

THE ROLE OF NON-CO₂ GREENHOUSE GASES AND AEROSOLS IN CLIMATE MITIGATION

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Forcing agents other than carbon dioxide, such as methane, nitrous oxide, halocarbons, and perhaps aerosol particles, may play a major role in mitigating climate change. Of these agents, methane is the most important greenhouse gas and has substantial mitigation potential. The role of black and organic carbon aerosols has attracted increasing interest and we explicitly include these carbonaceous aerosols in our calculations. This paper analyzes the potential role of different forcing agents in reducing future climate forcing in a multi-gas, integrated assessment model in which mitigation options compete and interact. Our framework includes all of the important atmospheric forcing agents: carbon dioxide, methane, nitrous oxide, halocarbons, sulfur dioxide, and carbonaceous aerosols along with an array of potential mitigation options. Through an integrated analysis of all available options we present a realistic portrait of the potential role of these forcing agents in limiting future climate change.

1. INTRODUCTION

There is general agreement that any actions to mitigate anthropogenic climate change should address all greenhouse gases. This concept is embodied in the Kyoto Protocol as national targets expressed in terms of total carbon equivalent emissions calculated by means of a Global Warming Potential (GWP) index. This principle is also found in the policy of the United States, which is based on a greenhouse gas intensity target.

Some have also argued that forcing agents such as black carbon aerosols and tropospheric ozone should be included in climate mitigation policies (Hansen *et al.* 2000). Here we undertake an integrated analysis of the potential contributions of greenhouse gases and aerosols to climate mitigation, focusing on the next fifty years. Our methodology will be to compare a reference and example policy scenario in an integrated context with common driving forces and interactions as embodied in MiniCAM, PNNL's long-term integrated assessment model. We will compare the changes in emissions, and the resulting consequences for radiative forcing, between these two scenarios.

2. METHODOLOGY AND DATA

The MiniCAM2001 model, as used for this paper, includes endogenous emissions estimates for a comprehensive suite of greenhouse gases and greenhouse gas and aerosol precursor compounds. The emissions sectors in MiniCAM include energy production and consumption, agriculture, land-use, industry, and urban (e.g., sewage treatment, landfills) sources. Emissions include: carbon dioxide (fossil fuel and cement manufacture), methane, nitrous oxide, a suite of halocarbon gases (HCFC245fa, HFC134a, HCFC125/227ea, HFC143a, SF₆, C₂F₆, and CF₄), nitrous oxides, (non-methane) volatile organic carbon compounds, carbon monoxide, sulfur dioxide, black carbon, and organic carbon. These emissions are fed into the coupled gas-cycle/climate model MAGICC (Raper *et al.* 1996; Wigley & Raper 1992; Wigley & Raper 2002), which calculates not only the direct forcing due to greenhouse gases, but also forcing from sulfate and black carbon aerosol and global forcing from tropospheric ozone (Wigley *et al.* 2002).

Base-year emissions data for methane, nitrous oxide, and the halocarbons were provided through the Energy Modeling Forum 21 (USEPA, 2003). Sulfur dioxide emissions are described in Smith, Pitcher, and Wigley (2003), reactive gas base-year emissions are taken from US EPA, Canada EPA, EDGAR 3.2, and various literature sources. Black carbon (BC) and organic carbon (OC) base year emissions are from Bond *et al.* (2003). In this analysis, carbonaceous (BC + OC) aerosol emissions from land-use and land-use changes (LULUC: forest fires, deforestation, agricultural waste, and savannah burning) are assumed to be constant. For all (non LULUC) emissions, when there is a consistent difference in current emissions factors between less and more industrialized regions, we assume that emissions factors converge as incomes increase. In addition, emissions factors are generally assumed to improve over time due to technological change, efficiency increases, and emissions controls.

We use the MiniCAM to generate both a reference case and a policy case. The reference case is the current MiniCAM implementation of the SRES B2 scenario (Nakicenovic & Swart 2000; Smith *et al.* 2003). The B2 scenario can be described as a "dynamics as usual" scenario with environmental policies continued into the future following historical trends. No climate policies are assumed to be implemented in our reference case. Since we have used the latest version of the MiniCAM, carbon emissions and other output details of the B2 reference scenario used here are not identical to those presented in the SRES.

