
Effects of air pollution control on climate: results from an integrated global system model

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8.1 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 because of shared generating processes. Most important among these processes is combustion of fossil fuels and biomass which produces carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), black carbon (BC) aerosols, and sulfur oxides (SO_x, consisting of some sulfate aerosols, but mostly SO₂ 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 (CH₄) 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 gigatonnes (1 GT = 10¹⁵ g) of reactive trace gases from the atmosphere; while the environmental impact of each gas is different, 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 non-linearity is exemplified by the fact that concentrations of ozone in urban areas for a given level of VOC emission 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 air pollution policies to consider CO, VOC, and NO_x emission reductions jointly rather than independently. In contrast, concentrations of ozone in the global middle and upper troposphere, where this gas exerts its major tropospheric radiative forcing of climate, are determined significantly by long-range transport from urban areas below and the stratosphere above, and ozone production by contrast is limited by low ambient NO_x levels.

We emphasize that this paper is not intended as a review of the extensive literature on various aspects of air pollution and climate, but rather as an opportunity to highlight some new results from one specific integrated approach to this subject. In order to interpret the results of our calculations presented later, however, it is necessary to understand some of the reasons for the above complexity and non-linearity in air chemistry. Hence, the next section provides a review of the key issues,

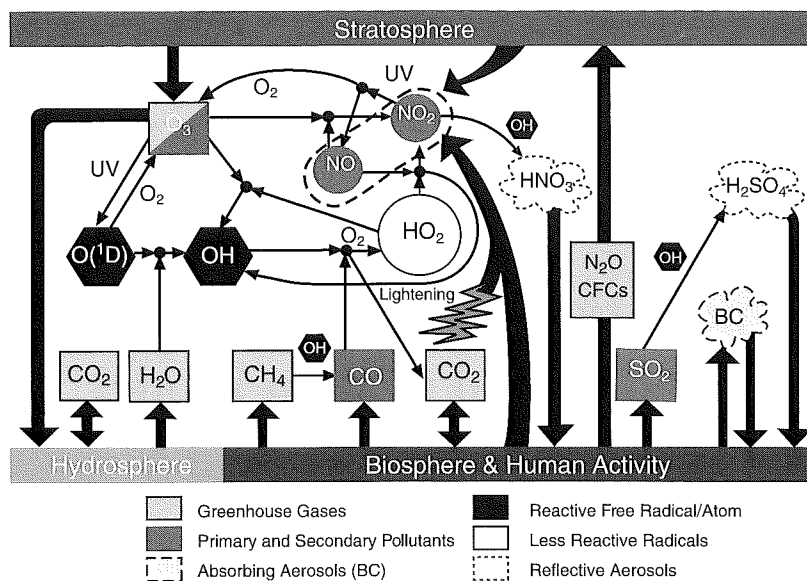


Figure 8.1 Summary of the chemistry in the troposphere important in the linkage between urban air pollution and climate (after Prinn, 1994, 2003). Volatile organic compounds as VOCs (not shown) are similar to CH₄ in their reactions with OH, but they form acids, aldehydes, and ketones in addition to CO.

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.

8.2 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 (Ehhalt, 1999; Prinn, 2003). This chemistry is also driven by emissions of NO_x, CO, CH₄, and VOCs and leads to the production of O₃ and OH. Figure 8.1 reviews, with much simplification, the chemical reactions involved (Prinn, 1994). This chemistry is important to climate change because it involves both climate-forcing greenhouse gases (H₂O, CH₄, O₃) and air pollutants (CO, NO, NO₂, O₃). It also involves aerosols (H₂SO₄, HNO₃, BC) that influence climate through reflecting sunlight (cooling the Earth) or absorbing sunlight (warming the atmosphere). Aerosols and gases also affect the productivity of ecosystems (negatively, through their exposure to O₃, and to H₂SO₄ and HNO₃ in acid rain; and positively, through deposition of nitrogen as nitrate or ammonium), and negatively affect human health (through inhalation). Also important are short-lived free radicals and atoms in two forms: very reactive species such as O(¹D) and OH, and less reactive ones such as HO₂, O(³P), NO, and NO₂.

