16

Global warming in the 21st century: an alternate scenario

15Jun00

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Contributed by James E. Hansen, Month day, 2000

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ABSTRACT 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 by non-CO_2 greenhouse gases (GHGs), such as CFCs, CH_4 and N_2O, not by the products of fossil fuel burning, CO_2 and aerosols, whose positive and negative climate forcings are partially offsetting. The growth rate of non-CO_2 GHGs has declined in the past decade. If sources of CH_4 and O_3 precursors were reduced in the future, the change of climate forcing by non-CO_2 GHGs in the next 50 years could be near zero. Combined with a reduction of black carbon emissions and plausible success in slowing CO_2 emissions, this 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.

Global surface temperature has increased about 0.5°C since 1975 (1,2), a burst of warming that has taken 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; ref. 4) considers a range of scenarios for future GHGs, which is further expanded in their Special Report on Emissions Scenarios (SRES; ref 9). Yet global warming simulations have focused on "business as usual" scenarios with rapidly increasing GHGs. These scenarios yield a steep, relentless increase of global temperature throughout the 21st century (4, 10) with warming of several degrees Celsius by 2100, if climate sensitivity is 2-4°C for doubled CO_2, as climate models suggest (4, 11, 12, 13). This can leave the impression that curtailment of global warming is almost hopeless. The 1997 Kyoto Protocol, which calls for industrialized nations to reduce their CO_2 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 21st century (15), and "thirty Kyotos" may be needed to reduce warming to an acceptable level (16).

We suggest equal emphasis on an alternate, more optimistic, scenario. This scenario focuses on reducing non-CO_2 GHGs and black carbon during the next 50 years. Our estimates of global climate forcings indicate that it is the processes producing non-CO_2 GHGs, rather than fossil fuel burning, that have caused observed global warming. This interpretation does not alter the desirability of limiting CO_2 emissions, because the future balance of forcings is likely to shift toward dominance of CO_2 over aerosols. However, we suggest that it is more practical to slow global warming than is sometimes assumed.

Climate forcings in the industrial era

Estimated climate forcings since 1850 are shown in Fig. 1, similar to previous presentations (4, 6). Forcings for specific GHGs differ as much as several percent from values we estimated earlier: CO_2 (-1%), CH_4 (+2%), N_2O (-3%), CFC-11(+6%) and CFC-12 (+8%). Our prior results, employed by 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_2, CH_4 and CFCs in Fig. 1, because they are produced by different processes and have different growth rates. We associate with CH_4 its indirect effects on tropospheric O_3 and stratospheric H_2O to make clear the importance of CH_4 as a climate forcing. We assume that ¼ of the 0.4 W/m^2 climate forcing due to increasing tropospheric O_3 is caused by increasing CH_4 (chap. 2 of ref. 4, 19). We calculate an indirect effect of 0.1 W/m^2 for CH_4 oxidized to H_2O in the stratosphere (20). The recent trend of stratospheric H_2O (20, 21) is even larger than CH_4 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_3 depletion, -0.1 W/m^2, is smaller than the -0.2 W/m^2 that we used earlier (6) because of changes in the vertical profile of O_3 depletion estimated from observations. O_3 trends recommended by WMO (22) have less depletion in the tropopause region (where O_3 loss causes surface cooling) and greater loss in the middle stratosphere (where O_3 loss causes surface warming) compared with the O_3 changes that we used previously (5, 6).

Climate forcing by CO_2 is the largest forcing, but it does not dwarf the others (Fig. 1). Forcing by CH_4 (0.7 W/m^2) is half as large as that of CO_2 and the total forcing by non-CO_2 GHGs (1.4 W/m^2) equals that of CO_2. Moreover, in comparing forcings due to different activities, we must note that the fossil fuels producing most of the CO_2 are also the main source of aerosols, especially sulfates, black carbon, and organic aerosols (4, 23).