We will compare our reference case to a policy case where a specific long-term CO₂ emissions target is imposed on the global energy-economic system. For purposes of this analysis, we will require the model to meet a carbon dioxide emissions path that leads to stabilization of carbon dioxide concentrations at a level of 450 ppmv in the year 2100 as described by Wigley *et al.* (1996). The reasons for this choice will be discussed below. For the policy case, MiniCAM applies a carbon price to all fossil fuels, proportional to their carbon content such that the specified target emissions value is met in each modeled year. The MiniCAM adjusts the mix of energy supply and demand technologies, including the

effect of the carbon price, to provide a least-cost energy supply solution at each time step.

Greenhouse gases other than CO₂ also contribute to reducing radiative forcing in the policy scenario. We apply the carbon price appropriate for the specified CO₂ target to all non-CO₂ greenhouse gases using 100-year GWPs. Climate policy-driven reductions for non-CO₂ gases are determined using externally derived Marginal Abatement Curves (MACs). The MACs used in MiniCAM are disaggregated by source sector, so that greenhouse gas mitigation is implicitly integrated into the model structure. The MACs are cast as percentage reductions as a function of the carbon price. For example, at a carbon price of \$50 per tonne of carbon, methane emissions from landfills are reduced by 50-70% (depending on the region). Reductions vary by gas, sector, region, and the carbon price. The MACs were developed by the US Environmental Protection Agency and made available through the Energy Modeling Forum 21. No MACs are applied to reactive gases or aerosol emissions.

Reductions, therefore, take place under a climate policy due to both direct mitigation efforts (only included here for greenhouse gases) and the indirect effects of other changes in driving forces. For example, a climate policy may reduce the use of coal. This will reduce coal production and, therefore, tend to reduce the emissions of methane from mining operations. Methane emissions from coal mining can also be directly reduced by mitigation devices by an amount determined by the MACs, as a function of carbon price, for that region and sector. In general, both effects are included in these calculations. Reductions in non-CO₂ greenhouse gases do not affect CO₂ emissions (such effects would be small).

3. REFERENCE CASE RESULTS

Over the next 50 years in the MiniCAM B2 reference case global emissions of most greenhouse gases increase while emissions of carbonaceous aerosols and sulfur dioxide decrease. While the exact magnitude of these changes will depend on scenario assumptions, the reasons for the overall direction of these changes can be outlined. Final energy use in the B2 scenario increases globally by almost a factor of two over this time period, driving increased use of both fossil fuels and non-fossil energy. Population and affluence also increase, driving increased production of food and use of manufactured products. While efficiency is assumed to continue to increase, the assumed increases are generally not enough to offset increased production levels, which results in emissions increases. Global aerosol emissions are an exception, as historical decreases already seen in OECD countries begin to be matched by emission decreases in non-OECD regions (Smith *et al.* 2003).

Carbonaceous aerosol emissions are a new addition to MiniCAM. The largest sources of black carbon emissions in the inventory used for this analysis (Bond *et al.* 2003) are: residential use of solid fuels (particularly biomass and coal); mobile sources; and industrial use of oil and coal. Use of biomass and coal in the residential sector, for heating and cooking, decreases significantly over the next

50 years in our base case. This decrease is driven largely by economic development in Asia and Latin America that drives a transition away from the use of traditional biomass and coal for household energy needs. Organic carbon emissions from residential sources also decrease. However, a large fraction of organic carbon emissions are from land use changes, which were assumed to be constant, resulting in a relatively small overall decrease in emissions.

The focus of this analysis is the effect of emission changes on climate mitigation. The most accurate method of comparing the effect of emissions changes is through the use of radiative forcing. The use of radiative forcing as a comparison measure appears to be quite accurate for well-mixed greenhouse gases and accurate to within perhaps 20% for reflective aerosols such as sulfate and organic carbon (see Harvey 2000). The effect of an absorbing aerosol such as black carbon is more difficult to characterize, although top of the atmosphere radiative forcing should capture the first order effects on the global energy balance (note, however, that the effect on surface temperature of black carbon appears to be different, relative to its radiative forcing, as compared to greenhouse gases).

