

# Global warming in the twenty-first century: An alternative scenario

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A common view is that the current global warming rate will continue or accelerate. But we argue that rapid warming in recent decades has been driven mainly by non-CO<sub>2</sub> greenhouse gases (GHGs), such as chlorofluorocarbons, CH<sub>4</sub>, and N<sub>2</sub>O, not by the products of fossil fuel burning, CO<sub>2</sub> and aerosols, the positive and negative climate forcings of which are partially offsetting. The growth rate of non-CO<sub>2</sub> GHGs has declined in the past decade. If sources of CH<sub>4</sub> and O<sub>3</sub> precursors were reduced in the future, the change in climate forcing by non-CO<sub>2</sub> GHGs in the next 50 years could be near zero. Combined with a reduction of black carbon emissions and plausible success in slowing CO<sub>2</sub> emissions, this reduction of non-CO<sub>2</sub> GHGs could lead to a decline in the rate of global warming, reducing the danger of dramatic climate change. Such a focus on air pollution has practical benefits that unite the interests of developed and developing countries. However, assessment of ongoing and future climate change requires composition-specific long-term global monitoring of aerosol properties.

climate change | greenhouse gases | aerosols | air pollution

The global surface temperature has increased by about 0.5°C since 1975 (1, 2), a burst of warming that has taken the global temperature to its highest level in the past millennium (3). There is a growing consensus (4) that the warming is at least in part a consequence of increasing anthropogenic greenhouse gases (GHGs).

GHGs cause a global climate forcing, i.e., an imposed perturbation of the Earth's energy balance with space (5). There are many competing natural and anthropogenic climate forcings, but increasing GHGs are estimated to be the largest forcing and to result in a net positive forcing, especially during the past few decades (4, 6). Evidence supporting this interpretation is provided by observed heat storage in the ocean (7), which is positive and of the magnitude of the energy imbalance estimated from climate forcings for recent decades (8).

The Intergovernmental Panel on Climate Change (IPCC) (4) has considered a range of scenarios for future GHGs, which is further expanded in its *Special Report on Emissions Scenarios* (9). Yet global warming simulations have focused on "business as usual" scenarios with rapidly increasing GHGs. These scenarios yield a steep, relentless increase in global temperature throughout the twenty-first century (4, 10) with warming of several degrees Celsius by 2100, if climate sensitivity is 2–4°C for doubled CO<sub>2</sub>, as climate models suggest (4, 11–13). These figures can give the impression that curtailment of global warming is almost hopeless. The 1997 Kyoto Protocol, which calls for industrialized nations to reduce their CO<sub>2</sub> emissions to 95% of 1990 levels by 2012 (14), is itself considered a difficult target to achieve. Yet the climate simulations lead to the conclusion that the Kyoto reductions will have little effect in the twenty-first century (15), and "30 Kyotos" may be needed to reduce warming to an acceptable level (16).

We suggest equal emphasis on an alternative, more optimistic, scenario. This scenario focuses on reducing non-CO<sub>2</sub> GHGs and black carbon during the next 50 years. Our estimates of global climate forcings indicate that it is the non-CO<sub>2</sub> GHGs that have

caused most observed global warming. This interpretation does not alter the desirability of limiting CO<sub>2</sub> emissions, because the future balance of forcings is likely to shift toward dominance of CO<sub>2</sub> over aerosols. However, we suggest that it is more practical to slow global warming than is sometimes assumed.

## Climate Forcings in the Industrial Era

Fig. 1 shows graphs of estimated climate forcings since 1850, which are similar to previous presentations (4, 6). Forcings for specific GHGs differ by as much as several percent from values we estimated earlier: CO<sub>2</sub> (–1%), CH<sub>4</sub> (+2%), N<sub>2</sub>O (–3%), chlorofluorocarbon 11 (CFC-11) (+6%), and CFC-12 (+8%). Our prior results, used by the IPCC (4), were analytic fits to calculations with a one-dimensional radiative-convective model (17). The present results (Table 1) are based on calculations of adjusted radiative forcing (5), using the SI2000 version of the Goddard Institute for Space Studies three-dimensional climate model (8, 13), with the absorption coefficients fit to line-by-line radiative transfer calculations, using current HITRAN (18) absorption line data. Thus the present results are improved in several ways.

**Estimated Forcings.** We separate CO<sub>2</sub>, CH<sub>4</sub>, and CFCs in Fig. 1 because they are produced by different processes and have different growth rates. We associate with CH<sub>4</sub> its indirect effects on tropospheric O<sub>3</sub> and stratospheric H<sub>2</sub>O to make clear the importance of CH<sub>4</sub> as a climate forcing. We assume that one-fourth of the 0.4 W/m<sup>2</sup> climate forcing due to increasing tropospheric O<sub>3</sub> is caused by increasing CH<sub>4</sub> (chapter 2 in ref. 4; ref. 19). We calculate an indirect effect of 0.1 W/m<sup>2</sup> for CH<sub>4</sub> oxidized to H<sub>2</sub>O in the stratosphere (20). The recent trend of stratospheric H<sub>2</sub>O (20, 21) is even larger than CH<sub>4</sub> could cause, but part of the observed trend may be a result of transport from the troposphere.

The estimated negative forcing due to stratospheric O<sub>3</sub> depletion, –0.1 W/m<sup>2</sup>, is smaller than the –0.2 W/m<sup>2</sup> that we used earlier (6) because of changes in the vertical profile of O<sub>3</sub> depletion estimated from observations. O<sub>3</sub> trends recommended by the World Meteorological Organization (22) have less depletion in the tropopause region (where O<sub>3</sub> loss causes surface cooling) and greater loss in the middle stratosphere (where O<sub>3</sub> loss causes surface warming) compared with the O<sub>3</sub> changes that we used previously (5, 6).

