Moderating Climate Change by Limiting Emissions of Both Short- and Long-Lived Greenhouse Gases

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ABSTRACT

As emissions continue to increase, both warming and the commitment to future warming are increasing at a rate of ~0.2°C per decade, with projections that the rate of warming will further increase if emissions controls are not put in place. Such warming and the associated changes are likely to cause severe impacts to key societal and environmental support systems, especially if the changes are abrupt or accelerate from present tendencies. Present estimates are that limiting the increase in global average surface temperature to no more than 2–2.5°C above its 1750 value will be required to avoid the most catastrophic, although certainly not all, consequences of climate change. Limiting peak warming and initiating a return to temperatures below present levels will require sharply reducing the global greenhouse gas (GHG) emissions by 2050 and to near zero by 2100. With fossil fuels providing over 80% of global energy, and increasing use apparently inevitable in many developing nations in order to raise the standard-of-living, reducing emissions sufficiently presents a very significant challenge, with neither developed nor developing nations yet ready to commit to an agreement without commensurate action by all nations. Analyses of the warming influences of the various greenhouse gases suggests that the extent of action needed is for: (1) developed nations to rapidly reduce their emissions of all greenhouse gases by order of 80% by 2050, and even further by later in the century; and (2) developing nations, in a first phase, to improve their carbon efficiency, reverse deforestation, and sharply limit their non-CO_2 GHG emissions (i.e., emissions of methane, black carbon, and pollutants contributing to tropospheric ozone), and then, as their per capita GDP rises to levels near those of developed nations, to join in initiating sharp reductions in their CO_2 emissions. Because aggressive, near-term reductions in non-CO_2 emissions by developing nations would both improve the environmental well-being of their citizens and offset the warming influence of their ongoing CO_2 emissions, this strategy would allow for their ongoing development while cost-effective CO_2-free energy technologies are developed. Such a coordinated approach would demonstrate the necessary commitment by all nations while recognizing the equity imbalance created by very different per capita emissions. To further limit global warming, if that proves necessary, and to counteract the warming influence of declining emissions of sulfur dioxide, geoengineering likely also merits consideration to reduce the seriousness of the most critical impacts.

Introduction

As projected first by Arrhenius (1896) and reaffirmed in the report of an expert panel of the President's Science Advisory Council (PSAC, 1965) more than 45 years ago, increasing emissions of carbon dioxide (CO_2) resulting from the combustion of coal, petroleum, and natural gas, along with changes in land cover, are increasing the atmospheric CO_2 concentration, changing the climate and impacting the environment and society.[1] Increases in the atmospheric concentrations of all gases with at least three atoms [so including water vapor (H_2O), CO_2, ozone (O_3)] are very important because these gases, while essentially invisible to solar radiation (i.e., they absorb only small amounts of solar radiation), absorb and then re-emit infrared (i.e., heat) radiation emitted by the Earth's surface and the various layers of the atmosphere. Much of the emitted radiation is back toward the Earth's surface, creating a very important and well-established warming influence often referred to as the *greenhouse* effect. The greater the atmospheric concentrations of these greenhouse gases, the greater their warming influence.

Analysis of the CO_2 concentration in the air bubbles trapped in ice cores now provide a record back in time for roughly 800,000 years (EPICA, 2004). Over this period, and somewhat further back in time, changes in the Earth's orbital elements, along with other feedback mechanisms, forced the climate to vary from extensive continental glaciation to milder interglacials (Berger, 2001). An important positive feedback resulted from changes in the CO_2 concentration, which exerted a smaller warming influence during the cold periods, when the concentration was pulled down to about 200 ppmv (parts per million by volume) as cold ocean waters took up more CO_2, than during the warm periods, when the CO_2 concentration rose to about 300 ppmv because of CO_2 being driven out of the ocean. During most of the Holocene, which is the most recent interglacial period and extends back roughly 8-10,000 years, ice core records indicate that the CO_2 concentration was roughly 280 ppmv.

Since the beginning of the Industrial Revolution in the mid 18th century, the CO_2 concentration has been rising, reaching about 300 ppmv in 1900, 310 ppmv in 1950, 365 ppmv in 2000, and nearly 390 ppmv in 2009 (IPCC, 2007a and updates by NOAA). This acceleration in the rate of increase matches very closely the rate of rise of CO_2 emissions. Figure 1, prepared by Raupach et al. (2007) and updated by the Global Carbon Project (see http://www.globalcarbonproject.org/), shows the recent time history of CO_2 emissions; some of the causes are also discussed in Canadell et al. (2007). The black curve shows emissions prior to 2000, indicating an annual rate of growth of about 0.9%, whereas the more recent compilations of emissions suggest that the growth rate has increased to over 3% per year (2009 emissions will likely be down somewhat) as the generation of electricity by coal combustion has been increased to meet the energy demands of China, India, and other nations seeking to economically develop and pull their citizens out of poverty.

