change of the forcings.

CO_2 growth rates. CO_2 is the most important forcing. Its growth depends upon the rate at which we add CO_2 to the air and upon how fast this human increment is removed via uptake by the ocean and the land. In the past three decades, since the oil embargo of 1973, the growth rate of fossil fuel CO_2 emissions has been 1.4%/year (Figure 11), yielding an increase of about 49% in annual CO_2 emissions between 1973 and 2002. The annual growth of CO_2 in the air increased by a comparable proportion (Figure 10). If we want the growth rate of CO_2 in the air to stabilize at the current rate, we probably need to decrease the CO_2 emissions growth rate to about 0%/year, i.e., CO_2 emissions (and thus fossil fuel burning) would need to remain approximately the same as today (unless CO_2 is captured and sequestered, in which case fossil fuel burning could increase).

Actual growth rate of CO_2 emissions in the 1990s, based on the recent update of DOE (Marland and Boden, Reference 11), was 0.7%/year. In the IPCC CO_2 scenarios (constructed before data for the full decade were available) the growth rate of CO_2 emissions in the 1990s is 1.5%/year, about twice the actual growth rate.

Is it practical to achieve flat CO_2 emissions during the next few decades, setting the stage for still lower emission rates later in the century? Such a scenario surely requires all of the following: (1) near-term and long-term emphasis on energy efficiency, (2) increased use of renewable energies that produce little or no net CO_2, and (3) long-term development of large energy sources that produce no CO_2 (e.g., next-generation nuclear power) and/or technologies to capture and sequester CO_2. By the second half of the century it is possible that there will be new technologies that help reduce climate forcings, e.g., by removing CO_2 from the air. In the near term, experience of recent decades suggests that it would be feasible to achieve flat CO_2 emissions via the multi-pronged effort mentioned above (efficiencies, renewables, other new technologies).

It is sometimes suggested that the recent ~1%/year growth rate of CO_2 emissions is an aberration resulting from the collapse of the Soviet Union's economy and is affected by possible under-reporting of China's emissions. On the contrary, the demise of inefficient systems is natural and there is much room for further gains in efficiency. Reported reductions of coal use in China in the late 1990s were probably exaggerated, as indicated by a 28% increase in reported coal use between 2001 and 2002 (Reference 11b). But such uncertainties do not modify the conclusion that a realistic description of business-as-usual is 1-1.5%/year growth of global CO_2 emissions, not 4%/year (see note 11c in References). The presumption inherent in the fast-growth IPCC scenarios, that the entire world will follow the energy path of the U.S. between 1945 and the early 1970s, developing a comparable dependence on fossil fuel supplies, with all the disadvantages that entails, is highly dubious.

These arguments do not imply that the transition from 1-1.5%/year CO_2 growth rate, which is a realistic description of "business-as-usual", to the 0%/year of the "alternative" scenario would be easy. On the contrary, it requires a concerted global effort of developed and developing countries. However, the change is small enough that it can be attained via

appropriate emphases on improved energy efficiencies, renewable energies, and other advanced technologies such as carbon sequestration and next generation nuclear power. This further reduction of the CO_2 growth rate is needed not so much because of its effect on climate change during the next few decades, which effect will be small, but rather because of its impact on our ability to stabilize atmospheric composition later in the century.

The change seems moderate, but it is crucial. 1%/year growth for 50 years yields an increase of 70% in the emission rate. 1.5%/year yields a factor of 2.1. The first steps that are taken in the 21st century are important, as they will determine the direction that we are headed.

Non-CO_2 forcings. Methane (CH_4) causes the second largest GHG climate forcing. Hansen and Sato (Reference 1a) show that the actual growth rate of CH_4 is falling below <u>all</u> IPCC scenarios. In the past two years the gap between the IPCC CH_4 scenarios and reality has widened. Other large anthropogenic forcings are those of BC and O_3. Unfortunately neither of these is being measured well enough globally to determine its rate of change. I leave it to the reader to mull: do you believe that the amount of these air pollutants will be larger in 2050 than it is today, as it is in the IPCC scenarios? If it is not, their added forcing will be zero or negative. Finally, note that IPCC assumes that the net climate forcing by CFCs and their replacements will increase this decade. Observations show that the CFC forcing is below the IPCC scenarios and may shift to a small negative annual change by 2005.

