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Effects of Air Pollution Control on Climate

Ronald G. Prinn, John Reilly, Marcus Sarofim, Chien Wang and Benjamin Felzer

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Effects of Air Pollution Control on Climate

Ronald Prinn[*], John Reilly[*], Marcus Sarofim[*], Chien Wang[*] and Benjamin Felzer[†]

Abstract

Urban air pollution and climate are closely connected due to shared generating processes (e.g., combustion) for emissions of the driving gases and aerosols. They are also connected because the atmospheric lifecycles of common air pollutants such as CO, NO_x and VOCs, and of the climatically important methane gas (CH_4) and sulfate aerosols, both involve the fast photochemistry of the hydroxyl free radical (OH). Thus policies designed to address air pollution may impact climate and vice versa. We present calculations using a model coupling economics, atmospheric chemistry, climate and ecosystems to illustrate some effects of air pollution policy alone on global warming. We consider caps on emissions of NO_x, CO, volatile organic carbon, and SO_x both individually and combined in two ways. These caps can lower ozone causing less warming, lower sulfate aerosols yielding more warming, lower OH and thus increase CH_4 giving more warming, and finally, allow more carbon uptake by ecosystems leading to less warming. Overall, these effects significantly offset each other suggesting that air pollution policy has a relatively small net effect on the global mean surface temperature and sea level rise.However, our study does not account for the effects of air pollution policies on overall demand for fossil fuels and on the choice of fuels (coal, oil, gas), nor have we considered the effects of caps on black carbon or organic carbon aerosols on climate. These effects, if included, could lead to more substantial impacts of capping pollutant emissions on global temperature and sea level than concluded here. Caps on aerosols in general could also yield impacts on other important aspects of climate beyond those addressed here, such as the regional patterns of cloudiness and precipitation.

Contents

1. INTRODUCTION

Urban air pollution has a significant impact on the chemistry of the atmosphere and thus potentially on regional and global climate. Already, air pollution is a major issue in an increasing number of megacities around the world, and new policies to address urban air pollution are likely to be enacted in many developing countries irrespective of the participation of these countries in any explicit future climate policies. The emissions of gases and microscopic particles (aerosols) that are important in air pollution and climate are often highly correlated due to shared generating processes. Most important among these processes is combustion of fossil fuels and biomass which

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produces carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), black carbon (BC) aerosols, and sulfur oxides (SO_x, comprised of some sulfate aerosols, but mostly SO_2 gas which subsequently forms white sulfate aerosols). In addition, the atmospheric lifecycles of common air pollutants such as CO, NO_x and VOCs, and of the climatically important methane (CH_4) and sulfate aerosols, both involve the fast photochemistry of the hydroxyl free radical (OH). Hydroxyl radicals are the dominant "cleansing" chemical in the atmosphere, annually removing about 3.7 gigatons (1 gigaton = 10^{15} gm) of reactive trace gases from the atmosphere; this amount is similar to the total mass of carbon removed annually from the atmosphere by the land and ocean combined (Ehhalt, 1999; Prinn, 2003).

In this paper we report exploratory calculations designed to show some of the major effects of specific global air pollutant emission caps on climate. In other words, could future air pollution policies help to mitigate future climate change or exacerbate it? For this purpose, we will need to consider carefully the connections between the chemistry of the atmosphere and climate. These connections are complex and their nonlinearity is exemplified by the fact that concentrations of ozone in urban areas for a given level of VOC emissions tend to increase with increasing NO_x emissions until a critical CO-dependent or VOC-dependent NO_x emission level is reached. Above that critical level, ozone concentrations actually decrease with increasing NO_x emissions emphasizing the need for policies to consider CO, VOC and NO_x emission reductions jointly rather than independently.

In order to interpret the results of our calculations presented later, it is necessary to understand some of the reasons for the above complexity and nonlinearity in air chemistry. Hence, the next section provides a review of the key issues, aimed especially at the non-expert. In two sections following that, we introduce the global model that we use for our calculations and present and interpret the results. We end with a summary and concluding remarks.

2. A CHEMISTRY PRIMER

The ability of the lower atmosphere (troposphere) to remove most air pollutants depends on complex chemistry driven by the relatively small amount of the sun's ultraviolet light that penetrates through the upper atmospheric (stratospheric) ozone layer (see: Ehhalt, 1999; Prinn, 2003). This chemistry is also driven by emissions of NO_x, CO, CH_4 and VOCs and leads to the production of O_3 and OH. **Figure 1** reviews, with much simplification, the chemical reactions involved (Prinn, 1994). The importance of this chemistry to climate change occurs because it involves both climate-forcing greenhouse gases (H_2O, CH_4, O_3) and air pollutants (CO, NO, NO_2). It also involves aerosols (H_2SO_4, HNO_3, BC) that influence climate (through reflecting or absorbing sunlight), productivity of ecosystems (through their exposure to O_3, and to H_2SO_4 and HNO_3 in acid rain), and human health (through inhalation). Also important are free radicals and atoms in two forms: very reactive species like $O(^1D)$ and OH, and less reactive ones like HO_2, $O(^3P)$, NO and NO_2.