The smooth curves shown in Figure 1 represent projections of emissions into the future prepared a decade ago for use as scenarios for model simulations of future climate change (IPCC, 2000). To span what was thought to be possible, these scenarios ranged from A2, B1, and B2 that, even

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[1] The science of climate change is evaluated and synthesized in the periodic reviews of the Intergovernmental Panel on Climate Change (IPCC); for further information see IPCC (2007a, 2007b, 2007c) and for a more general overview that also covers the fundamentals of climate change science, see MacCracken (2008).

in the absence of international emissions controls, projected a change over to energy technologies with reduced reliance on fossil fuels to scenarios A1T, A1FI, and A1B that, in the absence of controls, projected widespread reliance on coal as the world developed and petroleum supplies ran down. Surprisingly, at least for the expert community (e.g., Raupach et al., 2007), the recent compilations of global emissions indicate that the rate of increase in emissions has been faster than was envisioned possible by leading energy and economic experts only a decade ago (IPCC, 2000), causing the atmospheric CO_2 concentration to rise more rapidly than had been projected.

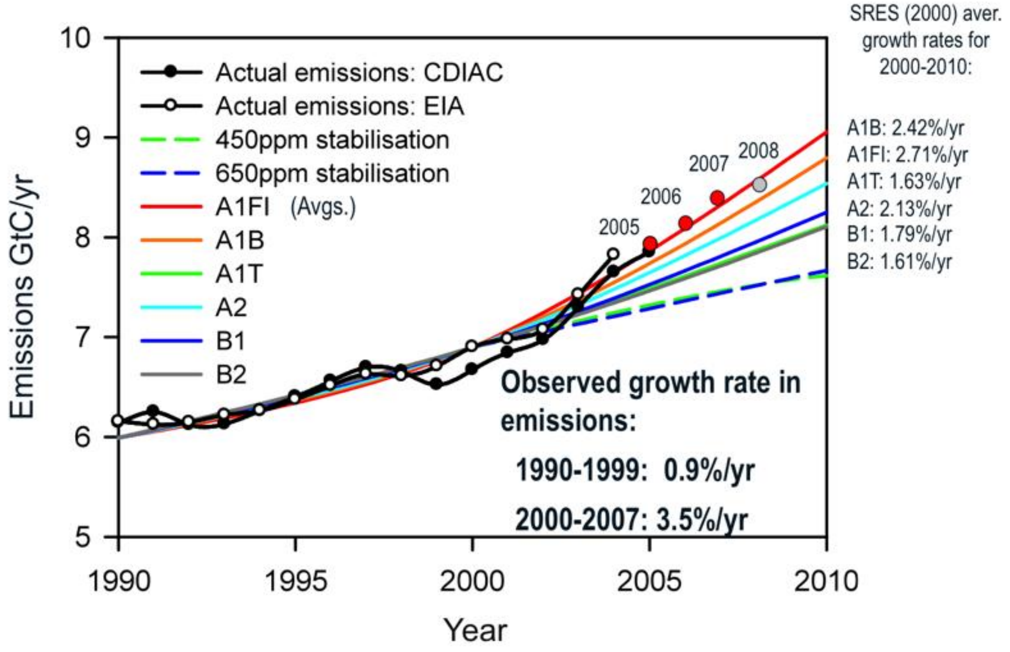

Figure 1: Time history of actual and projected emissions of CO_2 (as GtC/yr). The solid line projections indicate the emissions to be expected, for various conditions, in a world without limitations on emissions, and the dashed line projections indicate the allowable emissions if the world established an emissions path intended to stabilize the atmospheric CO_2 concentration at either 450 or 650 ppmv. The figure is from Raupach et al. (2007), updated by the Global Carbon Project (see http://www.globalcarbonproject.org/).

In 1992 at the Global Earth summit in Rio de Janeiro, the nations of the world negotiated the United Nations Framework Convention on Climate Change (UNFCCC), which sets the objective of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." With total CO_2 emissions from fossil fuel combustion and land cover change nearing 10 GtC/yr and the atmospheric concentration rising at almost 2.5 ppmv/yr, the world is far from stabilizing atmospheric composition, and, at the same time, ecosystems are being disrupted, water resources are being impacted, sea level is rising, and agriculture in some regions is being affected (IPCC, 2007b; UNEP, 2009).

The reasons for the increasing CO_2 emissions are quite clear: fossil fuels, being safe, transportable, and readily available at reasonable cost, provide over 80% of the world's energy, so the large, industrializing nations of east and south Asia are choosing coal in order to generate the energy needed to raise the standard-of-living of their citizens. Today's large, modern economies have been built relying on relatively inexpensive and available energy from fossil fuels, and, even after many of their heavy industrial operations have moved to the developing world, per capita carbon emissions remain high, being of order 5-6 tonnes of carbon per year in North America and about half that in Europe and elsewhere in the developed world. With per capita carbon emissions being very low (just over 1 tonne of carbon in China down to much lower values across Africa) and population high, even small increases in per capita energy derived from fossil fuels lead to a significant increase in emissions. Until the developed nations demonstrate that a modern economy can prosper with very low CO_2 emissions, the stage seems set for global emissions to keep rising, making stabilization of atmospheric composition a very imposing challenge for the next several decades.