Referring to Figure 8.1, when OH reacts with CH₄ the CH₄ is converted mostly to CO in steps that consume OH and also

produce HO₂. The OH in turn converts CO to CO₂, NO₂ to HNO₃, and SO₂ to H₂SO₄. The primary OH production pathway occurs when H₂O reacts with the O(¹D) atoms that come from dissociation of O₃ 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 CO₂ and H) or by removing H (e.g. from CH₄ to form CH₃ and H₂O). The H and CH₃ formed in these ways attach rapidly to O₂ to form hydroperoxy (HO₂) or methylperoxy (CH₃O₂) free radicals which are reactive but much less so than OH. If there is no way to rapidly recycle HO₂ 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 HO₂ to form NO₂ and to reform OH. Ultraviolet light then decomposes NO₂ to produce O atoms (which attach to O₂ to form O₃) and reform NO. Hence NO_x (the sum of NO and NO₂) is a catalyst which is not consumed in these reactions. The key net ozone-producing reactions being catalyzed by NO_x are CO + 2O₂ → CO₂ + O₃ and related reactions involving CH₄, and other VOCs. The production rate of OH by the above secondary path in polluted air is about five times as fast as the above primary pathway involving O(¹D) and H₂O (Ehhalt, 1999). The reaction of NO with HO₂ does not act as a sink for HO_x (the sum of OH and HO₂) but instead determines the ratio of OH to HO₂. Calculations for polluted air suggest that HO₂ concentrations are about 40 times as great as OH concentrations (Ehhalt, 1999). This is due mainly to the much greater reactivity of OH compared with HO₂. The ultimate sinks for the HO_x and NO_x free radicals involve formation of H₂O₂, HNO₃, and other water-soluble gases which can be removed

by rainfall and surface deposition. In addition to CO, the oxidation of VOCs produces water-soluble gases (e.g. aldehydes, ketones, organic acids) as well as organic aerosols, all of which can also be removed by wet and dry deposition.

If emissions of air pollutants that react with OH, such as CO, VOCs, CH₄, and SO₂, are increasing, then keeping all else constant, OH levels should decrease. This would increase the lifetime and hence concentrations of CH₄. However, increasing NO_x emissions should increase tropospheric O₃ (and hence the primary source of OH), as well as increasing the recycling rate of HO₂ to OH (the second source of OH). This OH increase should lower CH₄ concentrations. Thus an increase (decrease) in OH causes a decrease (increase) in CH₄ and other greenhouse gases and thus a decrease (increase) in radiative forcing of climate. Climate change will also influence OH. Higher ocean temperatures should increase H₂O 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 CH₄, decreasing the concentrations of both. Greater cloud cover will reflect more solar ultraviolet light, thus increasing OH above the clouds and decreasing it below, and vice versa.

Added to these interactions involving gases are those involving aerosols. For example, increasing SO₂ 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.

8.3 Integrated Global System Model

For our calculations, we use 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. To account for the very long timescales of oceanic circulation, the carbon cycle, and land ecosystems, the IGSM is initialized ("spun up") by integrating the model from 1765–1977 or 1860–1977 using historical forcings. Production runs then proceed from 1977 through 2100 (Prinn *et al.*, 1999; Webster *et al.*, 2003). The current structure of the IGSM is shown in Figure 8.2.

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 5-year intervals at the national and global levels. Natural emissions of

these gases are also important and are computed monthly 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, with 20-minute time steps, 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 (including the feedback between CH₄ emissions and OH), to agree reasonably well with ozone trace gas observations, 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 to simulate, the detailed non-linear 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. Also for this purpose, three categories of polluted urban areas are defined based on three threshold levels of NO_x emissions per unit area to best capture the chemical non-linearities (Mayer *et al.*, 2000). Also, the fraction of the global total emissions that occur in urban areas generally increases with time (see Section 8.4). The UAP allows 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 with 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 CO₂ 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 monthly including production of vegetation mass, land-atmosphere CO₂ exchanges, and soil nutrient contents in 18 globally distributed ecosystems. TEM then feeds back its