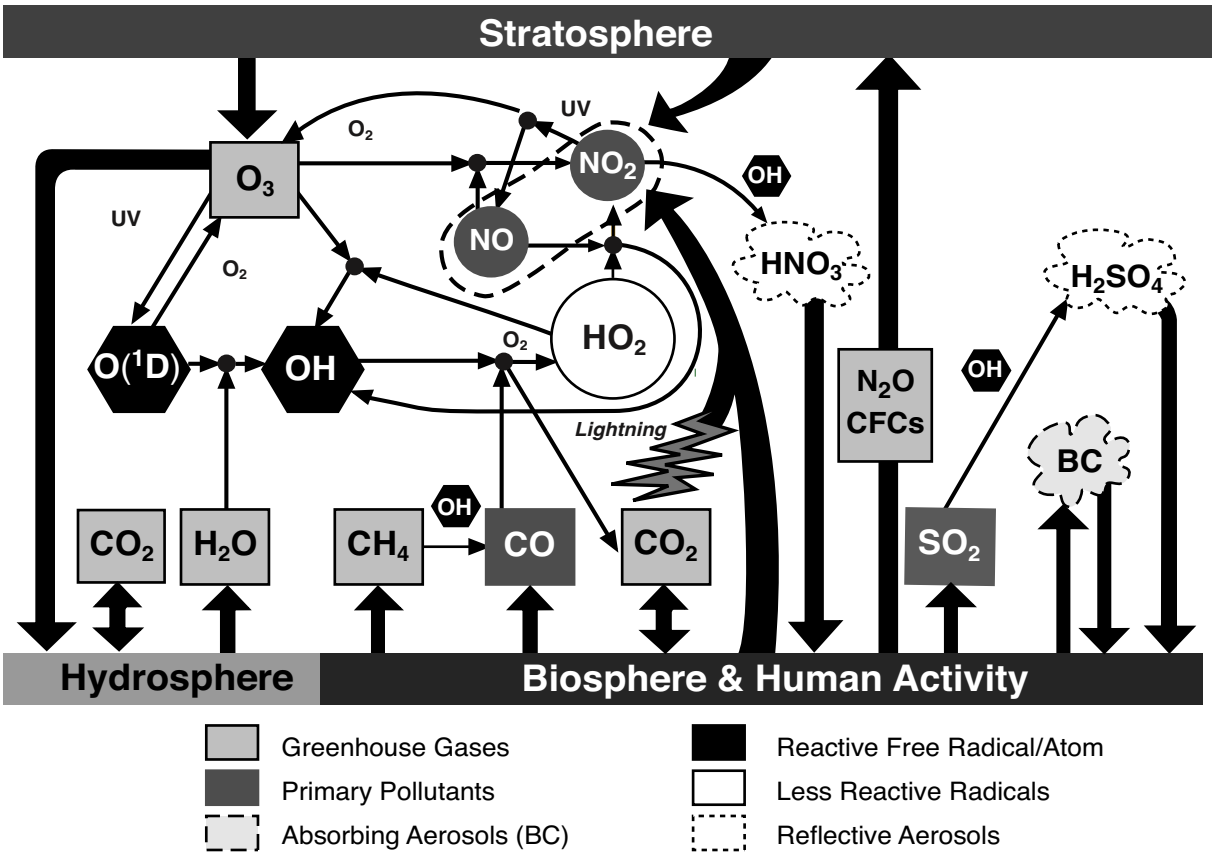

Figure 1. Summary of the chemistry in the troposphere important in the linkage between urban air pollution and climate (after Prinn, 1994, 2003). VOCs (not shown) are similar to CH_4 in their reactions with OH, but they form acids, aldehydes and ketones in addition to CO.

Referring to Figure 1, when OH reacts with CH_4 the CH_4 is converted mostly to CO in steps that consume OH and also produce HO_2. The OH in turn converts CO to CO_2, NO_2 to HNO_3, and SO_2 to H_2SO_4. The primary OH production pathway occurs when H_2O reacts with the $O(^1D)$ atoms that come from dissociation of O_3 by ultraviolet (UV) light. Within about a second of its formation, on average, OH reacts with other gases, either by donating its O atom (*e.g.*, to CO to form CO_2 and H) or by removing H (*e.g.*, from CH_4 to form CH_3 and H_2O). The H and CH_3 formed in these ways attach rapidly to O_2 to form hydroperoxy (HO_2) or methylperoxy (CH_3O_2) free radicals which are relatively unreactive. If there is no way to rapidly recycle HO_2 back to OH, then levels of OH are kept relatively low. The addition of NO_x emissions into the mix significantly changes the chemistry. Specifically, a second pathway is created in which NO reacts with HO_2 to form NO_2 and to reform OH. Ultraviolet light then decomposes NO_2 to produce O atoms (which attach to O_2 to form O_3) and reform NO. Hence NO_x (the sum of NO and NO_2) is a catalyst which is not consumed in these reactions. The production rate of OH by this secondary path in polluted air is about five times faster than the above primary pathway involving $O(^1D)$ and H_2O (Ehhalt, 1999). The reaction of NO with HO_2 does not act as a sink for HO_x (the sum of OH and HO_2) but instead determines the ratio of OH to HO_2. Calculations for

polluted air suggest that HO_2 concentrations are about 40 times greater than OH (Ehhalt, 1999). This is due mainly to the much greater reactivity of OH compared to HO_2.

If emissions of air pollutants that react with OH, such as CO, VOCs, CH_4, and SO_2, are increasing, then keeping all else constant, OH levels should decrease. This would increase the lifetime and hence concentrations of CH_4. However, increasing NO_x emissions should increase tropospheric O_3 (and hence the primary source of OH), as well as increase the recycling rate of HO_2 to OH (the second source of OH). This OH increase should lower CH_4 concentrations. Thus changing the level of OH causes greenhouse gas, and thus climate, changes. Climate change will also influence OH. Higher ocean temperatures should increase H_2O in the lower troposphere and thus increase OH production through its primary pathway. Higher atmospheric temperatures also increase the rate of reaction of OH with CH_4, decreasing the concentrations of both. Greater cloud cover will reflect more solar ultraviolet light, thus decreasing OH, and vice versa.