The relationships between atmospheric concentration and radiative forcing for the well-mixed greenhouse gases are relatively well known. The forcing from tropospheric ozone and, in particular, aerosols are less certain, however. Here we use central values derived from the IPCC Third Assessment Report (TAR; Ramaswamy *et al.* 2001). Relative to pre-industrial times we assume that the forcing changes up to 2000 are: 0.35 W/m² for tropospheric ozone, -0.4 W/m² for sulfate direct forcing, -0.8 W/m² for sulfate aerosol indirect forcing, 0.25 W/m² for fossil-fuel black carbon aerosol, -0.1 W/m² for fossil-fuel derived organic carbon

Forcing Agent	Reference Case Radiative Forcing (W/m ²)		
	Pre-industrial to		Pre-industrial to
	2000 (1)	2000-2050 (2)	2050 (1)+(2)
CO ₂	1.5	1.7	3.2
CH ₄	0.5	0.1	0.6
N ₂ O	0.2	0.1	0.3
Halocarbons	0.2	0.1	0.2
Tropospheric Ozone	0.3	0.1	0.5
Black Carbon	0.4	-0.1	0.3
Organic Carbon	-0.4	0.0	-0.4
Sulfate	-1.1	0.2	-0.9
Total Anthropogenic	1.6	2.3	3.9

Table 1—Radiative forcing from pre-industrial times to the year 2000 and from 2000-2050 for the reference case (W/m²). A positive radiative forcing represents a net warming influence over the specified period. In this table, and subsequent figures, the methane category includes both direct methane forcing plus the indirect-forcing due to stratospheric water vapor. The halocarbon category includes forcing due to CFCs, CFC substitutes and other halocarbons, plus the forcing due to stratospheric ozone depletion and subsequent recovery. Carbonaceous aerosol forcing figures include both fossil-fuel and land-use sources. Figures may not add due to independent rounding.

aerosol, and -0.2 for aerosols from land-use changes (assumed constant). The net effect of all aerosols is, thus, assumed to be -1.2 W/m^2 relative to pre-industrial times (a net cooling effect). Note that indirect aerosol effects are expected to occur for all aerosol species. These are not well understood and are represented here as part of the sulfate aerosol category. Note that these aerosol assumptions are somewhat different than those for MAGICC as used in the TAR.

Table 1 shows the radiative forcing from pre-industrial times up to the year 2000; the radiative forcing from 2000-2050 for the reference case; and the sum of these two values. The change in radiative forcing from 2000 to 2050 is much larger than the change from pre-industrial times to 2000. This is due to the presence of a significant cooling effect from aerosols in the historical period that has “masked” other forcing increases. Over the next half century the net effect of aerosols is found to be small, which is a marked transition from the historical period when emissions of aerosols and aerosol precursors increased substantially.

Radiative forcing changes over the next half century are dominated by the increase in carbon dioxide emissions. Note that, while the relationship between carbon dioxide concentrations and forcing is well quantified, the relationship between emissions and concentration is not nearly as well understood. Given the B2 reference case emissions, the resulting carbon dioxide concentration, and therefore forcing, could be significantly higher or lower than the value shown.

The change in forcing due to carbon dioxide from 2000 to 2050 is 1.7 W/m^2 , and the net effect of the other forcing components is to add an additional 0.6 W/m^2 . Increased forcing is seen from methane, nitrous oxide, and halocarbons. Increases in emissions of reactive gases, particularly NO_x , result in a global increase in tropospheric ozone. Long-term decreases in NO_x in OECD regions are more than offset by increases in other regions. Sulfur emissions decrease globally, leading to an increase in forcing relative to the year 2000 as the cooling effect of sulfate aerosols decreases. A decrease in black carbon emissions results in a net decrease in forcing from carbonaceous aerosols.