Climate forcing by CO<sub>2</sub> is the largest forcing, but it does not dwarf the others (Fig. 1). Forcing by CH<sub>4</sub> (0.7 W/m<sup>2</sup>) is half as large as that of CO<sub>2</sub>, and the total forcing by non-CO<sub>2</sub> GHGs (1.4 W/m<sup>2</sup>) equals that of CO<sub>2</sub>. Moreover, in comparing forcings

Abbreviations: GHGs, greenhouse gases; CFCs, chlorofluorocarbons; IPCC, Intergovernmental Panel on Climate Change.

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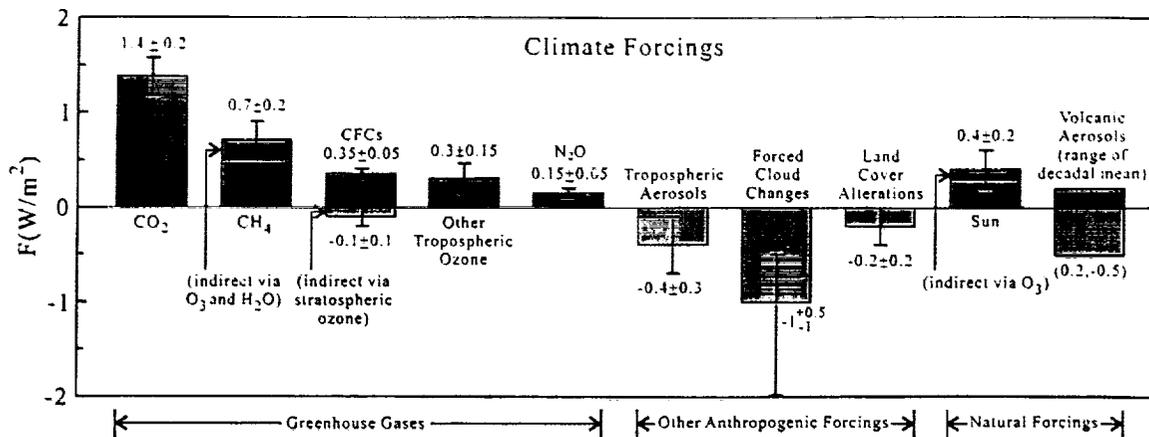


Fig. 1. Estimated climate forcings between 1850 and 2000.

due to different activities, we must note that the fossil fuels producing most of the CO<sub>2</sub> are also the main source of aerosols, especially sulfates, black carbon, and organic aerosols (4, 23). Fossil fuels contribute only a minor part of the non-CO<sub>2</sub> GHG growth via emissions that are not essential to energy production.

Aerosols cause a climate forcing directly by reflecting sunlight and indirectly by modifying cloud properties. The indirect effect includes increased cloud brightness, as aerosols lead to a larger number and smaller size of cloud droplets (24), and increased cloud cover, as smaller droplets inhibit rainfall and increase cloud lifetime (25). Absorbing aerosols cause a semidirect forcing by heating the atmosphere, thus reducing large-scale cloud cover (5). In addition, absorbing aerosols within cloud drops and in interstitial air decrease cloud brightness.

Forcing by atmospheric aerosols is uncertain, but research of the past decade indicates that it is substantial (4, 26–28). The aerosol forcing that we estimate (6) has the same magnitude (1.4 W/m<sup>2</sup>) but a sign that is opposite that of the CO<sub>2</sub> forcing. Fossil fuel use is the main source of both CO<sub>2</sub> and aerosols, with land conversion and biomass burning also contributing to both forcings. Although fossil fuels contribute to growth of some of the other GHGs, it follows that the net global climate forcing due to processes that produced CO<sub>2</sub> in the past century probably is much less than 1.4 W/m<sup>2</sup>. This partial offsetting of aerosol and greenhouse forcings has been discussed (29–31). Offsetting of global mean forcings does not imply that climate effects are negligible.

A corollary following from Fig. 1 is that climate forcing by non-CO<sub>2</sub> GHGs (1.4 W/m<sup>2</sup>) is nearly equal to the net value of all known forcings for the period 1850–2000 (1.6 W/m<sup>2</sup>). Thus, assuming only that our estimates are approximately correct, we assert that the processes producing the non-CO<sub>2</sub> GHGs have been the primary drive for climate change in the past century.

Table 1. Greenhouse gas radiative forcings

Gas	Radiative forcing
CO <sub>2</sub>	$F = f(c) - f(c_0)$ , where $f(c) = 4.996 \ln(c + 0.0005c^2)$
CH <sub>4</sub>	$F = 0.0406(\sqrt{m} - \sqrt{m_0}) - [g(m, n_0) - g(m_0, n_0)]$
N <sub>2</sub> O	$F = 0.136(\sqrt{n} - \sqrt{n_0}) - [g(m_0, n) - g(m_0, n_0)]$ , where $g(m, n) = 0.5 \ln[1 + 2 \times 10^{-5}(mn)^{0.75}]$
CFC-11	$F = 0.264(x - x_0)$
CFC-12	$F = 0.323(y - y_0)$

*c*, CO<sub>2</sub> (ppm); *m*, CH<sub>4</sub> (ppb); *n*, N<sub>2</sub>O (ppb); *x*, *y*, CFC-11 12 (ppb).

**Consistency Checks.** Two empirical pieces of information are consistent with our estimated net climate forcing: (i) global warming of the past century and (ii) observed heat storage in the ocean. The second of these is direct and fundamental.

Paleoclimate data (13, 32, 33) imply that the equilibrium global climate sensitivity for doubled CO<sub>2</sub> (a forcing of about 4 W/m<sup>2</sup>) is  $3 \pm 1^\circ\text{C}$  (thus  $3/4 \pm 1/4^\circ\text{C}$  per W/m<sup>2</sup>). This figure is similar to the sensitivity derived from climate models (4, 12), but it has a higher precision and confidence level. This climate sensitivity implies a thermal response time of the ocean surface of 50–100 years (32, 34). One implication of this ocean response time is that the observed global warming of  $3/4^\circ\text{C}$  since the late 1800s is consistent with the equilibrium warming of 1.2°C that a forcing of 1.6 W/m<sup>2</sup> implies, because about 70% of the forcing was introduced in the last 50 years (6, 35). The remaining global warming of 0.4–0.5°C that is “in the pipeline” is consistent with the present planetary energy imbalance of  $0.6 \pm 0.1 \text{ W/m}^2$  (8).