Added to these interactions involving gases, are those involving aerosols. For example, increasing SO_2 emissions and/or OH concentrations should lead to greater concentrations of sulfate aerosols which are a cooling influence. Accounting for all of these interactions, and other related ones (see *e.g*., Prinn, 2003), requires that a detailed interactive atmospheric chemistry and climate model be used to assess the effects of air pollution reductions on climate.

3. INTEGRATED GLOBAL SYSTEM MODEL

For our calculations, we utilize the MIT Integrated Global System Model (IGSM). The IGSM consists of a set of coupled submodels of economic development and its associated emissions, natural biogeochemical cycles, climate, air pollution, and natural ecosystems (Prinn *et al*., 1999; Reilly *et al*., 1999; Webster *et al*., 2002, 2003). It is specifically designed to address key questions in the natural and social sciences that are amenable to quantitative analysis and are relevant to environmental policy. The current structure of the IGSM is shown in **Figure 2**.

Chemically and radiatively important trace gases and aerosols are emitted as a result of human activity. The Emissions Prediction and Policy Analysis (EPPA) submodel incorporates the major relevant demographic, economic, trade, and technical issues involved in these emissions at the national and global levels. Natural emissions of these gases are also important and are computed in the Natural Emissions Model (NEM) which is driven by IGSM predictions of climate and ecosystem states around the world.

The coupled atmospheric chemistry and climate submodel is in turn driven by the combination of these anthropogenic and natural emissions. This submodel includes atmospheric and oceanic chemistry and circulation, and land hydrological processes. The atmospheric chemistry component has sufficient detail to include its sensitivity to climate and different mixes of emissions, and to address the effects on climate of policies proposed for control of air pollution and vice versa (Wang *et al*., 1998; Mayer *et al*., 2000). Of particular importance to the calculations presented here, the urban air pollution (UAP) submodel is based upon, and designed

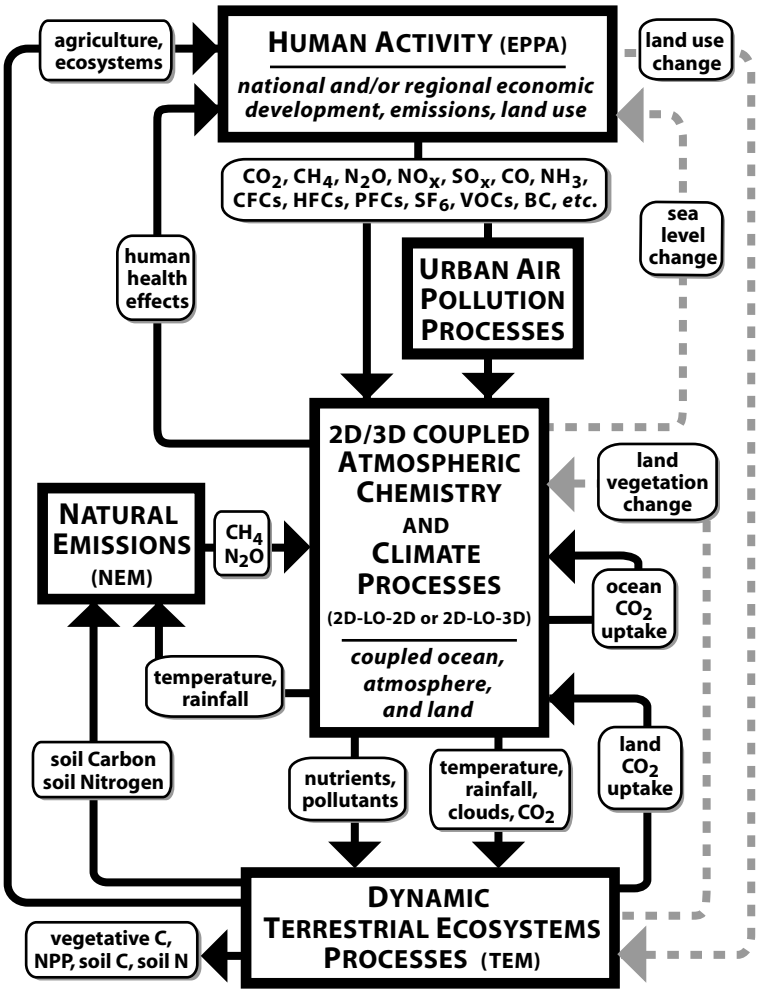

Figure 2. Schematic illustrating the framework, submodels, and processes in the MIT Integrated Global System Model (IGSM). Feedbacks between the component models that are currently included, or proposed for inclusion in later versions, are shown as solid or dashed lines respectively (adapted from Prinn *et al*., 1999).

to simulate, the detailed chemical and dynamical processes in current 3D urban air chemistry models (Mayer *et al*., 2000). For this purpose, the emissions calculated in the EPPA submodel are divided into two parts: urban emissions which are processed by the UAP submodel before entering the global chemistry/climate submodel, and non-urban emissions which are input directly into the large-scale model. The UAP enables simultaneous consideration of control policies applied to local air pollution and global climate. It also provides the capability to assess the effects of air pollution on ecosystems, and to predict levels of irritants important to human health in the growing number of megacities around the world. The atmospheric and oceanic circulation components in the IGSM are simplified compared to the most complex models available, but they capture the major processes and, with appropriate parameter choices, can mimic quite well the zonal-average behavior of the complex models (Sokolov and Stone, 1998; Sokolov *et al*., 2003). We use the version of the IGSM with 2D atmospheric and 2D oceanic

submodels here, although the latest version has a 3D ocean to capture better the deep ocean circulations that serve as heat and CO_2 sinks (Kamenkovich *et al*., 2002, 2003). The 2D/2D version we use here resolves separately the land and ocean (LO) processes at each latitude and so is referred to as the 2D-LO-2D version.