The dashed curves shown in Figure 1 indicate the challenge that stabilization of the atmospheric CO_2 concentration presents. Whether the world wants to set a course that would stabilize the CO_2 concentration at about 450 ppmv (about 60% over preindustrial) or 650 ppmv (about 130% over preindustrial), the dashed lines suggest that the least cost emissions path for staying below either of these levels would require sharply reducing the rate of growth in emissions right now—not well off in the future. With a 100% increase in the global CO_2 concentration associated with a projected *equilibrium* rise in global average temperature of between roughly 2 to 4.5°C (IPCC, 2007a), and with the present temperature already up about 0.8°C even with the offsetting cooling influence of sulfate aerosol emissions, the warming projected for unconstrained emissions scenarios has the world warmer than preindustrial by about 2.4 to 4°C by 2100, with further warming thereafter.

With warming of only 0.8°C already causing significant impacts in the Arctic (ACIA, 2004), to the ice sheets (Rignot, 2008), and for the ranges of a large number of plant and animal species (IPCC, 2007b), the likelihood is high for very severe environmental and societal impacts during the 21^{st} century. As global average temperature rises further, the situation could become even worse as the warming triggers thawing of the permafrost and potential release of stored carbon as either CO_2 or, in the worst case, CH_4, both of which would further amplify global warming. Because there appears to be a significant risk that warming of over 2°C could cause thresholds for such nonlinear effects (e.g., Schellnhuber et al., 2006; Lenton et al., 2008; Pittock, 2008), the leaders of the leading nations have agreed that their goal should be to limit global warming to no more than this amount (CEC, 2008). Recent scientific studies are suggesting that even this limited amount of warming may, however, greatly accelerate loss of mass from the Greenland and Antarctic ice sheets, and that avoiding substantial ice loss from the ice sheets will require that global average temperature be returned to below today's elevated value of temperature and CO_2 concentration (e.g., Wigley, 2005; Hansen, 2007).

In projecting future change, however, the rising concentration of CO_2 is not the only reason for concern. The concentrations of methane (CH_4), nitrous oxide (N_2O), halocarbons, and tropospheric ozone, along with the atmospheric loading of black carbon (soot), are also rising, and thereby exerting a strong warming influence on the climate (Hansen et al., 2005; Hansen et al., 2007. With the warming climate already intensifying storms (Emanuel, 2005; IPCC, 2007a) melting back Arctic sea ice and permafrost (ACIA, 2004), initiating loss of ice from mountain glaciers and ice sheets (IPCC, 2007a; Rignot, 2008), and with the ranges of important plan and animal species shifting (see IPCC, 2007b; UNEP, 2009), the world is in quite a predicament, with the future looking very insecure (Campbell et al., 2007). The rest of this paper focuses on a possible path forward that would be both workable and effective.

The Relative Warming Influences of Greenhouse Gases and Aerosols over the 21st Century

Virtually all of the public and intergovernmental discussion has identified reduction of CO_2 emissions as the most critical component of the steps needed to slow and then stop climate change. Careful studies of the carbon cycle indicate that the CO_2 emitted into the atmosphere is relatively rapidly mixed into the atmosphere, terrestrial biosphere, and upper ocean, such that the airborne fraction (i.e., the fraction of emissions that appears to persist in the atmosphere for many decades or longer as emissions are going up) ends up at about 50%. As a result, the annual rate of rise in the CO_2 concentration (in ppmv) is about one-quarter of global annual CO_2 emissions (in GtC) from fossil fuel combustion.[2]

Once the initial distribution of the emitted CO_2 increment across the three rapidly mixed reservoirs has occurred, it then takes many centuries to millennia for the elevated concentration to decrease as the CO_2 is mixed into the deep ocean (Solomon et al., 2009) and then, over longer periods, primarily into the ocean sediments. It is because of this very long-term persistence of the warming influence that it is essential that global emissions of CO_2 be substantially reduced and eventually virtually eliminated over the next several decades.

Another reason that there has been so much focus on emission of CO_2 is evident from Table 1. The second column shows, subdivided by gas or aerosol, the increase in forcing for cumulative emissions from 1750 to 2000, and the third column shows the projected forcing for 2100, using the mid-range business-as-usual emissions scenario presented in IPCC (2001) for illustrative purposes. The fourth column shows the differences, and makes clear that just over 75% (3.4/4.4) of the change in forcing from 2000 to 2100 is projected to be due to the increase in the CO_2 concentration. Based on this high percentage, it is quite natural for greatest attention to be paid to reducing CO_2 emissions, especially given the very long duration of the perturbation (e.g., see Keith, 2009, who notes that, on a percentage basis, the warming influence of CO_2 persists for longer than does the radioactive influence of nuclear waste).