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 also cause a semi-direct forcing by heating the atmosphere, thus reducing large-scale cloud cover (5). The semi-direct effect is implicitly included in the forced cloud change, if the evaluation includes the change of aerosol and cloud particle single-scattering albedos (the fraction of light hitting the particle that is reflected) and the resulting impact on cloud cover.

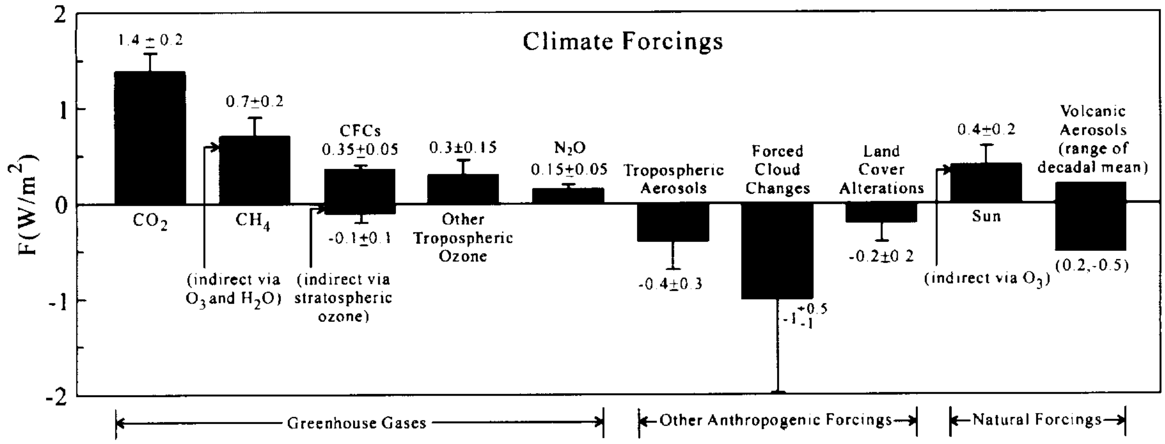

Fig. 1. Estimated climate forcings between 1850 and 2000.

Forcing by atmospheric aerosols is uncertain, but research of the past decade indicates that it is substantial (4, 26, 27, 28). The aerosol forcing that we estimate (6) has the same magnitude (1.4 W/m^2) but opposite sign of the CO_2 forcing. Fossil fuel use is the main source of both CO_2 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_2 in the past century probably is much less than 1.4 W/m^2. This partial offsetting of aerosol and greenhouse forcings has been discussed (29, 30, 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_2 GHGs (1.4 W/m^2) is nearly equal to the net value of all known forcings for the period 1850-2000 (1.6 W/m^2). Thus, assuming only that our estimates are approximately correct, we assert that the processes producing the non-CO_2 GHGs have been the primary drive for climate change in the past century.

Consistency checks. Two empirical pieces of information are consistent with our estimated net climate forcing: (1) global warming of the past century, and (2) 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_2 (a forcing of about 4 W/m^2) is 3±1°C (thus ¾ ± ¼ °C per W/m^2). This 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 observed global warming of ¾ °C since the late 1800s is consistent with the equilibrium warming of 1.2°C that a forcing of 1.6 W/m^2 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 ± 0.1 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 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 2×10^{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 of 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^2 averaged over the Earth's surface for that period (7). This 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 increasing from near zero in the 1950s to a mean of 0.5 W/m^2 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.

Table 1. Greenhouse gas radiative forcings.

Gas	Radiative forcing
CO_2	$F = f(c) - f(c_o)$, where $f(c) = 4.996\,\ln(c + 0.0005c^2)$
CH_4	$F = 0.0406(\sqrt{m} - \sqrt{m_o}) - [g(m,n_o) - g(m_o,n_o)]$
N_2O	$F = 0.136(\sqrt{n} - \sqrt{n_o}) - [g(m_o, n) - g(m_o,n_o)]$ where $g(m,n) = 0.5\,\ln[1 + 2\times10^{-5}(mn)^{0.75}]$
CFC-11	$F = 0.264(x - x_o)$
CFC-12	$F = 0.323(y - y_o)$

c, CO_2 (ppm); m, CH_4 (ppb); n, N_2O (ppb); x/y, CFC-11/12 (ppb).