It is reasonable to project that further change of the non-CO_2 forcings could be minimal in the 21st century. Small decreases of CFCs and of some air pollutants could tend to balance modest increases of other pollutants and N_2O. However, such a near balance will not happen automatically. It will require concerted actions and international cooperation.

"Alternative" and "2°C" scenarios. Let's consider two target scenarios: the "alternative" scenario, which yields a maximum additional global warming of about 1°C, and a "2°C" scenario. Warmings are defined relative to 2000. It is assumed that climate sensitivity is about 3°C for doubled CO_2 and that net additional non-CO_2 forcings in the 21st century are small. Maximum global warmings of ~1°C and ~2°C for these two scenarios occur in 2125-2150, based on simulations with the GISS climate model.

The "alternative" scenario is an extension of the scenario we defined for 2000-2050 (reference 6), with the annual CO_2 growth decreasing linearly to zero between 2050 and 2100 such that atmospheric CO_2 stops growing by 2100. Such an assumption, which is required for any scenario that achieves stabilization, implies at least a 50% reduction in fossil fuel use or CO_2 capture and sequestration.

The "2°C" scenario permits larger annual CO_2 growth, but after 2050 its annual CO_2 growth also decreases linearly to achieve zero CO_2 growth in 2100. The annual CO_2 increment in the "2°C" scenario almost doubles by mid-century, reaching 3 ppm/year in 2050. Thus the "2°C" scenario permits a realistic "business-as-usual" CO_2 growth rate (more than 1%/year) to persist for 50 years, but it would require a steep reduction of emissions after 2050.

CO_2 amounts in these scenarios are shown in Figure 15. CO_2 peaks at ~475 ppm in 2100 in the "alternative" scenario and at ~560 ppm in 2100 in the "2°C" scenario. It is perhaps unlikely that actual CO_2 growth (in the next 50 years) will exceed that of the "2°C" scenario, given the existence of concerns about global climate change.

It is informative to compare these two scenarios with IPCC scenarios. The manifold "story lines" in IPCC (2001) produce a plethora of scenarios, but when new scenarios are devised with each report it is hard to judge how well prior scenarios have fared against reality.

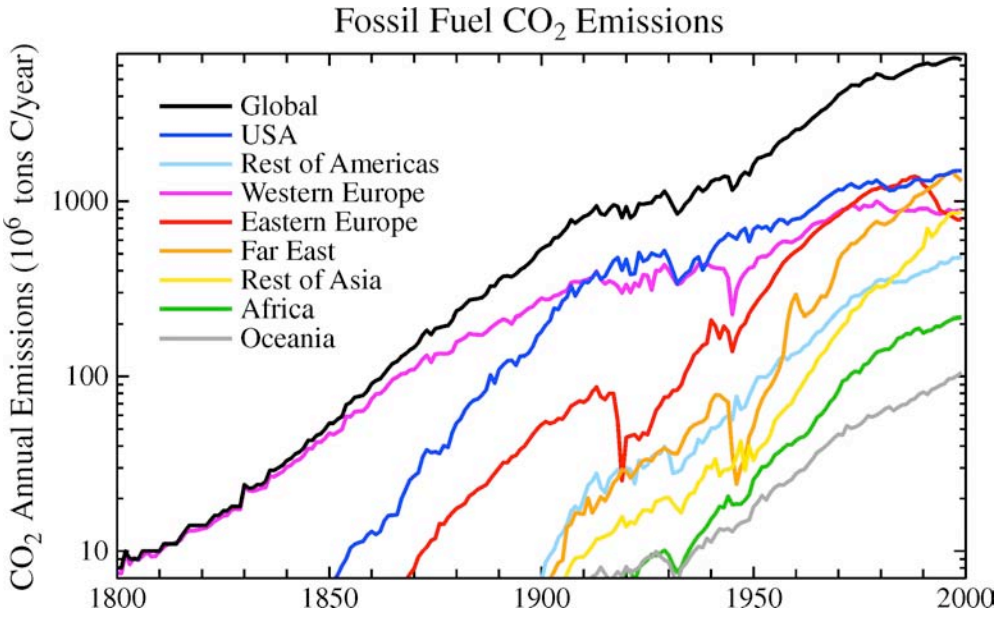

Figure 14. Fossil fuel CO_2 emissions by global region based on data of Marland and Boden [Reference 11].