Just looking at the changes in the contributions to radiative forcing of the various substances, however, does not provide an adequate portrayal of the potential for limiting overall global warming. The reason for this is that the different substances have very different lifetimes in the

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[2] To convert GtC (gigatonnes of carbon) to $GtCO_2$ (gigatonnes of CO_2), multiply by 3.67, and to then convert to $MMTCO_2$ (millions of metric tonnes of CO_2), which is the unit used in international negotiations, multiply by 1000. Note that 1 Gt = 1 Pg.

atmosphere. For example, black carbon and sulfate aerosols have an average atmospheric lifetime of at most one to two weeks, so their entire contributions to forcing in 2100 come from emissions during the last two weeks or so of 2099. More importantly, if emissions of black carbon were sharply and immediately reduced, their warming influence over the entire century would be eliminated. Similarly, chemical reactions limit the lifetime of methane in the atmosphere to about 12 years, so virtually all of methane's contribution to forcing in 2100 is a result of emissions after 2075, and an immediate cutback in emissions would lead to a sharp reduction in its important warming contribution that would take full effect within 25 years and persist throughout the century. A similar situation exists for the precursors that lead to tropospheric ozone; cut these emissions (e.g., by cleaning up transportation emissions), and the reduction in their warming influence would drop sharply over the first year and persist thereafter.

Table 1: Contributions of each of the primary greenhouse gases to radiative forcing (i.e., net downward flux at the tropopause) that drives warming of the surface-atmosphere system.

Climate changing gas or aerosol	**Radiative forcing (W/m^2) (1750-2000)**	**Projected business-as-usual (BAU) forcing scenario[1] for 2100 (W/m^2)**	**Change in projected BAU forcing[2] over the 21st century (W/m^2)**	**Persistence time of the atmospheric perturbation (years)**	**Change in forcing in 2100 due to 21st century emissions (W/m^2)**
Carbon dioxide (CO_2)	1.66	~5.1	~3.4	Up to thousands	~4
Methane (CH_4)	0.48	~0.9	~0.4	~12	~0.9
Nitrous oxide (N_2O)	0.16	~0.4	~0.25	~114	~0.35
Halocarbons	0.34	~0.4	~0.05	Up to thousands	~0.1
Tropospheric ozone (O_3)	0.35	~0.65	~0.3	Mostly, up to ~0.2	~0.65
Black carbon[3] (soot)	~0.4	~0.4	~0	Up to ~0.03, plus effect on snow albedo	~0.4
Sulfate aerosols (SO_4) direct	-0.4	-0.4	~0	Up to ~0.03	-0.4
Sulfate aerosols (SO_4), increase in cloud reflectivity	-0.7	-0.7	~0	Up to ~0.03	-0.7
TOTAL	**~2.3**	**~6.75**	**~4.4**		**~5.3**

Note 1: This scenario is derived from the UN Scientific Experts Group (SEG, 2007) and IPCC's Third Assessment Report (IPCC, 2001). Values are approximate; see referenced reports for details.

Note 2: Using the IPCC (2000) range of scenarios, IPCC (2007a) gives a range around these estimates of the change in forcing over the 21st century that does not affect the conclusions.

Note 3: Compilation of recent observations of aerosols in southern and eastern Asia by Ramanathan and Carmichael (2008) lead them to suggest that the present, and so likely the future, value for forcing for black carbon might well be roughly twice this amount, which would further strengthen the arguments made in this paper.

The potential for emissions cutbacks to lead to rapid reductions in the warming influence of methane, ozone precursors, and black carbon is not the case for the long-lived species. For CO_2, going to zero emissions immediately would still leave about half of the existing CO_2 forcing exerting its warming influence in 2100, with further reductions taking centuries (Solomon et al., 2009). The situation for some halocarbons is equally discouraging, although on average the decrease in their influence, like that of nitrous oxide (N_2O), is a bit more rapid than for CO_2.

The sixth column in Table 1 provides a rough indication of the significance of considering these differences in lifetime. Neglecting the cooling influence of the sulfate aerosols, which will be considered below, the warming influence of the higher CO_2 concentration is only about 60% of the total warming influence of all of the greenhouse gases on climate, whereas the results presented in column 4 suggested that it was over 75%. Just looking at the forcing in 2100, however, is not enough. What really needs to be done is to look at the integral of the warming influence over the 21st century resulting from emissions that occurred during the 21st century (see Moore and MacCracken, 2009), because these are the emissions that can potentially be reduced.

The most commonly used way to estimate the relative contributions of each gas is to consider the emissions of each, weighted by their Global Warming Potential (GWP). The GWP is the ratio of the time-integrated radiative influence of emission of a unit mass of a particular gas relative to the time-integrated radiative influence of emission of a unit mass of CO_2. Typically, the integration is over a period of 100 years, and when this is done, the contribution of global CO_2 emissions to global warming is typically about 75% of the total influence of all GHGs. The problem with this approach is that the period of time used is very important—for CO_2, using 100 years ignores the long-term influence of the CO_2 perturbation (Solomon et al., 2009), whereas for the short-lived gases, the 100-year integral significantly down plays their influence over the period of years to decades (CCSP, 2008). As an example, the 100-year GWP for methane is 22, whereas the 20-year GWP is 75 because virtually all of the influence of methane occurs within the first 20 years of its emission (IPCC, 2007a). For black carbon, the result is even more misleading as it remains in the atmosphere for only a week or two—its 100-year GWP is estimated to be about 460 and its 20-year GWP is 1600 (ICCT, 2009); were one to calculate its GWP relevant to its 1-2 week lifetime, it would likely be near 10^6. These numbers, of course, apply to unit amounts of emissions; what really matters are the total emissions of each GHG and the GWP for each.