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_2 and CH_4 - are shown in Fig. 2. IPCC IS92 scenarios (chap. 2, 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 GHGs including CFCs was already a 15% reduction from the principal 1990 IPCC scenario (38). The observed increase of CH_4 in the 1990s falls below the lowest IS92 scenario, while CO_2 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_2 and CH_4 amounts for 1999 were kindly provided by Ed Dlugokencky and Tom Conway of the NOAA Climate Monitoring and Diagnostics Laboratory (priv. comm.).

Carbon dioxide. The growth rate of forcing by CO_2 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 implies a recent increase of terrestrial and/or oceanic sinks for CO_2, which may be temporary. The largest annual increase of CO_2, 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_4 (Fig. 3B). The small interannual variability of CH_4 prior to

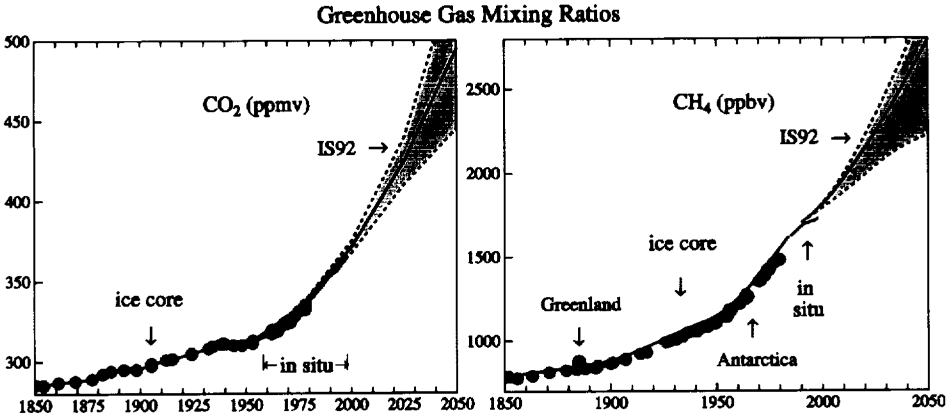

Fig. 2. Atmospheric CO_2 and CH_4 observations and range of IS92 scenarios (solid line is IS92a).

1982 reflects smoothing inherent in ice core data (37). Factors that may have slowed the CH_4 growth rate are recognized, as discussed below, but most of them are not accurately quantified.

Chlorofluorocarbons. 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 21st century (4, 41). But most of these are being phased out and, assuming compliance with production agreements (42), the net change of 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_2, CH_4 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_2 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 is increasing in the United States and China (39, 43).

The increase of atmospheric CO_2 in recent decades (Fig. 2) is about half of emissions from fossil fuels and tropical land use change, the remaining CO_2 being taken up by the ocean, terrestrial biosphere, and soils. The flat growth rate of CO_2 forcing, despite increased emissions, is at least in part a reflection of increased terrestrial sequestration of carbon in the 1990s (44). The prognosis for future sequestration is uncertain, but it is unlikely that a flat growth rate of CO_2 forcing can be maintained without a flattening of the growth rate of fossil fuel emissions, which have grown 1.2%/year since 1975 (Fig. 4).

Methane. A fraction of the decline of the CH_4 growth rate (Fig. 3B) may be due to stratospheric ozone depletion, which permits penetration of ultraviolet radiation into the troposphere and thus more production of OH, the primary sink for CH_4 (19, 45). But the principal reason is probably a reduced growth rate of CH_4 sources (37). The short lifetime of CH_4, about 8 years, means that a reduction of several percent in a major source could have caused the reduced growth rate of CH_4. Sources and sinks of CH_4 are not known to that accuracy (19, 45, 46).