The ocean is the only place that the energy from a planetary radiation imbalance can accumulate, because of the low thermal conductivity of land and the limit on ice melting implicit in the observed sea level rise (36). Thus observed ocean heat storage requires a planetary energy imbalance of the same magnitude. Analyses of global ocean data (7) reveal that ocean heat content increased by  $2 \times 10^{23}$  joules between the mid-1950s and the mid-1990s. This heat storage could be a natural dynamical fluctuation. But the simplest interpretation is that the change in ocean heat content and the implied planetary energy imbalance are a reflection of the net global climate forcing. Observed heat storage between the mid-1950s and mid-1990s yields a mean heating of 0.3 W/m<sup>2</sup> averaged over the Earth’s surface for that period (7). This finding is consistent with the ocean heat storage simulated in global climate models that use the forcings of Fig. 1; the heat storage in the models increases from near zero in the 1950s to a mean of 0.5 W/m<sup>2</sup> in the 1990s (8, 35). Thus observed ocean heat storage provides empirical evidence for the sign and approximate magnitude of the net climate forcing of Fig. 1.

### Greenhouse Gas Growth Rates

Atmospheric amounts of the principal human-influenced GHGs have been monitored in recent years and extracted for earlier times from bubbles of air trapped in polar ice sheets (37). Gases that cause the largest climate forcings, CO<sub>2</sub> and CH<sub>4</sub>, are shown in Fig. 2. IPCC IS92 scenarios (chapter 2 in ref. 4) for the next 50 years are also shown in Fig. 2. IS92a, at least so far, has been the most popular scenario for climate model simulations.

These climate forcing projections involve many assumptions and are very uncertain. The IS92a forcing for all well-mixed

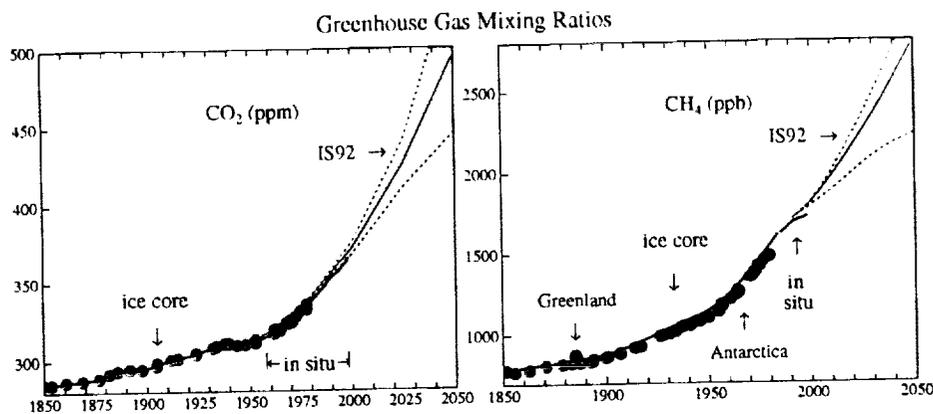


Fig. 2. Atmospheric CO<sub>2</sub> and CH<sub>4</sub> observations and range of IS92 scenarios (the solid red line is IS92a).

GHGs, including CFCs, was already a 15% reduction from the principal 1990 IPCC scenario (38). The observed increase in CH<sub>4</sub> in the 1990s falls below the lowest IS92 scenario, whereas CO<sub>2</sub> falls on the lowest IS92 scenario.

Trends of the climate forcings are revealed better by their annual growth rates, as shown in Fig. 3 for anthropogenic GHGs. The forcings are calculated from the equations of Table 1. The CO<sub>2</sub> and CH<sub>4</sub> amounts for 1999 were kindly provided by Ed Dlugokencky and Tom Conway of the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory (personal communication).

**Carbon Dioxide.** The growth rate of forcing by CO<sub>2</sub> doubled between the 1950s and the 1970s (Fig. 3A) but was flat from the late 1970s until the late 1990s, despite a 30% increase in fossil fuel use (39). This finding implies a recent increase in terrestrial and/or oceanic sinks for CO<sub>2</sub>, which may be temporary. The largest annual increase of CO<sub>2</sub>, 2.7 ppm, occurred in 1998. The annual increase was 2.1 ppm in 1999, although the growth rate had decreased to 1.3 ppm/year by the end of the year.

**Methane.** A dramatic growth rate change has occurred for CH<sub>4</sub> (Fig. 3B). The small interannual variability of CH<sub>4</sub> before 1982 reflects smoothing inherent in ice core data (37). Factors that may have slowed the CH<sub>4</sub> growth rate are recognized, as discussed below, but most of them are not accurately quantified.

**CFCs.** The growth rate of the two principal CFCs is near zero (Fig. 3C) and will be negative in the future as a result of production restrictions imposed by the Montreal Protocol (40). Other CFCs together cause a climate forcing that may approach that of CFC-12 early in the twenty-first century (4, 41). But most of these are being phased out, and, assuming compliance with

production agreements (42), the net change in CFC climate forcing in the next 50 years will be small, as discussed below.

### The Three Largest Climate Forcings

The largest anthropogenic climate forcings, by CO<sub>2</sub>, CH<sub>4</sub>, and aerosols (Fig. 1), pose the greatest uncertainties in attempts to project future climate change.

**Carbon Dioxide.** Coal and oil are now about equal sources of CO<sub>2</sub> emissions (Fig. 4). Coal is the source of potentially large future emissions, as its known resources are an order of magnitude greater than those of either oil or gas (43). Coal use has declined in much of the world, but it has been increasing in the United States and China (39, 43).