Figure 2 provides a graphical portrayal of this result. The lowest shaded area shows the carryover warming influence from concentrations elevated by emissions from prior to the year 2005[3]. Beyond the first few decades of the 21st century, virtually all of this radiative forcing is due to CO_2 emissions, which have come predominantly from the developed nations. Above this base category, each of the areas represents the warming influence from 21st century emissions of the indicated greenhouse gas. Because of their relatively short atmospheric lifetimes, the influences of methane and tropospheric ozone quickly return to their year 2000 influence and then change very slowly over the century. Because of its long lifetime, however, the influence of CO_2

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[3] These results were drawn simulations using the MAGICC model of Wigley (2008) with an emissions scenario in which anthropogenic emissions of all of the greenhouse gases were linearly decreased from their year 2000 values to zero in 2010 and held at zero thereafter.

emissions during the 21st century takes several decades to regain its dominant position. Emissions of halocarbons and nitrous oxide also play a role that merits attention, and efforts to limit halocarbon concentrations under the Montreal Protocol and subsequent agreements and amendments will certainly play an important role (Velders et al., 2007).

Integrating the influences of each greenhouse gas over the 21st century provides an indication of the relative contributions to warming. That the integral of the lowest area is substantial is an indication of the carry-on warming influence of past emissions, which will be complemented by the warming that will result from the ocean warming up to achieve equilibrium with the existing atmospheric composition. With respect to the influences from future emissions, that the sum of the areas of the methane and tropospheric ozone contributions and the CO_2 contribution are similar is an indication that the warming contributions of CO_2 and of the short-lived species are roughly comparable[4]. Clearly, to maximize the effectiveness of efforts to limit 21st century warming, it is roughly *equally* important to limit emissions of the long-lived (so CO_2, halocarbons and N_2O) and the short-lived, non-CO_2 greenhouse gases and aerosols (i.e., methane, ozone-producing pollutants, black carbon, etc.).

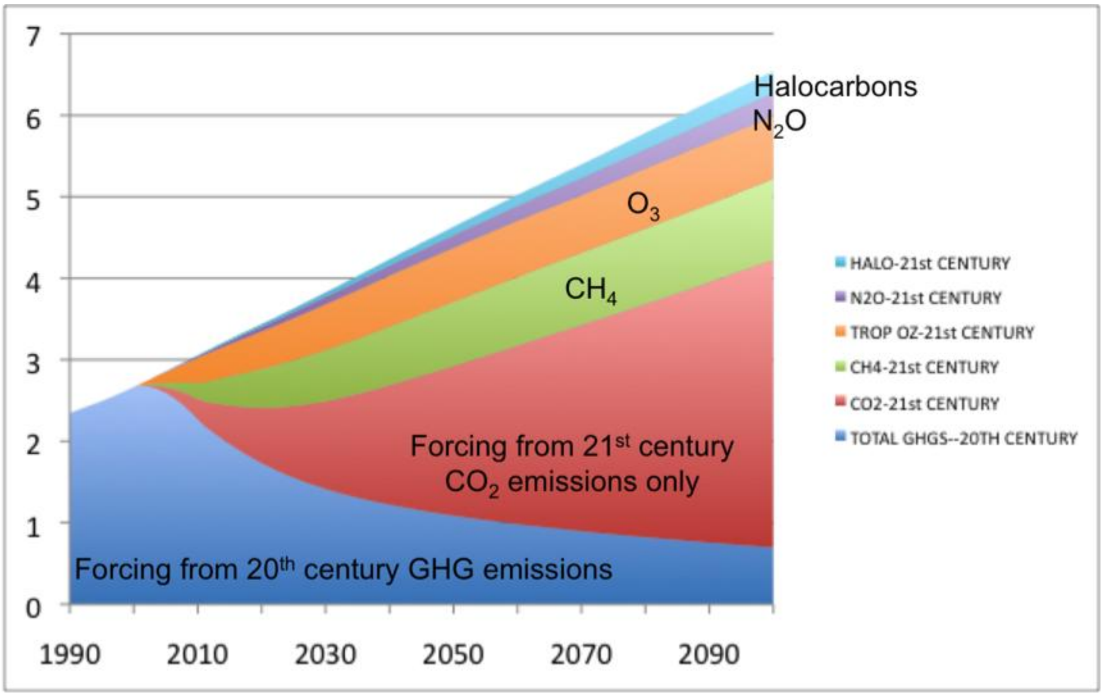

Figure 2: Projection of radiative forcing at the tropopause due to emissions of greenhouse gases prior to the 21st century (lower section) and from the emission of various greenhouse gases during the 21st century (five upper sections). For reference, a radiative forcing of approximately 2-3 W/m^2 is estimated, at equilibrium, to be associated with an increase in global average temperature of 2ºC above preindustrial conditions. Derived from simulation using MAGICC model of Wigley (2008).