The primary natural source of CH_4 is microbial decay of organic matter under anoxic conditions in wetlands (45, 47). 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 (47, 48), but if warming causes a drying of wetlands, it might reduce the CH_4 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_2 forcings in the past (Fig. 1) cannot continue indefinitely. As long-lived CO_2 accumulates, continued balancing requires a greater and greater aerosol load. This, we have argued (30), would be a Faustian bargain. Detrimental effects of aerosols, including acid rain and health impacts, will eventually limit aerosol amount, and thus expose latent greenhouse warming.

We do not have observations that define even the sign of the current trend of aerosol forcing, because that requires the trends of different aerosol compositions. The direct aerosol forcing depends on aerosol single scattering albedo (5, 49), thus on the amount of absorbing constituents. The 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 (50, 51) reveal an effect on cloud albedo at distances up to 1000 km from the carbon aerosol source.

An alternate scenario

Let us propose a climate forcing scenario for the next 50 years that adds little forcing, less than or about 1 W/m^2, and then ask whether the elements of the scenario are plausible. The next

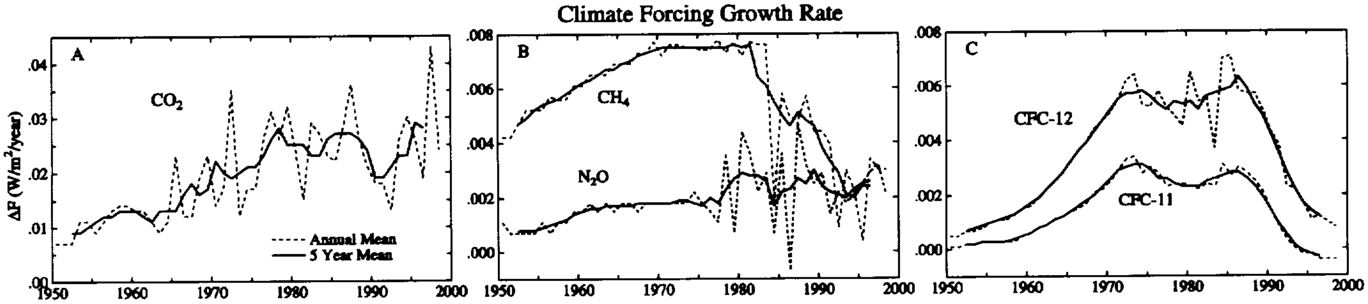

Fig. 3. Climate forcings by individual greenhouse gases: (A) CO_2, (B) CH_4, and N_2O), (C) CFC-11 and CFC-12, based on trace gas data available from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory.

50 years is the most difficult time to affect CO_2 emissions due to 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_2 GHGs and to reduce black carbon emissions. This will mitigate an inevitable, even if slowing, growth of CO_2. By mid-century 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_2 sequestration.

Carbon dioxide. This scenario calls for the mean CO_2 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^2 for an average annual CO_2 increment of 1.5 ppm.

Is such a CO_2 growth rate plausible? We note that the CO_2 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 suggests that there are opportunities to achieve reduced emissions consistent with strong economic growth. Limiting CO_2 growth to 75 ppm in the next 50 years probably requires a moderate decrease of CO_2 emission rates, as continuation of high terrestrial sequestration of CO_2 is uncertain.

In the near term (2000-2025) this scenario can be achieved via 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 (52) 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 (Fig. 8 of 54), but the IPCC SRES scenarios (9) include a subset that is consistent with our CO_2 scenario.

On the longer term (2025-2050) attainment of a decreasing CO_2 growth rate will require greater use of energy sources that produce little or no CO_2. 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 on 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^2 for CH_4 change in the next 50 years. This requires reducing anthropogenic CH_4 sources by about 30%. Most CH_4 sources are susceptible to reductions, many in ways that are otherwise beneficial (55, 56). Reduction of CH_4 would have the added benefit of increasing atmospheric OH and reducing tropospheric O_3, a pollutant that is harmful to human health and agriculture (57).