The increase in atmospheric CO<sub>2</sub> in recent decades (Fig. 2) represents about half of the emissions from fossil fuels and changes in tropical land use; the remaining CO<sub>2</sub> from these sources is taken up by the ocean, terrestrial biosphere, and soils. The flat growth rate of CO<sub>2</sub> forcing, despite increased emissions, is at least in part a reflection of increased terrestrial sequestration of carbon in the 1990s (44). The slowing growth rate of emissions may itself allow a higher proportion of CO<sub>2</sub> emissions to be sequestered. Thus the prognosis for future sequestration is uncertain, but maintenance of a flat growth rate of CO<sub>2</sub> forcing surely requires a flattening of the growth rate of fossil fuel emissions, which have grown 1.2%/year since 1975 (Fig. 4).

**Methane.** The decline in the CH<sub>4</sub> growth rate (Fig. 3B) probably is caused in part by changes of chemical emissions (such as CO and NO<sub>x</sub>) that affect OH, the primary sink for CH<sub>4</sub> (19, 45, 46). However, a reduced growth rate of CH<sub>4</sub> sources also may be involved (37, 47). The short lifetime of CH<sub>4</sub>, about 8 years, means that a reduction of several percent in a major source could have

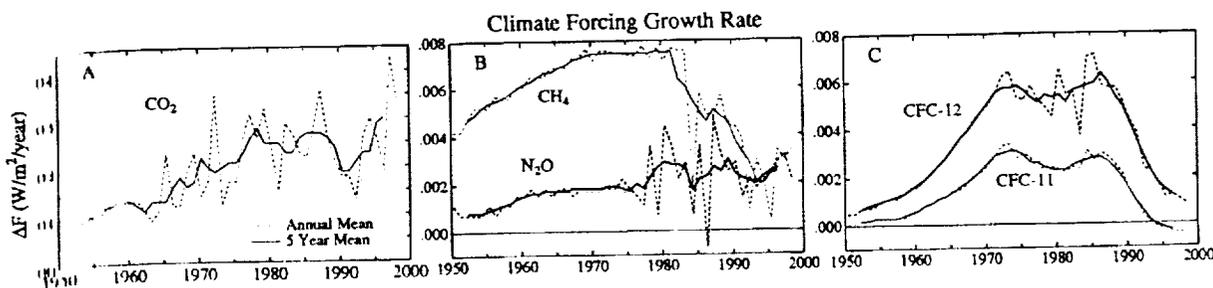


Fig. 3. Growth rates of climate forcings by individual GHGs—CO<sub>2</sub> (A), CH<sub>4</sub> and N<sub>2</sub>O (B), and CFC-11 and CFC-12 (C)—based on trace gas data available from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory.

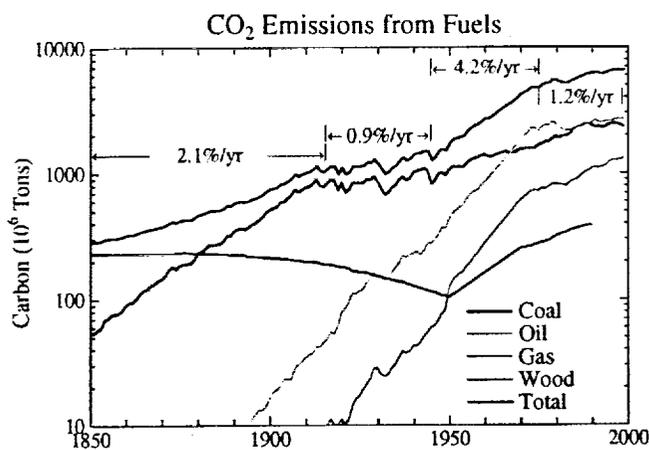


Fig. 4. CO<sub>2</sub> emissions from fuel use (40). The estimate for wood is by N. Makarova (The Rockefeller University; personal communication).

caused the reduced growth rate of CH<sub>4</sub>. Sources and sinks of CH<sub>4</sub> are not known to that accuracy (19, 45, 48).

The primary natural source of CH<sub>4</sub> is microbial decay of organic matter under anoxic conditions in wetlands (45, 49). Anthropogenic sources, which in sum may be twice as great as the natural source (45), 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. Global warming could cause the natural wetland source to increase (49), but if warming causes a drying of wetlands, it might reduce the CH<sub>4</sub> source.

**Aerosols.** Climate forcing by anthropogenic aerosols may be the largest source of uncertainty about future climate change. The approximate global balancing of aerosol and CO<sub>2</sub> forcings in the past (Fig. 1) cannot continue indefinitely. As long-lived CO<sub>2</sub> accumulates, continued balancing requires a greater and greater aerosol load. Such a solution, we have argued (30), would be a Faustian bargain. Detrimental effects of aerosols, including acid rain and health impacts, will eventually limit the permissible atmospheric aerosol amount and thus expose latent greenhouse warming.

We do not even know the sign of the current trend of aerosol forcing, because such information would require knowledge of the trends of different aerosol compositions. Direct aerosol forcing depends on aerosol single scattering albedo (5, 50) and thus on the amount of absorbing constituents. Indirect aerosol forcing also depends on aerosol absorption, through the semi-direct effect on cloud cover (5) and the cloud particle single scattering albedo. Calculations for cloud particles with imbedded black carbon cores (51) suggest an effect on cloud albedo at distances up to 1,000 km from the carbon aerosol source.