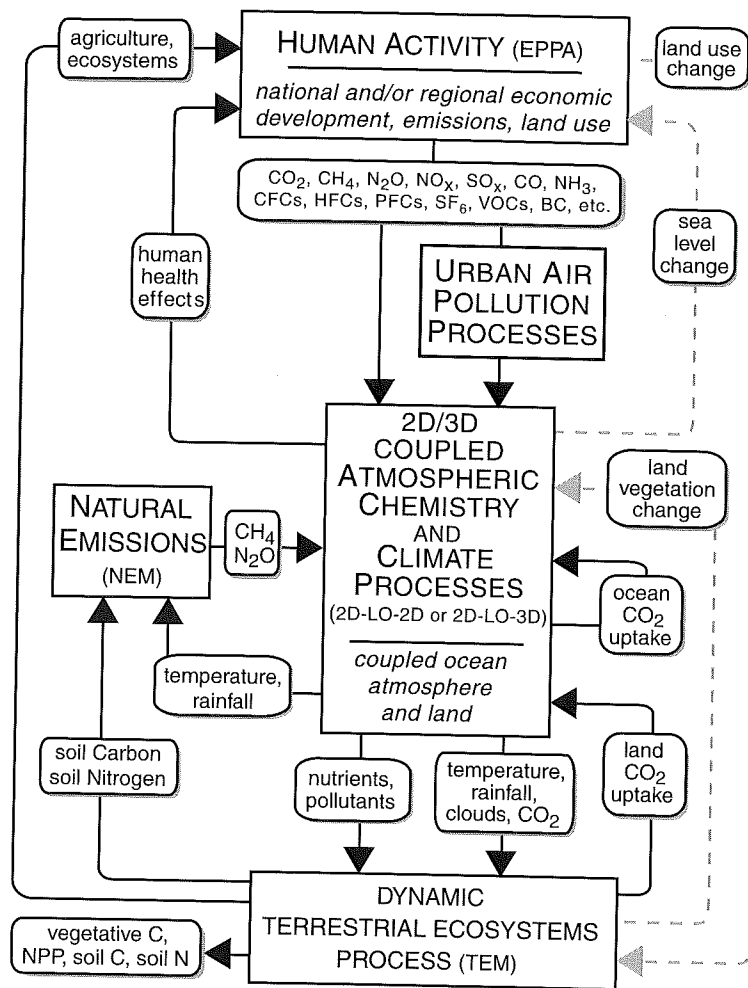


Figure 8.2 Schematic illustrating the framework, submodels, and processes in the MIT Integrated Global System Model (IGSM). Feedbacks between the component models that are currently included, or proposed for inclusion in later versions, are shown as solid or dashed lines respectively (adapted from Prinn *et al.*, 1999).

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 aerosols (see Figure 8.1). 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.

8.4 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 emissions are held constant from 2005 to 2100 for individual pollutants, or combinations of these pollutants from all anthropogenic activities including agriculture. These are compared with a reference run (denoted "ref") in which there is no explicit policy to reduce greenhouse gas emissions and no specific new policies to reduce air pollution (see Reilly *et al.*, 1999; Webster *et al.*, 2002). In the reference, urban emissions account for 16, 28, and 27% of global

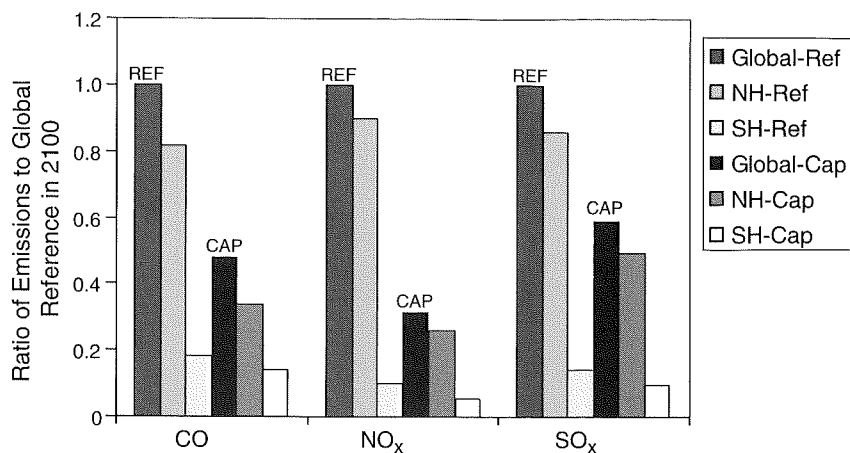


Figure 8.3 Global, northern hemispheric (NH), and southern hemispheric (SH) emissions in the year 2100 of CO/VOC, NO_x, and SO_x, when they are capped at 2005 levels (CAP), are shown as ratios to emissions in the reference (REF) case (no caps).

total CO, NO_x, and SO_x emissions in 2000 and 63, 75, and 64% in 2100, respectively.