The outputs from the coupled atmospheric chemistry and climate model then drive a Terrestrial Ecosystems Model (TEM; Xiao *et al*., 1998) which calculates key vegetation properties including production of vegetation mass, land-atmosphere CO_2 exchanges, and soil nutrient contents in 18 globally distributed ecosystems. TEM then feeds back its computed CO_2 fluxes to the climate/atmospheric chemistry submodel, and its soil nutrient contents to NEM, to complete the IGSM interactions. The current IGSM does not include treatment of black carbon (BC) aerosols (see Figure 1). Detailed studies with a global 3D chemistry and climate model indicate multiple, regionally variable and partially-offsetting, effects of BC on absorption and reflection of sunlight, reflectivity of clouds, and the strength of lower tropospheric convection (Wang, 2004). These detailed studies also suggest important BC-induced changes in the geographic pattern of precipitation, not surprisingly since aerosols have important and complex effects on cloud formation, and on whether clouds will even produce precipitation. Methods to capture these effects in the IGSM are currently being explored. In light of the difficulty in simulating these and other regional effects, the numerical results presented here are limited to temperature and sea level effects, primarily at the global and hemispheric level.

4. NUMERICAL EXPERIMENTS

To investigate, at least qualitatively, some of the important potential impacts of controls of air pollutants on temperature, we have carried out runs of the IGSM in which individual pollutant emissions, or combinations of these emissions, are held constant from 2005 to 2100. These are compared to a reference run (denoted "ref") in which there is no explicit policy to reduce greenhouse gas emissions (see Reilly *et al.*, 1999; Webster *et al*., 2002).

Specifically, in five runs of the IGSM, we consider caps at 2005 levels of emissions of the following air pollutants:

(1) NO_x only (denoted "NO_x cap"),
(2) CO plus VOCs only (denoted "CO/VOC cap"),
(3) SO_x only (denoted "SO_x cap"),
(4) Cases (1) and (2) combined (denoted "3 cap"),
(5) Cases (1), (2) and (3) combined (denoted "all cap").

Cases (1) and (2) are designed to show the individual effects of controls on NO_x and reactive carbon gases (CO, VOC), although such individual actions are very unlikely. Case (3) addresses further controls on emissions of sulfur oxides from combustion of fossil fuels and biomass, and from industrial processes. Cases (4) and (5) address combinations more likely to be representative of a real comprehensive air pollution control approach.

One important caveat in interpreting our results is that we are neglecting the effects of air pollutant controls on: (a) the overall demand for fossil fuels (*e.g.*, leading to greater efficiencies in energy usage and/or greater demand for non-fossil energy sources), and (b), the relative mix of fossil fuels used in the energy sector (*i.e*. coal versus oil versus gas). Consideration of these effects, which may be very important, will require calculation in the EPPA model of the impacts of NO_x, CO, VOC and SO_x emission reductions on the cost of using coal, oil, and gas. Such calculations have not yet been included in the current global economic models (including EPPA) used to address the climate issue. Such inclusion requires relating results from existing very detailed studies of costs of meeting near-term air pollution control to the more aggregated structure, and longer time horizon, of models used to examine climate policy.

In **Figure 3** we show the ratios of the emissions of NO_x, CO/VOC, and SO_x in the year 2100 to the reference case in 2100 when their emissions are capped at 2005 levels. Because these chemicals are short-lived (hours to several days for NO_x, VOCs, and SO_x, few months for CO), the effects of their emissions are largely restricted to the hemispheres in which they are emitted (and for the shortest-lived pollutants restricted to their source regions). Figure 3 therefore shows hemispheric as well as global emission ratios. For calibration, the reference global emissions of NO_x, CO/VOC, and SO_x in 2100 are about 5, 2.5, and 1.5 times their 2000 levels.

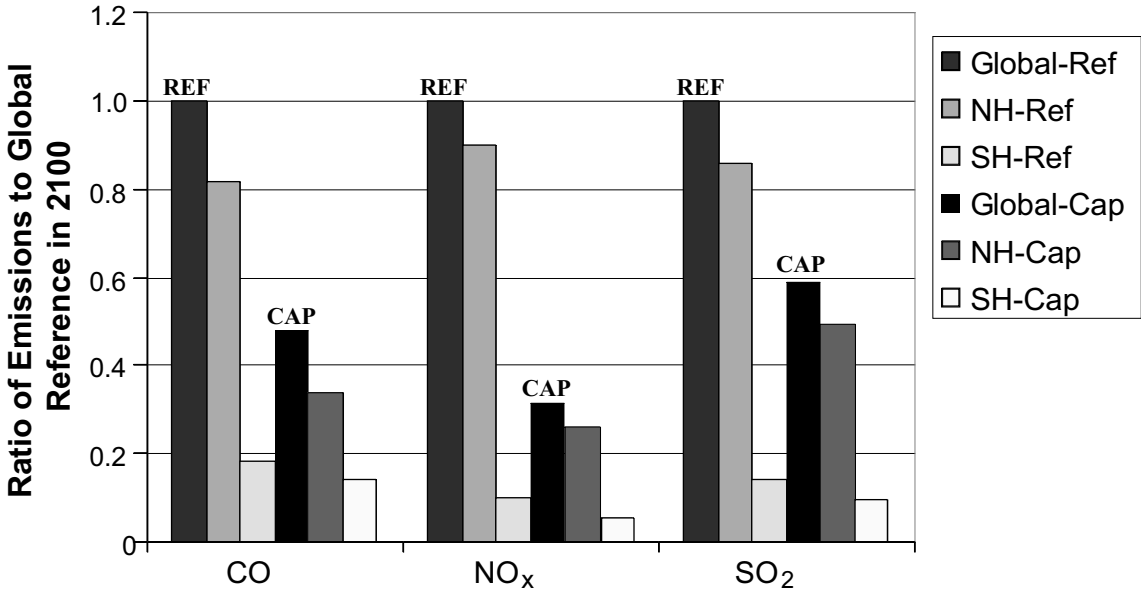

Figure 3. Global, northern hemispheric (NH) and southern hemispheric (SH) emissions in the year 2100 of CO/VOC, NO_x and SO_x, when they are capped at 2005 levels (CAP), are shown as ratios to emissions in the reference (REF) case (no caps).