### An Alternative Scenario

Let us propose a climate forcing scenario for the next 50 years that adds little forcing (Fig. 5), less than or about 1 W/m<sup>2</sup>, and then ask whether the elements of the scenario are plausible. The next 50 years is the most difficult time to affect CO<sub>2</sub> emissions, because of the inertia of global energy systems, as evidenced by Fig. 4. The essence of the strategy is to halt and even reverse the growth of non-CO<sub>2</sub> GHGs and to reduce black carbon emissions. Such a strategy would mitigate an inevitable, even if slowing, growth of CO<sub>2</sub>. By midcentury improved energy efficiency and advanced technologies, perhaps including hydrogen-powered fuel cells, should allow policy options with reduced reliance on fossil fuels and, if necessary, CO<sub>2</sub> sequestration.

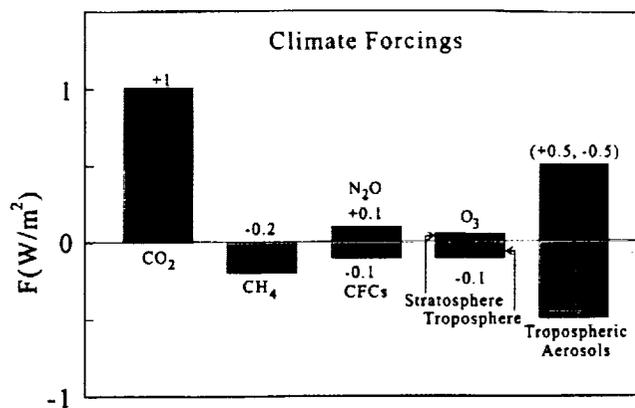


Fig. 5. A scenario for additional climate forcings between 2000 and 2050. Reduction of black carbon moves the aerosol forcing to lower values.

**Carbon Dioxide.** This scenario calls for the mean CO<sub>2</sub> growth rate in the next 50 years to be about the same as in the past two decades. The additional forcing in 50 years is about 1 W/m<sup>2</sup> for an average annual CO<sub>2</sub> increment of 1.5 ppm.

Is such a CO<sub>2</sub> growth rate plausible? We note that the CO<sub>2</sub> growth rate increased little in the past 20 years, while much of the developing world had rapid economic growth. The United States also had strong growth with little emphasis on energy efficiency, indeed with increasing use of energy-inefficient sports utility vehicles. This fact suggests that there are opportunities to achieve reduced emissions consistent with strong economic growth. Limiting CO<sub>2</sub> growth to 75 ppm in the next 50 years probably requires a moderate decrease in CO<sub>2</sub> emission rates, as continuation of high terrestrial sequestration of CO<sub>2</sub> is uncertain.

In the near term (2000–2025) this scenario can be achieved by improved energy efficiency and a continued trend toward decarbonization of energy sources, e.g., increased use of gas instead of coal. Technologies for improved efficiency exist (ref. 52; available at [www.natcap.org](http://www.natcap.org)), and implementation can be driven by economic self-interest, but governments need to remove barriers that discourage buying of energy efficiency (53). Business-as-usual scenarios often understate a long-term trend toward decarbonization of the energy supply (figure 8 in ref. 54), but the IPCC *Special Report on Emissions Scenarios* (9) includes a subset that is consistent with our CO<sub>2</sub> scenario.

In the longer term (2025–2050) attainment of a decreasing CO<sub>2</sub> growth rate will require greater use of energy sources that produce little or no CO<sub>2</sub>. Some renewable energy systems will be developed without concern for climate. But if such systems are to play a substantial role by the second quarter of the century, it is important to foster research and development investments now in generic technologies at the interface between energy supply and end use—e.g., gas turbines, fuel cells, and photovoltaics (43).

**Methane.** Our scenario aims for a forcing of  $-0.2$  W/m<sup>2</sup> for CH<sub>4</sub> change in the next 50 years. This goal requires the reduction of anthropogenic CH<sub>4</sub> sources by about 30%. Most CH<sub>4</sub> sources are susceptible to reductions, many in ways that are otherwise beneficial (55, 56). Reduction of CH<sub>4</sub> would have the added benefit of increasing atmospheric OH and reducing tropospheric O<sub>3</sub>, a pollutant that is harmful to human health and agriculture (57).

The amount of CH<sub>4</sub> produced by rice cultivation, perhaps the largest anthropogenic source, depends on cultivar choice (58), irrigation management (59), and fertilization (60). Mitigation strategies that maintain yields include intermittent irrigation

(61), with the added advantage of reducing plant pests and malaria-carrying mosquitoes. Ruminants offer substantial potential for emission reduction via dietary adjustments (62), as the farmer's objective is to produce meat, milk, or power from the carbon in their feed, not CH<sub>4</sub>. CH<sub>4</sub> losses from leaky natural gas distribution lines could be reduced, especially in the former Soviet Union, which is served by an old system that was built without financial incentives to reduce losses (63). Similarly, CH<sub>4</sub> escaping from landfills, coal mining and oil drilling sites, and anaerobic waste management lagoons can be reduced or captured, with economic benefits that partially or totally offset the costs (56).

The economic benefits of CH<sub>4</sub> capture probably are insufficient to bring about the 30% CH<sub>4</sub> reduction that we suggest. But with additional incentives—e.g., as part of multigas strategies for limiting GHG climate forcing (64)—a 30% reduction in CH<sub>4</sub> sources seems reasonable. In addition, it will be necessary to avoid new large CH<sub>4</sub> sources. For example, in new pipeline distribution systems in Asia it will be important to use technology that minimizes losses.

The pollutant carbon monoxide (CO) contributes to increased CH<sub>4</sub> and O<sub>3</sub> through its effect on OH (65, 66). A small downward trend in atmospheric CO has occurred in recent years, apparently as a result of pollution control in Western countries (67). More widespread use of advanced technologies that reduce CO emissions will help achieve CH<sub>4</sub> and O<sub>3</sub> reductions.