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

1. NO_x only (denoted "NO_x cap"), with urban CO, NO_x, and SO_x emissions being 30, 31, and 26% of their 2100 global totals;
2. CO plus VOCs only (denoted "CO/VOC cap"), with urban CO, NO_x, and SO_x emissions being 42, 75, and 64% of their 2100 totals;
3. SO_x only (denoted "SO_x cap"), with urban CO, NO_x, and SO_x emissions being 63, 75, and 58% of their 2100 totals;
4. Cases (1) and (2) combined (denoted "3 cap"), with urban CO, NO_x, and SO_x emissions being 18, 31, and 26% of their 2100 totals;
5. Cases (1), (2), and (3) combined (denoted "all cap"), with urban CO, NO_x, and SO_x emissions being 18, 31, and 29% of their 2100 totals.

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 approach to air pollution control. Note that, relative to the reference cases (2) and (3), the caps on NO_x emissions that occur in cases (1), (4), and (5) lead to smaller total number, and a shift from the higher to the lower intensity categories, of polluted urban areas (see urban emission percentages above, and Section 8.3).

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 8.3 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 8.3 therefore shows hemispheric as well as global emission ratios. For calibration, the reference emissions in 2100 of CO₂, CH₄, SO_x, NO_x, CO, and VOCs are 24 GtC/yr, 864 megatonne (Mt) CH₄/yr, 235 Mt SO_x/yr, 397 Mt NO_x/yr, 2.6 Gt CO/yr, and 530 Mt VOC/yr respectively (1 Mt = 10¹² g). The reference global emissions of NO_x, CO/VOC, and SO_x in 2100 are about 4, 2.5, and 1.5 times their 2000 levels. Note that while our reference emissions have some similarities to the central IPCC IS92a scenarios (IPCC, 2000), they differ specifically in having substantially increasing SO_x, NO_x, CO, and VOC emissions through 2100 since

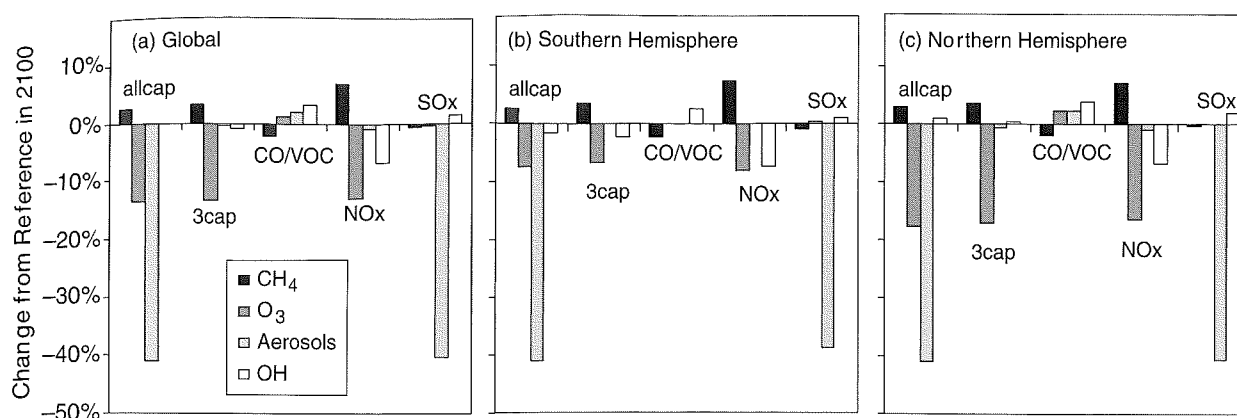


Figure 8.4 Concentrations of climatically and chemically important species (CH_4 , O_3 , aerosols, OH) in the five cases with capped emissions are shown as percentage changes from their relevant global or hemispheric average values in the reference case for the year 2100 (a) Global-average; (b) southern hemispheric; and (c) northern hemispheric concentrations.

they assume no specific air pollution policies beyond those already existing (Webster *et al.*, 2002).