The total forcing over 2000-2050 in the reference case is 2.3 W/m^2 . To put this value into context, for an equilibrium climate sensitivity ranging from 1.5 to $4.5 \text{ }^\circ\text{C}/\text{CO}_2$ doubling this forcing would result in an additional 1 to $3 \text{ }^\circ\text{C}$ of global-mean equilibrium temperature increase (in addition to the uncertain anthropogenic increase experienced up to the year 2000).

4. POLICY CASE FORCING CHANGE

The policy case used for this analysis limits carbon dioxide concentrations to 450 ppmv in 2100. This case is fairly stringent, with global carbon dioxide emissions by 2050 lower than they are at present. We choose this particular scenario for illustrative purposes, because it highlights the role of non- CO_2 forcing agents and it results in a CO_2 forcing similar to that suggested by Hansen *et al.* (2000). We do not imply that such a case is desirable (or necessarily even feasible). By 2050 all available mitigation options for non- CO_2 greenhouse gases are in force. The substantial decrease in fossil fuel use necessary to meet this target also results

in a significant decreases in tropospheric ozone relative to the base case. The total forcing from 2000 to 2050 is 1.8 W/m^2 , or 0.5 W/m^2 less than the base case.

Figure 1 shows the change in radiative forcing over 2000-2050 between the policy and reference cases. A positive number in this Figure means that there has been a reduction in forcing in the policy case. The largest forcing reduction is, by far, for carbon dioxide. Additional forcing reductions are seen for methane, tropospheric ozone, black carbon, and the halocarbons. These forcing reductions were, however, offset by forcing increases from sulfur dioxide and organic carbon. Excluding sulfur dioxide, the non- CO_2 forcing agents exhibited a forcing reduction of 0.34 W/m^2 , or roughly half of the reduction seen for carbon dioxide. This reduction, however, was offset by an increase in forcing of almost 0.5 W/m^2 in sulfate forcing. The net effect of all non- CO_2 forcing agents in this case is, therefore, a small increase in forcing.

Note that some of the forcing changes shown are due to the indirect effects of the carbon emissions reduction. All of the carbon dioxide and aerosol reductions, and most of the changes seen in troposphere ozone are accounted for by such indirect changes. Most of the reduction in methane forcing is due to direct actions to reduce methane emissions (tapping landfill gases, coal bed methane recovery, etc.). A portion (25%) of the reduction in tropospheric ozone forcing is due to the direct reductions in methane emissions. The remainder is due largely to indirect