**CFCs.** The Montreal Protocol is aimed at reversing stratospheric ozone depletion. A secondary benefit is reduction of climate forcing by the controlled gases. If production phase-out follows the current plan (40), the forcing by controlled gases will be about 0.15 W/m<sup>2</sup> less in 2050 than at present, primarily because of declining amounts of CFC-12 and CFC-11. Uncontrolled gases, some of which are substitutes for ozone-depleting chemicals, are likely to increase and cause a positive forcing of about that same magnitude in the next 50 years; the largest contributor to this forcing is HFC-134a (chapter 2 of ref. 4).

Verification of the CFC phase-out requires continuing attention and atmospheric monitoring (42), but overall the protocol has been a model of international environmental cooperation. The Protocol's Multilateral Fund recently approved \$150 million for China and \$82 million for India, the two largest remaining producers, for complete phase-out of their CFC production (40). The cost of the fund over a decade was about \$1 billion (40).

At present the net change in climate forcing by these gases over the next 50 years is expected to be about zero. If the phase-out were extended to include additional gases, such as HFC-134a, and destruction of the accessible bank of CFC-12, a negative forcing change of -0.1 W/m<sup>2</sup> would seem possible.

**Tropospheric Ozone.** Climate forcing by anthropogenic tropospheric O<sub>3</sub> is now  $0.4 \pm 0.15$  W/m<sup>2</sup> (4, 6). Principal precursor emissions are volatile organic compounds and nitrogen oxides (NO<sub>x</sub>) (57, 68). Primary sources of the precursors are transportation vehicles, power plants, and industrial processes (57). Business-as-usual scenarios have O<sub>3</sub> continuing to increase in the future (4, 68). Because O<sub>3</sub> in the free troposphere can have a lifetime of weeks, tropospheric O<sub>3</sub> 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 O<sub>3</sub> 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/year in the United States alone.

Despite limited success of past attempts to reduce O<sub>3</sub> (57), the human and ecological costs of this pollutant suggest that it should be a target for international cooperation in the next half-century. Air pollution in some Asian regions is already extreme, with high ecological and health costs. Unlike the Kyoto

negotiations on CO<sub>2</sub> emissions, which cast the developed and developing worlds as adversaries, all parties should have congruent objectives regarding O<sub>3</sub>. Analogous to the approach to CFCs, sharing of technology may have mutual environmental and economic benefits.

Tropospheric O<sub>3</sub> is decreasing downwind of regions such as Western Europe, where NO<sub>x</sub> emissions are controlled (67), but increasing downwind of East Asia (69). There is a clear potential for cleaner energy sources and improved combustion technology to achieve an O<sub>3</sub> reduction. Our scenario assumes that a small reduction of tropospheric O<sub>3</sub> forcing, at least sufficient to balance the expected rebound of stratospheric O<sub>3</sub>, is plausible by 2050.

**Aerosols.** Aerosols, unlike GHGs, are not monitored to an accuracy defining their global forcing and its temporal change. It is often assumed (4) that aerosol forcing will become more negative in the future, which would be true if all aerosols were to increase in present proportions. However, it is just as likely that aerosol forcing will become less negative. Such an outcome is possible, e.g., if nonabsorbing sulfates decrease because of regulations aimed at reducing acid rain.

Black carbon reduces aerosol albedo, causes a semidirect reduction of cloud cover, and reduces cloud particle albedo. All of these effects cause warming. Conceivably a reduction of climate forcing by 0.5 W/m<sup>2</sup> or more could be obtained by reducing black carbon emissions from diesel fuel and coal. This reduction might become easier in the future, with more energy provided via electricity grids from power plants (43). But a quantitative understanding of the role of absorbing aerosol in climate change is required to formulate reliable policy recommendations.

Aerosols have to be monitored globally, thus by satellite, because of their heterogeneity. Measurements must yield precise aerosol optical depth, size distribution, and composition to define the direct forcing and provide data to analyze indirect effects. Such measurements are possible with precision multi-spectral (UV to infrared) polarimetry, with each region viewed over a wide range of angles (70). These data should be accompanied by visible imaging for scene definition and infrared interferometry to yield a temperature profile and cloud properties. Simultaneous lidar data could provide precise vertical profiles of the aerosols.

### Summary

Business-as-usual scenarios provide a useful warning about the potential for human-made climate change. Our analysis of climate forcings suggests, as a strategy to slow global warming, an alternative scenario focused on reducing non-CO<sub>2</sub> GHGs and black carbon (soot) aerosols. Investments in technology to improve energy efficiency and develop nonfossil energy sources are also needed to slow the growth of CO<sub>2</sub> emissions and expand future policy options.

A key feature of this strategy is its focus on air pollution, especially aerosols and tropospheric ozone, which have human health and ecological impacts. If the World Bank were to support investments in modern technology and air quality control in India and China, for example, the reductions in tropospheric ozone and black carbon would not only improve local health and agricultural productivity but also benefit global climate and air quality.

**Non-CO<sub>2</sub> GHGs.** These gases are probably the main cause of observed global warming, with CH<sub>4</sub> causing the largest net climate forcing. There are economic incentives to reduce or capture CH<sub>4</sub> emissions, but global implementation of appropriate practices requires international cooperation. Definition of

appropriate policies requires better understanding of the CH<sub>4</sub> cycle, especially CH<sub>4</sub> sources.

Climate forcing by CFCs and related chemicals is still growing today, but if Montreal Protocol restrictions are adhered to, there should be no net growth in this forcing over the next 50 years. A small decrease from today's forcing level is possible, at least comparable in magnitude to the expected small rebound in stratospheric O<sub>3</sub> forcing.

Tropospheric O<sub>3</sub> increases in business-as-usual scenarios, which assume that CH<sub>4</sub> increases and that there is no global effort to control O<sub>3</sub> precursors. Despite limited success in past efforts to reduce O<sub>3</sub>, the human health and ecological impacts of O<sub>3</sub> are so great that it represents an opportunity for international cooperation. At least it should be possible to prevent tropospheric O<sub>3</sub> forcing in 2050 from exceeding that of today.