The situation for the aerosol (or aerosol precursor) emissions is also important to consider (Charlson et al., 1992), especially because the changes in forcing can occur so rapidly. The

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[4] With respect to total warming contribution, however, CO_2 is clearly the dominant human-affected greenhouse gas, for CO_2 is also responsible for the dominant share of the 20th century carryover influence—and the influence of past and 21st century CO_2 emissions will extend far beyond 2100.

contribution of emissions of black carbon to warming is emerging as an increasingly important. While indicated in Table 1 as contributing about 0.4 W/m^2 to the warming influence (so about 0.3ºC at equilibrium), observations in southern and eastern Asia by Ramanathan and Carmichael (2008) suggest that the warming influence of black carbon may actually be twice the size estimated by IPCC (2001, 2007a). To the extent this is the case, the importance of reducing emissions of black carbon and other non-CO_2 greenhouse gases becomes even more important.

In contrast to the warming influence of black carbon, emissions of SO_2, primarily from the elevated stacks of coal-fired power plants, are estimated (using central values) to cause a cooling influence due to their clear-sky effects of -0.4 W/m^2 and a further cooling influence of -0.7 W/m^2 due to their brightening influence on clouds (IPCC, 2007a). This total cooling influence, if removed, would be expected, after the oceans have had time to come into equilibrium, to lead to an increase in the global average surface temperature of roughly 0.8ºC (range about 0.6 to 1.3ºC). Most emissions scenarios project that emissions of SO_2 will be dropping over coming decades as air pollution controls are put in place to improve health and visibility.

A Practical Path Forward

Global average temperature is already about 0.8ºC above its preindustrial value. Model calculations carried out in support of IPCC's Fourth Assessment (IPCC, 2007a), in which the greenhouse gas and aerosol loadings of the year 2000 were held constant thereafter, projected that another 0.5ºC of warming would occur as the oceans warmed and the climate came into equilibrium. Going to near-zero net emissions from coal-fired power plants, which will be essential to limiting long-term global warming, would also lead to near zero emissions of SO_2, thereby leading to rapid loss of the cooling influences of sulfate aerosols. Such a loss would uncover the full warming influence of the present concentrations of greenhouse gases, likely leading to further warming of about 0.8ºC. Thus, even if the world could immediately reduce emissions of the long-lived greenhouse gases to levels that would stabilize atmospheric composition, a change that would likely seriously disrupt economic development, the world would seem to face a warming of at least 2ºC.

The more realistic situation, in which emissions of CO_2 and other GHGs rise and then are reduced over subsequent decades, has been projected recently to lead to a warming of at least 4ºC during this century (see http://www.metoffice.gov.uk/climatechange/news/latest/four-degrees.html). Such a warming would cause all sorts of undesired impacts (IPCC, 2007b), but it is the seemingly inevitable outcome if the world is unsuccessful in negotiating sharp reductions in emissions at the December's COP-15 meeting in Copenhagen (i.e., 15th meeting of the Conference of the Parties to the UN Framework Convention on Climate Change). No wonder the discouragement of the scientific community about stopping global warming is leading to increasing consideration of geoengineering interventions to limit climate change (Crutzen, 2006; Wigley, 2006; Victor et al., 2009), including injection of sulfate aerosols into the stratosphere (Crutzen, 2006; Rasch et al., 2008; Robock et al., 2009), brightening of the troposphere (Latham et al., 2008; MacCracken, 2009), and large-scale scrubbing of CO_2 from the atmosphere (Keith, 2009).

An alternative, although not completely satisfactory approach to global geoengineering, is to focus on sharply reducing the emissions of non-CO_2 greenhouse gases and black carbon. Specifically, if, in addition to limiting CO_2 emissions by reversing deforestation and aggressively reducing the net CO_2 emissions from fossil fuel combustion (or at least in the developing world, substantially increasing energy efficiency), substantial reductions are made in the emissions of the short-lived gases and warming aerosols, it seems likely that, even if SO_2 emissions are reduced, the increase in global average temperature could be limited to about 2-2.5ºC. For the developed (i.e., OECD) nations, a rough outline of what would be required is to:

a) Cut net CO_2 emissions by about 80% by 2050 and 90% or more within a few more decades. A strong and early start is needed to demonstrate that modern societies can prosper with low greenhouse gas emissions (IPCC, 2007c; Brown, 2008). According to the EASY strategy put forth by Harte and Harte (2008), the primary steps needed are to: increase efficiency (E), electrify the transportation sector (A), generate electricity from solar, wind, other renewables and nuclear (S), and live life showing greater concern for the environment (Y). If CO_2 scrubbing becomes viable, its implementation would also be helpful (Keith, 2009).
b) For the other long-lived species, namely halocarbons and N_2O, significant reductions also appear possible (e.g., Velders et al., 2007).
c) For methane, which is the primary short-lived greenhouse gas, a reduction in emissions of about 60% by 2050 and 80% or more by 2100 would be very beneficial. In the US (EPA, 2008), methane emissions relating to fossil fuels account for about 40% of current emissions, and sharp reductions can likely be accomplished as fossil fuel use is brought down. About 30% of methane emissions are related to landfills, waste treatment, and stationary combustion, and there are already economical means to limit these emissions. The rest is largely related to agriculture, and limited capture of methane emissions by manure management and even at cattle feeding lots is practical. The threat to this approach is that thawing of permafrost regions could lead to a compensating increase in emissions, although this could occur in any case and sharply accelerate warming.
d) Electrifying the transportation sector would be expected to lead to sharp reductions in emissions of volatile organics, carbon monoxide, and nitrogen oxides. Achieving a 50% reduction by 2050 and a 90% cutback by 2100 would not only significantly reduce the global warming influence of tropospheric ozone, but also have beneficial effects on public health and crop production.
e) The sharp reduction in net CO_2 emissions, especially from coal-fired power plants would be expected to lead to a sharp reduction in SO_2 emissions, and thus in the cooling offset provided by sulfate aerosols. At the same time, however, visibility would improve and health effects would be reduced. Research is needed to determine whether injection of sulfate aerosols into the stratosphere (Rasch et al., 2008; Robock et al, 2009) or the troposphere in remote areas (MacCracken, 2009) might be an effective and not significantly disruptive and damaging means of more rapidly limiting global warming than is possible as a result of emissions reductions.

For the non-OECD nations, for reasons of equity and ethics, any strategy aimed at limiting climate change must also be designed to alleviate poverty and promote a more sustainable relationship with their environment—if living from year to year is a life and death challenge, there is little reason to be concerned about long-term climate change. That both short- and long-term objectives relating to development and climate change can be pursued in a coordinated manner is, fortunately, becoming more and more apparent (see SEG, 2007; World Bank, 2009).

Because beginning an immediate reduction in their CO_2 emissions would be likely to greatly restrict economic development in developing nations, relegating them to ongoing poverty, it has not been surprising that there has been a refusal of developing nations to do more over the next few decades than to limit the rate of growth in their emissions. In 2001, even though US per capita emissions were roughly five times those of the largest developing nations, this refusal was one of the reasons that president George W. Bush gave for withdrawing the US from the process of finalizing the Kyoto Protocol's implementation. Similar sentiments seem to remain widespread as negotiations for the post-Kyoto Protocol near the critical point.

To bridge the sharp disagreement, MacCracken (2008) and Moore and MacCracken (2009) have proposed a two-phase approach for the developing nations that would take advantage of the important contribution that can be made by limiting emissions of the short-lived greenhouse gases and aerosols. They propose the following:

Phase 1: The first steps, which would begin immediately, and continue until national per capita GDP and greenhouse gas emissions rose to the bottom of the hopefully declining range of per capita emissions in developed nations, the non-OECD nations would:

a) Limit growth in their CO_2 emissions by committing to aspirational goals to improve the energy efficiency of their economies, thus reducing the amount of CO_2 generated per dollar of GDP, seeking to reach (or exceed) the levels of present OECD nations over coming decades (and the OECD nations would pledge to help in this effort via technology transfer and helpful and verifiable financial measures). These actions would not only reduce the prospective CO_2 contribution to climate change, but also assist in their economic development, environmental clean-up, and alleviation of poverty. Using already developed technologies, commitments to reductions in emissions of halocarbons and nitrous oxides would also be valuable.

b) Reverse deforestation. This step would not only increase uptake of carbon, but it is also vital to stabilize soils, enhance wildlife and biodiversity, and encourage ecotourism. In that cutting of trees and shrubs for biofuels is a primary factor in deforestation, use of more efficient wood-burning cooking stoves could also play an important role in reducing the pressure on forests and the time devoted to gathering firewood.

c) Aggressive reduction of CH_4 emissions. While the mix of sources in developing nations is different than in developed nations, there are substantial opportunities for emission reductions by sucking methane out of coal mines (which would reduce incidence of coal mine explosions), tightening up the natural gas and petroleum distribution systems (which would also increase energy efficiency and reduce air pollution), capturing methane from waste treatment and landfills (which would provide a useful fuel), and even by altering and/or reducing production from agriculture.

d) Reduce emissions of air pollutants. Pollutant emissions are not only causing serious health and environmental problems, but are also contributing to the build-up of tropospheric ozone and thus global warming. Many countries are already moving to reduce emissions from their transportation systems, both by raising mileage standards and imposing emission limits. Although not originally put in place to limit climate change, efforts by developing nations to reduce air pollutant emissions deserve credit and encouragement.

e) Reduce emissions of black carbon. Recent observations are indicating that black soot may even be the second most important warming influence (Ramanathan and Carmichael, 2008), making reduction of such emissions a very important component of a comprehensive effort to limit global warming. Primary sources are burning of biomass and biofuels (e.g., in inefficient cook-stoves), use of kerosene for light and cooking (kerosene use is estimated to be about a million barrels of oil per day), and two-stroke and diesel engines. One key step would be to provide rural families with small solar panels that can power a cell phone, a computer, and a small light that would help lengthen the time for study and education. Again, developing countries have the potential to play a major role in reducing emissions and warming, and a commitment to pursue appropriate actions merits official encouragement.