4.1 Effects on concentrations

In **Figure 4**, the global and hemispheric average lower tropospheric concentrations of CH_4, O_3, sulfate aerosols, and OH in each of the above five capping cases are shown as percentage changes from the relevant global or hemispheric reference. From Figure 4a, the major global effects of capping SO_x are to decrease sulfate aerosols and slightly increase OH (due to lower SO_2 which is an OH sink). Capping of NO_x leads to decreases in O_3 and OH and an increase in CH_4 (caused by the lower OH which is a CH_4 sink). The CO and VOC cap increases OH and thus increases sulfate (formed by OH and SO_2) and decreases CH_4. Note that CO and VOC changes have opposing effects on O_3 so the net changes when they are capped together are small. Combining NO_x, CO and VOC caps leads to an O_3 decrease (driven largely by the NO_x decrease) and a slight increase in CH_4 (the enhancement due to the NO_x caps being partially offset by the opposing CO/VOC caps). Finally, capping all emissions causes substantial lowering of sulfate aerosols and O_3 and a small increase in CH_4.

The two hemispheres generally respond somewhat differently to these caps due to the short air pollutant lifetimes and dominance of northern over southern hemispheric emissions (Figs. 4b and 4c). The northern hemisphere contributes the most to the global averages and therefore responds similarly (compare Figs. 4a and 4c). The southern hemisphere shows very similar decreases in sulfate aerosol from its reference when compared to the northern hemisphere when either SO_x or all emissions are capped (compare Figs. 4b and 4c).

When compared to the southern hemisphere, the northern hemispheric ozone levels decrease by much larger percentages below their northern hemisphere reference when either NO_x, NO_x/CO/VOC, or all emissions are capped. Capping NO_x emissions leads to significant decreases in OH and thus increases in methane in both hemispheres (Figs. 4b and 4c). Because methane has a long lifetime (about 9 years, Prinn *et al.*, 2001) relative to the interhemispheric

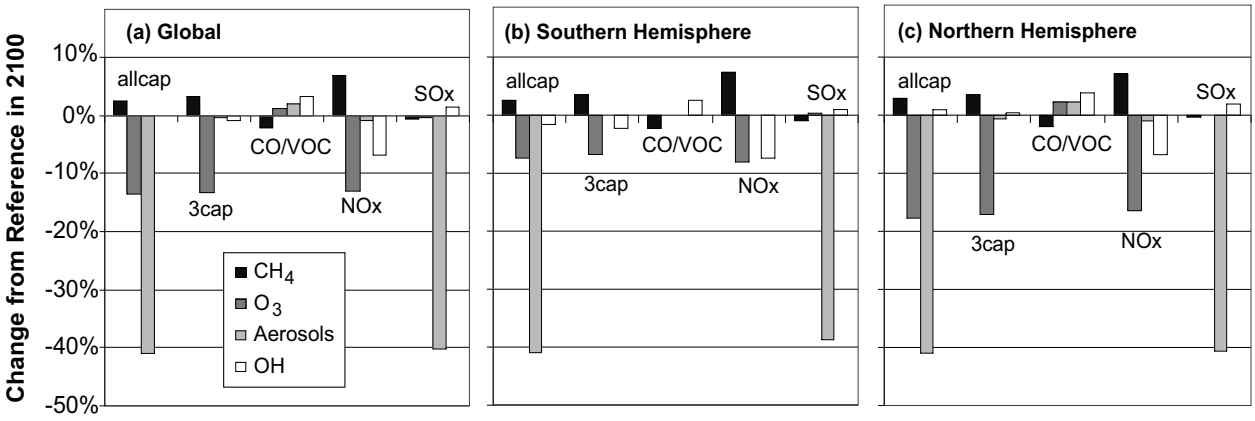

Figure 4. Concentrations of climatically and chemically important species (CH_4, O_3, aerosols, OH) in the five cases with capped emissions are shown as percent changes from their relevant global or hemispheric average values in the reference case for the year 2100: (a) global-average; (b) southern hemispheric; and (c) northern hemispheric concentrations.

mixing time (about 1 to 2 years), its global concentrations are influenced by OH changes in either hemisphere alone, or in both. Hence CH_4 also increases in both hemispheres when NO_x/CO/VOC or all emissions are capped even though the OH decreases only occur in the northern hemisphere in these two cases (see Figs. 4b and 4c).

4.2 Effects on ecosystems

Effects of air pollution on the land ecosystem sink for carbon can be significant due to reductions in ozone-induced plant damage (**Figure 5**, see also Felzer *et al.*, 2004). Net primary production (NPP, the difference between plant photosynthesis and plant respiration), as well as net ecosystem production (NEP, which is the difference between NPP and soil respiration plus decay, and represents the net land sink), both increase when ozone decreases. This is evident in the case illustrated in Figure 5 where all pollutants are capped and ozone decreased by about 13% globally (Figure 4a). The effect is even greater when we assume that cropland and managed forests receive optimal levels of nitrogen fertilizer ("with Fertilizer" case; Felzer *et al*., 2004a,b). The land sink (NEP) is increased by 30 to 49% or 0.6 to 0.9 gigatons of carbon (in CO_2) in 2100 through the illustrated pollution caps (Figure 5, 1 gigaton=10^{15} gm).