**Carbon Dioxide.** CO<sub>2</sub> will become the dominant climate forcing, if its emissions continue to increase and aerosol effects level off. Business-as-usual scenarios understate the potential for CO<sub>2</sub> emission reductions from improved energy efficiency and decarbonization of fuels. Based on this potential and current CO<sub>2</sub> growth trends, we argue that limiting the CO<sub>2</sub> forcing increase to 1 W/m<sup>2</sup> in the next 50 years is plausible.

Indeed, CO<sub>2</sub> emissions from fossil fuel use declined slightly in

1998 and again in 1999 (71), while the global economy grew. However, achieving the level of emissions needed to slow climate change significantly is likely to require policies that encourage technological developments to accelerate energy efficiency and decarbonization trends.

**Aerosols.** Climate forcing due to aerosol changes is a wild card. Current trends, even the sign of the effect, are uncertain. Unless climate forcings by all aerosols are precisely monitored, it will be difficult to define optimum policies.

We argue that black carbon aerosols, by means of several effects, contribute significantly to global warming. This conclusion suggests one antidote to global warming, if it becomes a major problem. As electricity plays an increasing role in future energy systems, it should be relatively easy to strip black carbon emissions at fossil fuel power plants. Stripping and disposal of CO<sub>2</sub>, although more challenging, provide an effective backup strategy.