2050 Forcing Difference (Reference – Policy)

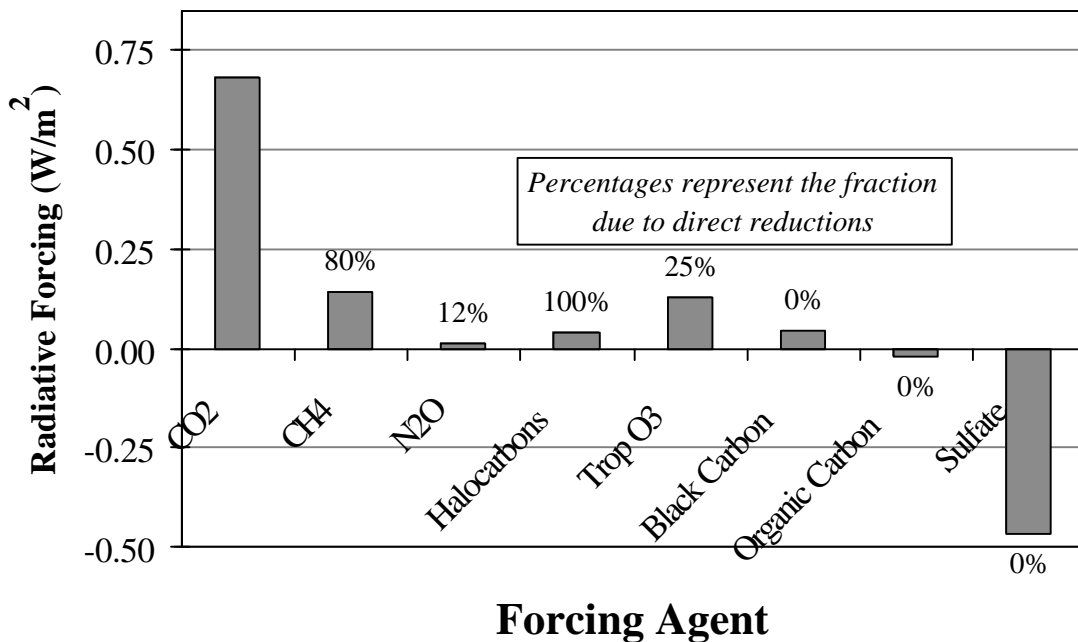


Figure 1—The change in radiative forcing from 2000-2050 between the reference and policy case. A positive value means that the policy case has a lower forcing for that substance than the reference case. Categories are as in Figure 1. The percentages show the fraction of the reduction due to direct actions to reduce non- CO_2 greenhouse gases. The remainder of the reductions are due to the indirect effect of the CO_2 reduction (such as reduced use of fossil fuels).

reductions in reactive gas emissions.

5. UNCERTAINTIES

Given that we have specified the carbon dioxide concentration target for these scenarios, the principal remaining uncertainties are in the magnitude of aerosol forcings, the magnitude of black carbon emissions, and the amount of reductions available for non-CO₂ greenhouse gases. The present-day forcing values for all of the aerosol species are highly uncertain. A change in the assumption for any of these forcings would directly affect these results. If the assumed sulfate aerosol forcing were halved, for example, then the value of the forcing and forcing changes shown here would also be approximately halved. In addition, there are thought to be indirect aerosol effects for carbonaceous aerosols that are too uncertain to be included explicitly in these calculations (Ramaswamy *et al.* 2001).

Recent work indicates that the positive forcing from black carbon could be larger than assumed here. Consider a simple sensitivity case where we assume that global black carbon forcing is 0.7 W/m² (for a 0.4 W/m² fossil BC forcing) and that the total sulfate aerosol effect is -0.8 W/m². The net global aerosol effect of aerosols in 2000 under these assumptions is still negative, but reduced to -0.5 W/m² as compared to -1.1 W/m² in our reference case above. The magnitude of the sulfate and black carbon effects to 2050 are changed proportionally, with changes of -0.17 and +0.16 respectively (compare to Figure 1). This results in a total forcing reduction (reference-minus-policy) over 2000-2050 of 0.75 W/m², compared to 0.56 W/m² under our previous assumptions. The change in aerosol assumptions, therefore, resulted in a larger forcing reduction, with an increased role for black carbon aerosol forcing.

There are some general limits, however, to the amount that the radiative forcing assumptions for each species can be varied. There is a general view that a significant net aerosol cooling effect exists, based in part on climate “pattern match” studies in which historical climate changes are matched with general circulation model (GCM) results (Penner *et al.* 1997; Forest *et al.* 2002). Observational studies also indicate that the net direct forcing effect of biomass burning aerosols is negative, which places limits on the relative forcing effect of black and organic carbon aerosols for a given set of emission inventory values.

Finally, the role of methane and nitrous oxide mitigation may be under reported in this calculation because climate-policy reductions for methane and nitrous oxide were available only for energy and urban sources. Marginal abatement cost curves for the reduction of emissions from agriculture are being developed. Once these are available a similar calculations will produce a larger reduction in methane emissions in particular. Similarly, no climate policy driven reduction in black carbon emissions were included in these calculations.

6. CONCLUSIONS

We have presented here preliminary calculations of the role of the most important greenhouse gases and aerosol species in climate mitigation over the next

fifty years. Under an example policy case, in which the role of non-CO₂ forcing agents is maximized, we find that carbon dioxide provides the largest forcing reduction by far. Sulfate aerosols produce the next largest forcing change, contributing a net positive effect (relative to 2000) over the next fifty years. Under our reference case assumptions, reductions in methane and tropospheric ozone contribute significantly to forcing reduction in the policy case. The remaining forcing agents considered (nitrous oxide, halocarbons, and carbonaceous aerosols) contribute less than 0.1 W/m² each to forcing reduction. Under a sensitivity test the change in black carbon forcing over the next half century is increased, however sulfate-forcing change is still the second most important change.

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