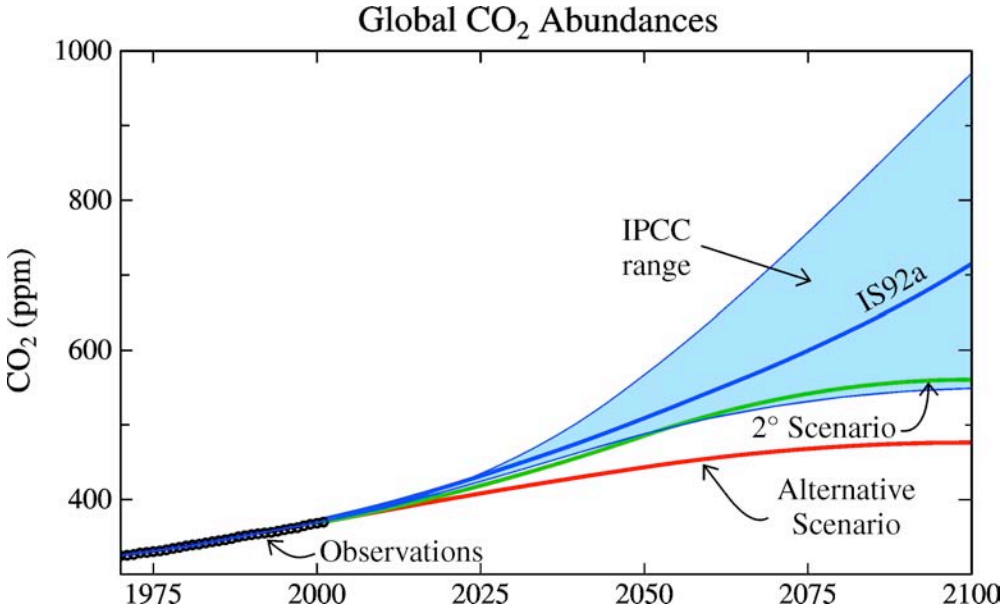

Figure 15. CO_2 in the range of IPCC (2001) "marker" scenarios, and in our "alternative" and "2° C" scenarios. In the alternative scenario ΔCO_2 decreases linearly from 1.7 ppm/year in 2000 to 1.3 ppm/year in 2050 and then linearly to zero in 2100; CO_2 peaks at ~475 ppm in 2100. In the "2°C" scenario ΔCO_2 increases linearly from 1.7 ppm/year in 2000 to 3 ppm/yr in 2050 and then decreases linearly to zero in 2100; CO_2 peaks at ~560 ppm in 2100. Upper and lower limits of IPCC range are their scenarios A1FI and B1 [IPCC, 2001, Appendix II, p. 807 and Figure 18, p.65]. IS92a is the updated version of that scenario in IPCC (2001), which incorporates recent carbon cycle modeling. A still broader range of IPCC scenarios is included in their Special Report on Emission Scenarios (SRES) document (Reference 12b). CO_2 scenarios for the alternative and "2°C scenarios are given at http://www.giss.nasa.gov/data/simodel/ghgases/Fig1A.ext.txt.

Fortunately the standard emission scenario of previous reports, IS92a, has been retained in IPCC (2001) with atmospheric CO_2 amounts obtained from updated carbon cycle calculations. The "alternative" and "2°C" scenarios both fall far below IS92a. The "alternative" scenario falls far below the range of IPCC (2001) marker scenarios, while the "2°C" scenario is near the bottom of that IPCC range. Of late the real world has been close to the "alternative" scenario (Figure 13).

The conclusion that the real world is likely to fall somewhere in the range between the "alternative" and "2°C" scenarios (at least for the next several decades) has the practical implication of heightening the importance of the non-CO_2 forcings. The large CO_2 forcing in most IPCC scenarios had left the impression that nothing except CO_2 was important. Figure 4 is a better measure of the relative importance of different forcings. The non-CO_2 forcings deserve emphasis comparable to that placed on CO_2.