These ecosystem calculations do not include the additional positive effects on NPP and NEP of decreased acid deposition and decreased exposure to SO_2 and NO_2 gas, that would result from the pollution caps considered. They also do not include the negative effects on NPP and NEP of decreasing nutrient nitrate and possibly sulfate deposition that also arise from these caps.

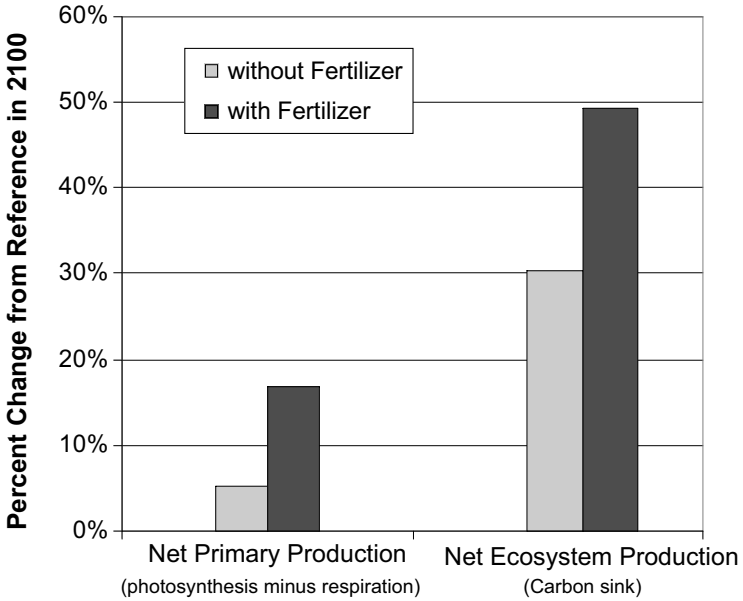

Figure 5. Net annual uptake of carbon by vegetation alone (net primary production) and vegetation plus soils (net ecosystem production, the land carbon sink) for the NO_x/SO_x/CO plus VOC capped (allcap) case is shown for the year 2100 as a percentage change from the reference case. The results show the effects with optimal nitrogen use through fertilization on cropland (with Fertilizer) or with levels of nitrogen in croplands assumed to be the same as those in equivalent natural ecosystems (without Fertilizer).

4.3 Economic effects

If we could confidently value damages associated with climate change, we could estimate the avoided damages in dollar terms resulting from reductions in temperature due to the lowered level of atmospheric CO_2 caused by the above increases in the land carbon sink achieved with the ozone caps. We could similarly value the temperature changes due to caps in other pollutants besides ozone. However monetary damage estimates suffer from numerous shortcomings (*e.g.*, Jacoby, 2004). Felzer *et al*. (2004a,b) valued increases in carbon storage in ecosystems due to decreased ozone exposure in terms of the avoided costs of fossil fuel CO_2 reductions needed to achieve an atmospheric stabilization target. The particular target they examined was 550 ppm CO_2. The above extra annual carbon uptake (due to avoided ozone damage) of 0.6 to 0.9 gigatons of carbon is only 2 to 4% of year 2100 reference projections of anthropogenic fossil CO_2 emissions (which reach nearly 25 gigatonsC/year in 2100 according to Felzer *et al*. (2004b)). However, as these authors point out, this small level of additional uptake can have a surprisingly large effect on the cost of achieving a climate policy goal. Here we conduct a similar analysis using a 5% discount rate, and adopting the policy costs associated with 550 ppm CO_2 stabilization, to estimate the policy cost savings that would result from the increased carbon uptake through 2100 in the "allcap" compared to the "ref" scenarios shown in Figure 5. The savings are $2.5 ("without Fertilizer") to $4.7 ("with Fertilizer") trillion (1997 dollars). These implied savings are 12 to 22% of the total cost of a 550ppm stabilization policy.

The disproportionately large economic value of the additional carbon uptake has two reasons. One reason is that the fossil carbon reduction savings are cumulative; the total reference 2000-2100 carbon uptake is 36 (without Fertilizer) and 75 (with Fertilizer) gigatons, or about 6 to 13 years of fossil carbon emissions at current annual rates. A second reason is that the additional uptake avoids the highest marginal cost options. This assumes that the implemented policies would be cost effective in the sense that the least costly carbon reduction options would be used first, and more costly options would only be used later if needed. An important caveat here is that, as shown in Felzer *et al*. (2004a,b), a carbon emissions reduction policy also reduces ozone precursors so that an additional cap on these precursors associated with air pollution policy results in a smaller additional reduction, and less avoided ecosystem damage. A pollution cap as examined here, assuming there was also a 550ppm carbon policy in place, leads to only a 0.1 to 0.8 gigaton increase in the land sink in 2100 (compare 0.6 to 0.9 gigatons in Figure 5) and a cumulative 2000-2100 increase of carbon uptake of 13 to 40 gigatons of carbon, which is about one-half of the above increased cumulative uptake when the pollution cap occurs assuming there is no climate policy.

4.4 Effects on temperature and sea level

The impact of these various pollutant caps on global and hemispheric mean surface temperature and sea level changes from 2000 to 2100 are shown in **Figure 6** as percentages relative to the global-average reference case changes of 2.7°C and 0.4 meters respectively.

The largest increases in temperature and sea level occur when SO_x alone is capped due to the removal of reflecting (cooling) sulfate aerosols. Because most SO_x emissions are in the northern hemisphere, the temperature increases are greatest there. For the NO_x caps, temperature increases in the southern hemisphere (driven by the CH_4 increases), but decreases in the northern hemisphere (due to the cooling effects of the O_3 decreases exceeding the warming driven by the CH_4 increases). For CO and VOC reductions, there are small decreases in temperature driven by the accompanying aerosol increases and CH_4 reductions, with the greatest effects being in the northern hemisphere where most of the CO and VOC emissions (and aerosol production) occur.