Phase 2: With so many people, significant growth in CO_2 emissions from developing nations alone could, if not controlled, lead to very significant global warming. Therefore, in addition to continuing to pursue all the actions in phase 1, it will be essential that the developing nations, beginning generally within a few decades, also take steps to join the developed nations in driving their CO_2 (and other greenhouse gas) emissions toward zero. An appropriate commitment might well be for each nation to never exceed the per capita emissions of developed nations, which, to seriously deal with global warming, need to be coming down rapidly over coming decades (Moore and MacCracken, 2009). The recent study by the Energy Modeling Forum (http://emf.stanford.edu/research/emf22/) found that fore-knowledge that a nation would, at a specified date, graduate from a first phase without a hard CO_2 emissions limit into a second phase with declining limits for CO_2 emissions would lead investors to shift their investments into low or no carbon energy technologies starting well before a nation's graduation date in order to minimize stranded investments. In addition, that many of the developing nations may be manufacturing the low carbon energy technologies (e.g., solar panels, wind turbines, etc.) needed by the developed nations would likely facilitate their early use in the developing nations.

As to the ability to reduce overall emissions, if, for example, the non-OECD nations can, by 2100 or earlier, collectively cut in half CO_2 emissions that are presently projected for 2040, then per capita emissions in both developed and developing nations would be near equal and at the very low levels needed to stabilize the climate. With aggressive emission reductions, there may even be the potential to start pushing the atmospheric CO_2 concentration back toward mid-20th century levels, which it is increasing likely will be required to stabilize the mass of water held by mountain glaciers and ice sheets (Wigley 2005; Hansen, 2007).

Summary

Without strong action, the most recent emissions projections will lead to global warming of several degrees Celsius by the end of the century, far above the 2°C goal set by world leaders based on warming that seems likely to trigger 'dangerous' changes to the climate, sea level, ice sheets, ecosystems and more (Schellnhuber et al., 2006; Lenton et al., 2008). With the CO_2 concentration rising at a high rate as a result of accelerating emissions, halting the increase in temperature will require reducing net global emissions of CO_2 by 80% or more over coming decades.

In addition to this essential step to limit long-term warming, reducing the concentrations of short-lived greenhouse gases and the atmospheric loading of black carbon is also critical to limiting warming over the next few decades. Indeed, of the emissions that can potentially be controlled, the contributions of non-CO_2 greenhouse gases and loading of black carbon will contribute approximately as much to 21st century warming as do this century's emissions of CO_2 (CO_2 emitted prior to 2000 will also be an unavoidable contributor to the warming).

The only path to limiting global warming to less than about 2.5°C thus appears to be a combined effort to reduce the emissions of CO_2, non-CO_2 greenhouse gases, and black carbon. To achieve sufficient reductions, a comprehensive strategy is needed":

- The OECD nations (which generally have high per capita emissions of CO_2 and some other greenhouse gases and aerosols) need to move expeditiously to demonstrate that a modern economy can prosper with reduced emissions, as a few nations are working hard to do; and
- The non-OECD nations (which generally have low per capita emissions of fossil fuel CO_2 due to a lower standard of living and low per capita use of fossil fuels, but much higher emissions of biomass CO_2, methane, air pollutants leading to tropospheric ozone, and black carbon) need, over the next couple of decades, to greatly increase their energy efficiency, reverse their deforestation (and forest diebacks that may result from climate change), and sharply reduce their emission of non-CO_2 greenhouse gases. Then, as poverty is alleviated and new, clean energy technologies are proven, these nations need to join in sharply reducing their CO_2 emissions, taking advantage of the technologies and approaches being utilized by the developed nations.

If emissions are cut sharply enough, there appears to be a narrow path forward, though one for which there will surely be some significant impacts. More likely, due to the apparent inability or unwillingness to cut CO_2 emissions sharply enough due to concerns of cost and backlash, the cuts will be slower, allowing the warming to become greater, which in turn opens up the question of whether, despite its shortcomings, climate engineering (i.e., solar radiation management) will be required to both offset the warming influence of the increased greenhouse gases and to strengthen the cooling effect of the sulfate aerosols presently associated with coal combustion. Such efforts are conceivable (Crutzen, 2006; Rasch et al., 2008; AMS, 2009: Robock et al., 2009; MacCracken, 2009), but likely viable over the long-term only if the emissions of CO_2 and non-CO_2 greenhouse gases are on a sharp downward trajectory. Without emissions reduction, the legacy passed to future generations will be daunting and debilitating (Campbell et al., 2008); with emissions reduction, perhaps aided by geoengineering, there is the potential that at least some of the worst effects of climate change can be moderated, although there is really no time to spare in getting started.

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