Summary opinion re scenarios. Emphasis on extreme scenarios may have been appropriate at one time, when the public and decision-makers were relatively unaware of the global warming issue, and energy sources such as "synfuels", shale oil and tar sands were receiving strong consideration. Now, however, the need is for demonstrably objective climate forcing scenarios consistent with what is realistic under current conditions. Scenarios that accurately fit recent and near-future observations have the best chance of bringing all of the important players into the discussion, and they also are what is needed for the purpose of providing policy-makers the most effective and efficient options to stop global warming.

IPCC scenarios encompass a great range, especially in the IPCC SRES document (Reference 12b), which includes CO_2 growth rates faster and slower than the range of "marker" scenarios that are included in IPCC (2001) and illustrated in our Figure 15. However, IPCC does not specify the likelihood of the scenarios or examine the direction of current real-world growth rates. A realistic "business-as-usual" scenario would have CO_2 growth rates in the range 1-1.5%/year, thus on a course comparable to our "2°C" scenario for the next few decades.

I have argued that achievement of a 1°C scenario would be feasible based on increased emphasis on energy efficiencies, renewable energies, and advanced technologies. However, I am not implying that this "alternative scenario" would be easy to achieve. Indeed, it surely requires concerted world-wide actions. Furthermore, stabilization of atmospheric composition by the end of the century eventually will require substantial reductions of CO_2 emissions. If fossil fuels remain the prime source of energy, this implies the need for large-scale sequestration of CO_2. I have not discussed propositions to counterbalance global warming with geo-engineered cooling, because the suggestions that have been made, such as a large shade in space or human-injected aerosols in the stratosphere, appear to be uneconomic and fool-hearty in comparison with the actions that would slow global warming.

The great uncertainty about scenarios concerns the level of global warming that would constitute dangerous anthropogenic interference. I have argued that ice sheet stability may require that global warming be kept less than about 1°C. Hopefully I am wrong, because that may be a difficult scenario to achieve. Others have suggested 2°C, and IPCC implies that even larger warming would have little effect on sea level. Research on the stability of the ice sheets deserves high priority. A curious point that we have raised concerns the contribution of black carbon to the disintegration of ice sheets. The implication is that by reducing black carbon emissions we could raise somewhat the level of warming that would constitute dangerous anthropogenic interference. However, I am not suggesting that black carbon is the primary factor affecting ice sheet stability.