The amount of CH_4 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_4. CH_4 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_4 escaping at landfills, in coal and oil mining, and from anaerobic waste management lagoons, can be reduced or captured, with economic benefits that partially or totally offset the costs (56).

Economic benefits of CH_4 capture probably are insufficient to bring about the 30% CH_4 reduction that we suggest. But with additional incentives, e.g., as part of multi-gas strategies for limiting GHG climate forcing (64), a 30% reduction of CH_4 sources seems reasonable. In addition, it will be necessary to avoid new large CH_4 sources. For example, in new pipeline distribution systems in Asia it will be important to use technology that minimizes losses.

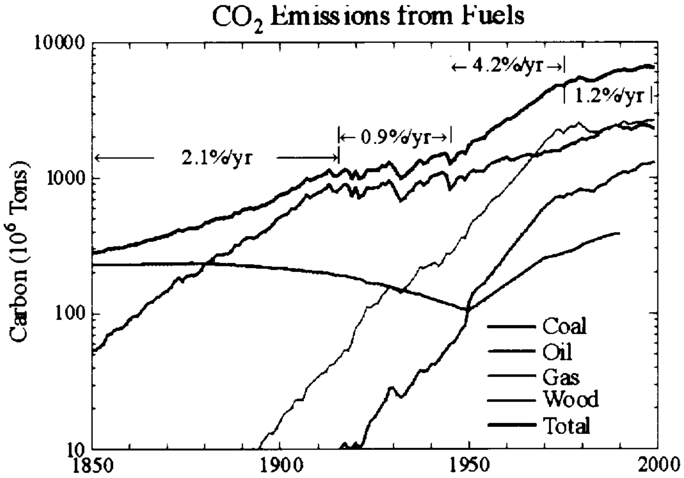

Fig.4. CO_2 emissions from fuel use (40): estimate for wood by N. Makarova, Rockefeller University.

The pollutant carbon monoxide (CO) contributes to increased CH_4 and O_3 through its effect on OH (65, 66). A small downward trend of CO has occurred in recent years, apparently a result of pollution control in Western countries (67). More widespread use of advanced technologies that reduce CO emissions will help achieve CH_4 and O_3 reductions.

Chlorofluorocarbons. The Montreal Protocol is aimed at reversing stratospheric ozone depletion. A secondary benefit is reduction of climate forcing by the controlled halocarbons. If production phase-out follows the current plan (40), the forcing by controlled gases will be about 0.15 W/m^2 less in 2050 than at present, primarily due to declining amounts of CFC-12 and CFC-11. Uncontrolled halocarbons, some of them substitutes for ozone-depleting chemicals, are likely to increase and cause a positive forcing of about that same magnitude in the next 50 years, with the largest contributor being HFC-134a (chap. 2 of 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 \$150M for China and \$82M 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 \$1B (40).

At present the net change in climate forcing by halocarbons over the next 50 years is expected to be about zero. If the halocarbon 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^2 seems possible.

Tropospheric ozone. Climate forcing by anthropogenic tropospheric O_3 is now 0.4±0.15 W/m^2 (4, 6). Principal precursor emissions are volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (57, 68). Primary sources of the precursors are transportation vehicles, power plants and industrial processes (57). Business-as-usual scenarios have O_3 continuing to increase in the future (4, 68). Because O_3 in the free troposphere can have a lifetime of weeks, tropospheric O_3 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_3 have adverse health and ecosystem effects. Annual costs of the impacts on human health and crop productivity are each estimated to be of the order of \$10B/year in the United States alone.

Despite limited success of past attempts to reduce O_3 (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_2 emissions, which cast the developed and developing worlds as adversaries, all parties should have congruent objectives regarding O_3. Analogous to the approach for CFCs, sharing of technology may have mutual environmental and economic benefits.