When NO_x, CO, and VOCs are all capped, the nonlinearity in the system is evidenced by the fact that the combined effects are not simple sums of the effects from the individual caps. Ozone

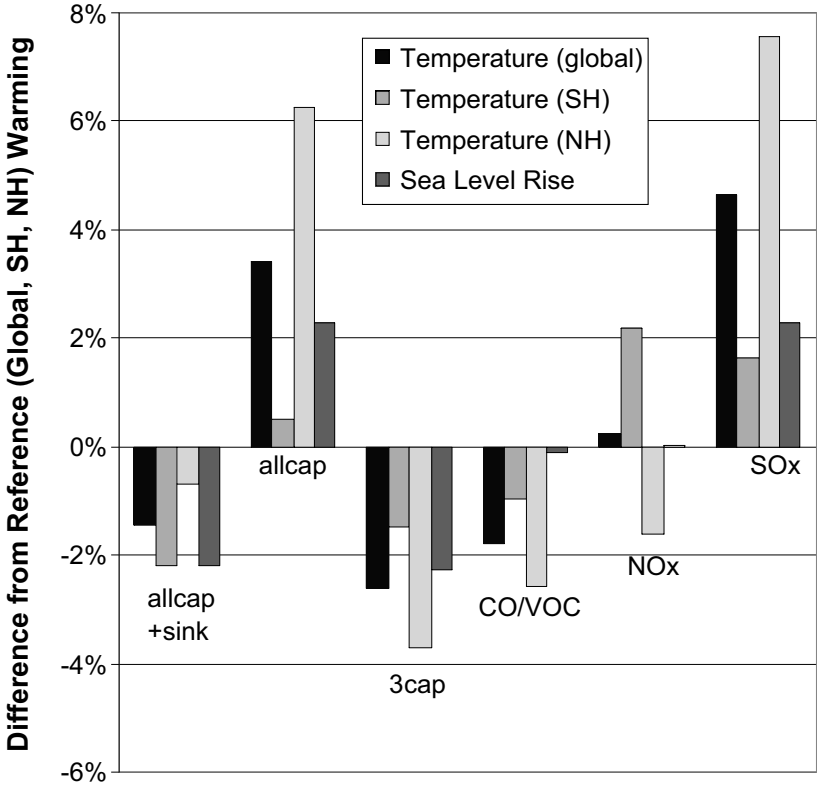

Figure 6. Effects of air pollution caps in the five capping cases on the global, northern hemispheric and southern hemispheric average temperature increases, and the global sea level rise, between 2000 and 2100 are shown as percent changes from their average values (global or hemispheric) in the reference case. Also shown are the equivalent results for the case where the enhanced sink due to the ozone cap is included along with the caps on all pollutants. For this case, we assume the average of the fertilized and non-fertilized sink enhancements from Figure 5.

decreases and aerosol increases (offset only slightly by CH_4 increases) lead to even less warming and sea level rise than obtained by adding the CO/VOC and NO_x capping cases. Finally the capping of all emissions yields temperature and sea level rises that are smaller but qualitatively similar to the case where only SO_x is capped, but the rises are greater than expected from simple addition of the SO_x-capped and CO/VOC/NO_x-capped cases. Nevertheless, the capping of CO, VOC and NO_x serves to reduce the warming induced by the capping of SO_x.

Note that these climate calculations in Figure 6 omit the cooling effects of the CO_2 reductions caused by the lessening of the inhibition of the land sink by ozone (Figure 5). This omission is valid if we presume that anthropogenic CO_2 emissions, otherwise restricted by a climate policy, are allowed to increase to compensate for these reductions. This was the basis for our economic analysis in the previous section. To illustrate the lowering of climate impacts if we allowed the sink-related CO_2 reductions to occur, we show a sixth case in Figure 6 ("allcap+sink") which combines the capping of all air pollutant emissions with the enhanced carbon sink from Figure 5. Now we see that the sign of the warming and sea level rise seen in the "allcap" case is reversed in the "allcap+sink" case. If we could value this lowering of climate impacts, it would provide an alternative to the economic analysis in section 4.3.

5. SUMMARY AND CONCLUSIONS

To illustrate some of the impacts of air pollution policy on climate change, we examined five highly idealized but informative scenarios for placing caps on emissions of SO_x, NO_x, CO plus VOCs, NO_x plus CO plus VOCs, and all of these pollutants combined. These caps kept global emissions at 2005 levels through 2100 and their effects on climate were compared to a reference run with no caps applied. Our purpose was not to claim that these scenarios are in any way realistic or likely, but rather that they served to illustrate quite well the complex interactions between air pollutant emissions and changes in temperature and sea level.

In general, placing caps on NO_x alone, or NO_x, CO and VOCs together, leads to lower ozone levels, and thus less radiative forcing of climate change by this gas, and to less inhibition by ozone of carbon uptake by ecosystems which also leads to less radiative forcing (this time by CO_2). Less radiative forcing by these combined effects means less warming and less sea level rise.