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- Hansen, J., Ruedy, R., Glascoe, J. & Sato, M. (1999) *J. Geophys. Res.* **104**, 30997–31022.
- Jones, P. D., New, M., Parker, D. E., Martin, S. & Rigor, I. G. (1999) *Rev. Geophys.* **37**, 173–199.
- Mann, M. E., Bradley, R. S. & Hughes, M. K. (1999) *Geophys. Res. Lett.* **26**, 759–762.
- Intergovernmental Panel on Climate Change (1996) *Climate Change 1995*, eds. Houghton J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. & Maskell, K. (Cambridge Univ. Press, Cambridge, U.K.).
- Hansen, J., Sato, M. & Ruedy, R. (1997) *J. Geophys. Res.* **102**, 6831–6864.
- Hansen, J., Sato, M., Laci, A., Ruedy, R., Tegen, I. & Matthews, E. (1998) *Proc. Natl. Acad. Sci. USA* **95**, 12753–12758.
- Levitus, S., Antonov, J. I., Boyer, T. P. & Stephens, C. (2000) *Science* **287**, 2225–2229.
- Hansen, J., Sato, M., Ruedy, R., Laci, A., Asamoah, K., Beckford, K., Borenstein, S., Brown, E., Cairns, B., Carlson, B., et al. (1997) *J. Geophys. Res.* **102**, 25679–25720.
- Nakicenovic, N., Davidson, O., Davis, G., Grubler, A., Kram, T., La Rovere, E. L., Metz, B., Morita, T., Pepper, W., Pitcher, H., et al. (2000) *Special Report on Emissions Scenarios* (Cambridge Univ. Press, Cambridge, U.K.).
- Supplee, C. & Pinneo, J. B. (1998) *Natl. Geogr.* **193**, 38–71.
- Manabe, S. & Wetherald, R. (1975) *J. Atmos. Sci.* **32**, 3–15.
- Charney, J. (1979) *Carbon Dioxide and Climate* (Natl. Acad. Press, Washington, DC).
- Hansen, J., Ruedy, R., Laci, A., Sato, M., Nazarenko, L., Tausnev, N., Tegen, I. & Koch, D. (2000) in *General Circulation Model Development*, ed. Randall, D. (Academic, New York), pp. 127–164.
- Bolin, B. (1998) *Science* **279**, 330–331.
- Wigley, T. M. L. (1998) *Geophys. Res. Lett.* **25**, 2285–2288.
- Malakoff, D. (1997) *Science* **278**, 2048.
- Hansen, J., Fung, I., Laci, A., Rind, D., Lebedeff, S., Ruedy, R., Russell, G. & Stone, P. (1988) *J. Geophys. Res.* **93**, 9341–9364.
- Rothman, L., Rinsland, C., Goldman, A., Massie, S., Edwards, D., Flaud, J., Perrin, A., Camy-Peyret, C., Dana, V., Mandin, J., et al. (1998) *J. Quant. Spec. Rad. Trans.* **60**, 665–710.
- Lelieveld, J., Crutzen, P. J. & Dentener, F. J. (1998) *Tellus* **50B**, 128–150.
- Shindell, D. (2000) *Geophys. Res. Lett.*, in press.
- Forster, P. M. de F. & Shine, K. P. (1999) *Geophys. Res. Lett.* **26**, 3309–3312.
- World Meteorological Organization (1999) *Scientific Assessment of Ozone Depletion: Global Ozone Research and Monitoring Project*, Report 44 (World Meteorological Organization, Geneva).
- Andreae, M. (1995) in *World Survey of Climatology*, ed. Henderson-Sellers, A. (Elsevier, Amsterdam), Vol. 16, pp. 347–398.
- Twomey, S. A. (1991) *Atmos. Environ.* **25A**, 2435–2442.
- Albrecht, B. A. (1989) *Science* **245**, 1227–1230.
- Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A., Hansen, J. E. & Hofmann, D. J. (1992) *Science* **255**, 423–430.
- Chuang, C. C., Penner, J. E., Taylor, K. E., Grossman, A. S. & Walton, J. J. (1997) *J. Geophys. Res.* **102**, 3761–3778.
- Kiehl, J. T., Schneider, T. L., Rasch, P. J., Barth, M. C. & Wong, J. (2000) *J. Geophys. Res.* **105**, 1441–1457.
- Mitchell, J. M. (1975) in *The Changing Global Environment*, ed. Singer, S. F. (Reidel, Dordrecht, the Netherlands), pp. 149–173.
- Hansen, J. E. & Laci, A. A. (1990) *Nature (London)* **346**, 713–719.
- Wigley, T. M. L. (1991) *Nature (London)* **349**, 503–506.
- Hansen, J., Laci, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. & Lerner, J. (1984) in *Climate Processes and Climate Sensitivity*, eds. Hansen, J. E. & Takahashi, T. (Am. Geophys. Union, Washington, DC), Vol. 29, pp. 130–163.
- Hoffert, M. I. & Covey, C. (1992) *Nature (London)* **360**, 573–576.
- Hansen, J., Russell, G., Laci, A., Fung, I., Rind, D. & Stone, P. (1985) *Science* **229**, 857–859.
- Hansen, J., Laci, A., Ruedy, R., Sato, M. & Wilson, H. (1993) *Natl. Geograph. Res. Explor.* **9**, 142–158.
- Douglas, B. C. (1997) *Surveys Geophys.* **18**, 279–292.
- Etheridge, D. M., Steele, L. P., Francey, R. J. & Langenfelds, R. L. (1998) *J. Geophys. Res.* **103**, 15979–15993.
- Mitchell, J. F. B. & Gregory, J. M. (1992) *Annex in Climate Change 1992*, eds. Houghton, J. T., Callander, B. A. & Varney, S. K. (Cambridge Univ. Press, Cambridge, U.K.).
- Marland, G. & Boden, T. (1998) *CO<sub>2</sub> Information Center* (Oak Ridge Natl. Lab., Oak Ridge, TN).
- Report of the Eleventh Meeting of the Parties to the Montreal Protocol on Substances That Deplete the Ozone Layer (United Nations Environmental Programme, New York).
- Christidis, N., Hurley, M. D., Pinnock, S., Shine, K. P. & Wallington, T. J. (1997) *J. Geophys. Res.* **102**, 19597–19609.
- Fraser, P. J. & Prather, M. J. (1999) *Nature (London)* **398**, 663–664.
- Nakicenovic, N., Grubler, A. & McDonald, A. (1998) *Global Energy Perspectives* (Cambridge Univ. Press, Cambridge, U.K.).
- Battle, M., Bender, M. L., Tans, P. P., White, J. W. C., Ellis, J. T., Conway, T. & Francey, R. J. (2000) *Science* **287**, 2467–2470.
- Cicerone, R. J. & Oremland, R. S. (1988) *Global Biogeo. Cycles* **2**, 299–327.
- Karlsdottir, S. & Isaksen, I. S. A. (2000) *Geophys. Res. Lett.* **27**, 93–96.
- Dlugokencky, E. J., Masarie, K. A., Lang, P. M. & Tans, P. P. (1998) *Nature (London)* **393**, 447–450.
- Fung, I., John, J., Lerner, J., Matthews, E., Prather, M., Steele, L. P. & Fraser, P. J. (1991) *J. Geophys. Res.* **96**, 13033–13065.
- Matthews, E. (2000) in *Atmospheric Methane*, ed. Khalil, M. A. K. (Springer, Berlin), pp. 202–233.
- Hansen, J., Sato, M., Laci, A. & Ruedy, R. (1997) *Philos. Trans. R. Soc. London B* **352**, 231–240.
- Heintzenberg, J. & Wendisch, M. (1996) *Beitr. Phys. Atmos.* **69**, 491–499.
- Hawken, P., Lovins, A. & Lovins, L. H. (1999) *Natural Capitalism* (Little, Brown, New York).
- Lovins, A. B. & Lovins, L. H. (1997) *Climate: Making Sense and Making Money* (Rocky Mountain Institute, Snowmass, CO).
- Ausubel, J. H. (1995) *Energy Policy* **23**, 411–416.
- Hogan, K. B., Hoffman, J. S. & Thompson, A. M. (1991) *Nature (London)* **354**, 181–182.
- Hogan, K. B. (1993) *Options for Reducing Methane Emissions Internationally*, U.S. EPA Report to Congress (Environmental Protection Agency, Washington, DC).
- McKee, D. J. (1994) *Tropospheric Ozone* (Lewis, Boca Raton, FL).
- Denier Van der Gon, H. (2000) *Global Biogeo. Cycles* **14**, 61–72.
- Sass, R. L., Fisher, F. M., Wang, Y. B., Turner, F. T. & Jund, M. F. (1992) *Global Biogeo. Cycles* **6**, 249–262.
- Schmidt, J. (2000) *Nature (London)* **403**, 375–376.
- Neue, H. U. & Roger, P. A. (1993) in *Atmospheric Methane*, ed. Khalil, M. A. K. (Springer, Berlin), pp. 254–298.
- McCrabb, G. J., Berger, K. T., Magner, T., May, C. & Hunter, R. A. (1997) *Aust. J. Agric. Res.* **48**, 323–329.
- Reshetnikov, A. I., Paramonova, N. N. & Shashkov, A. A. (2000) *J. Geophys. Res.* **105**, 3517–3529.
- Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Mellilo, J., Stone, P., Sokolov, A. & Wang, C. (1999) *Nature (London)* **401**, 549–555.
- Thompson, A. M. & Cicerone, R. J. (1986) *J. Geophys. Res.* **91**, 10853–10864.
- Prather, M. J. (1996) *Geophys. Res. Lett.* **23**, 2597–2600.
- Simmonds, P. G., Seuring, S., Nickless, G. & Derwent, R. G. (1997) *J. Atmos. Chem.* **28**, 45–59.
- Lelieveld, J. & Dentener, F. J. (2000) *J. Geophys. Res.* **105**, 3531–3551.
- Lee, S., Akimoto, H., Nakane, H., Kurosenko, S. & Kinjo, Y. (1998) *Geophys. Res. Lett.* **25**, 1637–1640.
- Hansen, J., Rossow, W., Carlson, B., Laci, A., Travis, L., Del Genio, A., Fung, I., Cairns, B., Mishchenko, M. & Sato, M. (1995) *Clim. Change* **31**, 247–271.
- Brown, L. R., Renner, M. & Halwell, B. (2000) *Vital Signs 2000* (Norton, New York).