Tropospheric O_3 is decreasing downwind of regions such as Western Europe where NO_X emissions are controlled (67), but increasing downwind of Eastern Asia (69). There is a clear potential for cleaner energy sources and improved combustion technology to achieve an O_3 reduction. Our scenario assumes that a reduction of O_3 forcing by 0.1 W/m^2 is plausible by 2050, even with fossil fuels remaining the predominant energy source.

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 increased in present proportions. However, it is just as likely that aerosol forcing will become less negative. This can happen, e.g., if non-absorbing sulfates decrease because of regulations to reduce acid rain.

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

Aerosols need to be monitored globally, thus by satellite, because of their heterogeneity. Measurements must yield precise aerosol optical depth, size distribution, and composition in order to define the direct forcing and provide data to analyze indirect effects. This is possible with precision multispectral (ultraviolet 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 the 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 alternate scenario focused on reducing non-CO_2 GHGs and black carbon (soot) aerosols. Investments in technology to improve energy efficiency and develop non-fossil energy sources are also needed to slow the growth of CO_2 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, e.g., 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_2 GHGs. These gases are probably the main cause of observed global warming, with CH_4 causing the largest net climate forcing. There are economic incentives to reduce or capture CH_4 emissions, but global implementation of appropriate practices requires international cooperation. Definition of appropriate policies requires better understanding of the CH_4 cycle, especially CH_4 sources.

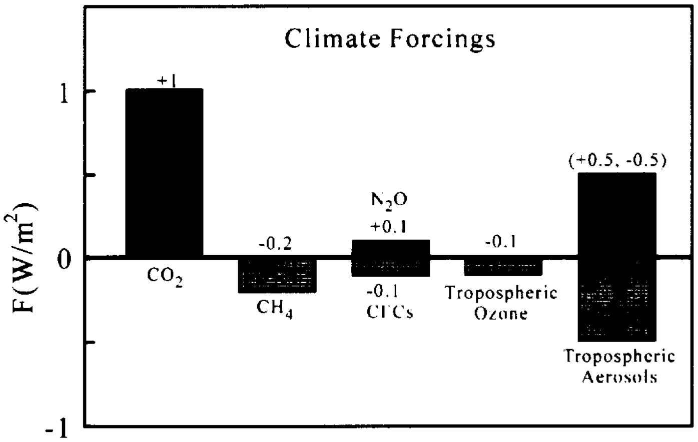

Fig. 5. A scenario for additional climate forcings between 2000 and 2050. Reduction of black carbon moves the aerosol forcing to lower values.

Climate forcing by CFCs is still growing today, but, if Montreal Protocol restrictions are adhered to, there should be no net growth of the CFC forcing over the next 50 years. A small decrease of the CFC forcing from today's level is possible.

Tropospheric O_3 increases in business-as-usual scenarios, which assume that CH_4 increases and that there is no global effort to control O_3 precursors. Despite limited success in past efforts to reduce O_3, the human health and ecological impacts of O_3 are so great that it represents an opportunity for international cooperation. At least it should be possible to prevent O_3 forcing in 2050 from exceeding that of today.

CO_2. CO_2 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_2 emission reductions from improved energy efficiency and decarbonization of fuels. Based on this potential and current CO_2 growth trends, we argue that limiting the CO_2 forcing increase to 1W/m^2 in the next 50 years is plausible.

Indeed, CO_2 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 are uncertain even in the sign of the effect. Unless climate forcings by all aerosols are precisely monitored, it will be difficult to define optimum policies.

We argue that black carbon aerosols, via several effects, contribute significantly to global warming. This 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 disposing of CO_2, though more challenging, provides an effective backup strategy.

We thank Jesse Ausubel, Tom Boden, Ralph Cicerone, Joel Cohen, Tom Conway, Ed Dlugokencky, Jos Lelieveld, Nadejda Makarova, Elaine Matthews, Michael Prather and Peter Stone for data and comments on our manuscript.

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