Placing caps on NO_x alone also leads to decreases in OH and thus increases in CH_4. These OH decreases and CH_4 increases are lessened (but not reversed) when there are simultaneous NO_x, CO and VOC caps. Increases in CH_4 lead to greater radiative forcing. Placing caps on SO_x leads to lower sulfate aerosols, less reflection of sunlight back to space by these aerosols (direct effect) and by clouds seeded with these aerosols (indirect effect), and thus to greater radiative forcing of climate change due to solar radiation. Enhanced radiative forcing by these aerosol and CH_4 changes combined leads to more warming and sea level rise. Hence these impacts on climate of the pollutant caps partially cancel each other. Specifically, depending on the capping case, the 2000-2100 reference global average climate changes are altered only by +4.8 to –2.6%

(temperature) and +2.2 to –2.2 % (sea level). Except for the NO_x alone case, the alterations of temperature are of the same sign but significantly greater in the northern hemisphere (where most of the emissions and emission reductions occur) than in the southern hemisphere. Note that for the NO_x alone caps, the temperature decrease caused by ozone reductions is greater than the temperature increase driven by methane increases in the northern hemisphere while the opposite is true in the southern hemisphere (Figure 6).

It is well established that urban air pollution control policies are beneficial for human health and downwind ecosystems. As far as ancillary benefits are concerned, our calculations suggest that air pollution policies may have only a small influence, either positive or negative, on mitigation of global-scale climate change. However, even small contributions to climate change mitigation can be disproportionately important in economic terms. This occurs because, as we show in the case of increased carbon uptake, these effects mean that the highest cost climate change mitigation measures, those occurring at the margin, can be avoided. To further check on the validity of our conclusions, future work should include:

(1) the effects of air pollution policy on overall demand for fossil fuels and individual demands for coal, oil and gas;

(2) the effects of caps on black carbon (as a regulated air pollutant) on climate;

(3) the effects on ecosystems of changes in deposition rates of acids, nitrates, and sulfates and levels of exposure to SO_2 and NO_2 resulting from air pollution reductions.

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6. REFERENCES

Ehhalt, D.H., 1999: Gas phase chemistry of the troposphere. *Topics in Physical Chemistry*, **6**: 21-109.

Felzer, B., Kicklighter, D., Melillo, J., Wang, C., Zhuang, Q., and Prinn, R., 2004a: Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus B*, **56**: 230-248.

Felzer, B., Reilly, J., Melillo, J., Kicklighter, D., Wang, C., Prinn, R., Sarofim, M., and Zhuang, Q.: 2004b: *Past and future effects of ozone on net primary production and carbon sequestration using a global biogeochemical model*. MIT JPSPGC Report 103 (http://mit.edu/globalchange/www/MITJPSPGC_Rpt103.pdf); *Climatic Change*, in press

Jacoby, H.D., 2004: Informing climate policy given incommensurable benefits estimates. *Global Environmental Change Part A*, **14**(3): 287-279; MIT JPSPGC Reprint 2004-7.

Kamenkovich, I.V., Sokolov, A.P. and Stone, P., 2002: An efficient climate model with a 3D ocean and statistical-dynamical atmosphere. *Climate Dynamics*, **1**: 585-598.

Kamenkovich, I.V., Sokolov, A.P. and Stone, P., 2003: Feedbacks affecting the response of the thermohaline circulation to increasing CO_2: A study with a model of intermediate complexity. *Climate Dynamics*, **21**: 119-130.

Mayer, M., Wang, C. Webster, M., and Prinn, R.G.: 2000. Linking local air pollution to global chemistry and climate. *J. Geophysical Research*, **105**: 20,869-20,896.

Prinn, R.G., 1994, The interactive atmosphere: Global atmospheric-biospheric chemistry. *Ambio,* **23**: 50-61.

Prinn, R.G., 2003: The cleansing capacity of the atmosphere. *Annual Reviews Environment and Resources,* **28**: 29-57.

Prinn, R.G., Huang, J., Weiss, R., Cunnold, D., Fraser, P., Simmonds, P., McCulloch, A., Harth, C., Salameh, P., O'Doherty, S., Wang, R., Porter, L., and Miller, B., 2001: Evidence for substantial variations of atmospheric hydroxyl radicals in the past two decades. *Science,* **292**:1882-1888.

Prinn, R.G., Jacoby, H., Sokolov, A., Wang, C., Xiao, X., Yang, Z., Eckaus, R., Stone, P., Ellerman, A.D., Melillo, J., Fitzmaurice, J., Kicklighter, D., Holian, G. and Liu, Y., 1999: Integrated Global System Model for climate policy assessment: feedbacks and sensitivity studies. *Climatic Change*, **41**: 469-546.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A. and Wang, C., 1999: Multi-gas assessment of the Kyoto Protocol. *Nature*, **401**: 549-555.

Sokolov, A., and Stone, P., 1998: A flexible climate model for use in integrated assessments. *Climate Dynamics*, **14**: 291-303.

Sokolov, A., Forest, C.E. and Stone, P., 2003: Comparing oceanic heat uptake in AOGCM transient climate change experiments. *J. Climate*, **16**: 1573-1582.

Wang, C., Prinn, R. and Sokolov, A., 1998: A global interactive chemistry and climate model: Formulation and testing. *J. Geophysical Research*, **103**: 3399-3417.

Wang, C., 2004: A modeling study on the climate impacts of black carbon aerosols. *J. Geophysical Research*, **109**: D03106, doi: 10.1029/2003JD004084.

Webster, M.D., Babiker, M., Mayer, M., Reilly, J.M., Harnisch, J., Sarofim, M.C., and Wang, C., 2002: Uncertainty in emissions projections for climate models. *Atmospheric Environment,* **36**: 3659-3670.

Webster, M.D., Forest, C.E., Reilly, J.M., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R.G., Sarofim, M., Sokolov, A., Stone, P.H., and Wang, C., 2003: Uncertainty analysis of climate change and policy response. *Climatic Change*, **61**: 295-320.

Xiao, X., Melillo, J., Kicklighter, D., McGuire, A., Prinn, R., Wang, C., Stone, P. and Sokolov, A., 1998: Transient climate change and net ecosystem production of the terrestrial biosphere. *Global Biogeochemical Cycles,* **12**: 345-360.

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