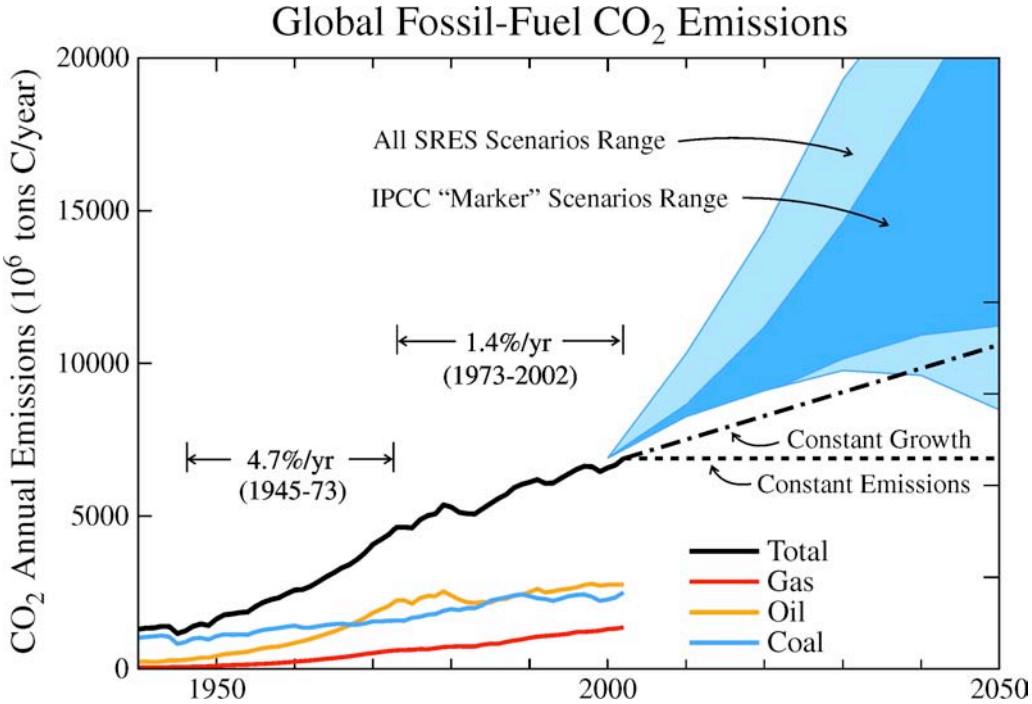

Figure 16. Fossil fuel CO_2 emissions as in Figure 11, but with a linear scale. IPCC/SRES emission scenarios were defined in the mid 1990s, which accounts for their offset in 2000.

Lay person's CO_2 emissions graph. The presentation of fossil-fuel CO_2 emissions in Figure 11 reveals the fundamental changes in growth rate that have occurred over long periods and the time scales over which different energy sources have penetrated global energy use (an estimate for wood is added to that figure in Reference 6a). However, the logarithmic scale for emissions might mislead a lay person. An alternative (linear) presentation (Figure 16) reveals additional information for a limited period.

The sea change in energy growth rates that occurred in 1973, with the oil embargo and energy price increase, is less apparent in Figure 16 than in Figure 11, although the discerning eye might note the change from exponential growth prior to 1973 to essentially linear growth (constant growth) since 1973. A realistic projection of current trends is a continuation of that constant growth rate, the dash-dot line in Figure 16.

"Constant growth" at the rate of the past three decades falls below the IPCC scenarios, and "constant emissions" falls far below the IPCC scenarios. The dark blue area is the range of "marker" scenarios in the primary IPCC publication (Reference 6a), while the lighter blue area adds the full range of scenarios in the IPCC SRES publication (Reference 6b). The IPCC scenarios that extend far off-scale (high) are impractical to show in entirety with a linear scale, but they do not need to be shown as they are unrealistic.

The "constant growth" and "constant emissions" tracks are approximately what is needed to achieve the "2°C" and "alternative" climate scenarios, which are designed to keep additional global warming below 2°C and 1°C, respectively. Keeping CO_2 emissions from exceeding the "constant growth" track for the next few decades may be, comparatively, "easy". Achievement of the "constant emissions" path, on the other hand, requires a second sea change in fossil fuel use trends. We will present quantitative evidence elsewhere that this "alternative" scenario could be achieved via feasible emphasis on energy efficiencies, renewable energies and other advanced technologies.

This discussion refers to CO_2 emissions during the next few decades. The (uncaptured) CO_2 emissions in both the 2°C and 1°C scenarios must begin to decrease prior to mid-century to achieve stabilization of atmospheric CO_2 amount, as agreed in the Framework Convention on Climate Change. To keep additional global warming from exceeding 1°C, which I have argued is the most plausible value for the level of DAI, implies the need for a change in CO_2 emission rates at least as dramatic as that initiated in 1973. This will require an unprecedented level of international cooperation.

James E. Hansen[*] (jhansen@giss.nasa.gov)
NASA Goddard Institute for Space Studies, and
Columbia University Earth Institute
2880 Broadway, New York, NY 10025

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About the author: Dr. James Hansen heads the Goddard Institute for Space Studies, which is a division of the NASA Goddard Space Flight Center and a unit of the Columbia University Earth Institute located on the Columbia campus in New York City. Dr. Hansen was trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa. His primary research for the past 25 years has been on studies and computer simulations of the Earth's climate, for the purpose of understanding the human impact on global climate. Dr. Hansen is best known for his testimony on climate change to congressional committees in the 1980s that helped raise broad awareness of the global warming issue. He was elected to the National Academy of Sciences in 1995 and, in 2001, received both the Heinz Award for the environment as well as the American Geophysical Union's Roger Revelle Medal.

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[*] Affiliations for identification only; interpretations in this paper are the opinion of the author and are not meant to represent the position of any organization.