8.4.1 Effects on concentrations

In Figure 8.4, 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. Note that the global production of O_3 and destruction of CO and CH_4 are both dominated by non-urban area chemistry, whereas the transformations of the much shorter-lived SO_x , NO_x , and VOCs also have a significant contribution from urban area chemistry. From Figure 8.4a, the major global effects of capping SO_x are to decrease sulfate aerosols and slightly increase OH (owing 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 the CO and VOC cap without a NO_x cap has only a small effect on O_3 . Combining NO_x , CO, and VOC caps leads to a substantial 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 because of the short air pollutant lifetimes and dominance of northern over southern hemispheric emissions (Figures 8.4b and 8.4c). The northern hemisphere contributes the most to the global averages and therefore the globe responds to the caps similarly to the northern hemisphere (compare Figures 8.4a and 8.4c). The southern hemisphere shows very similar decreases in sulfate aerosol from its

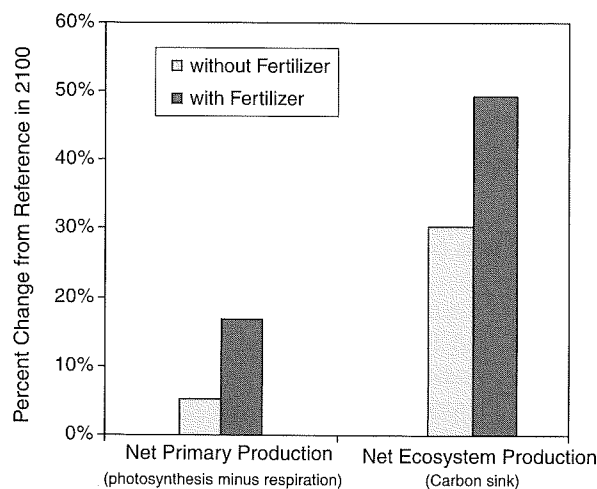


Figure 8.5 Net annual uptake of carbon by vegetation alone (net primary production) and vegetation plus soils (net ecosystem production, the land carbon sink) for the $\text{NO}_x/\text{SO}_x/\text{CO}$ plus VOC capped (allcap) case is shown for the year 2100 as a percentage change from the reference 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).

reference when compared to the northern hemisphere when either SO_x or all emissions are capped (compare Figures 8.4b and 8.4c).

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 , $\text{NO}_x/\text{CO}/\text{VOC}$, or all emissions are capped. Capping NO_x emissions leads to significant decreases in non-urban OH and thus increases in methane in both hemispheres (Figures 8.4b and 8.4c). Because methane has a long lifetime (about 9 years; Prinn *et al.*, 2001) relative to the interhemispheric mixing time

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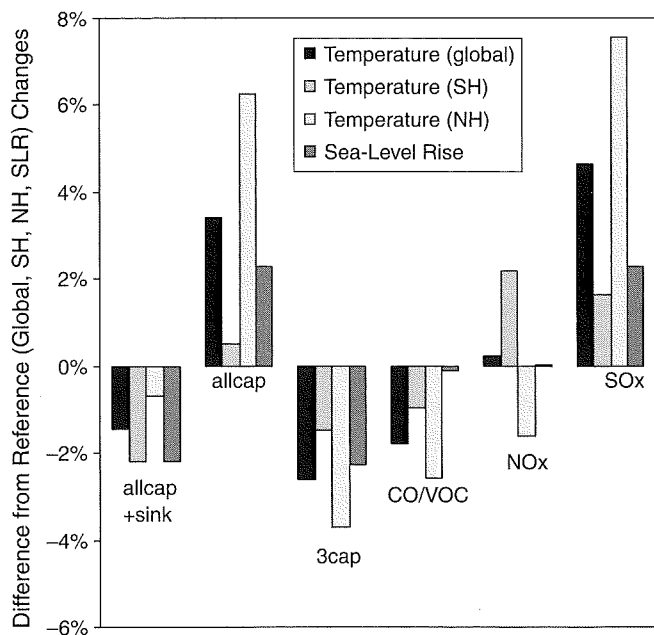


Figure 8.6 Impacts of the five types of air pollution caps on the global, northern hemispheric and southern hemispheric average temperature increases, and the global sea-level rise (SLR), between 2000 and 2100 are shown as changes from their average values (global or hemispheric) in the reference case. The equivalent results are also shown for the case where the enhanced sink due to the ozone decrease 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 8.5.

(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 $\text{NO}_x/\text{CO}/\text{VOC}$ or all emissions are capped even though the OH decreases only occur in the southern hemisphere in these two cases (see Figures 8.4b and 8.4c).

8.4.2 Effects on ecosystems

Effects of air pollution controls on the land ecosystem sink for carbon can be significant owing to reductions in ozone-induced plant damage (Figure 8.5; see also Felzer *et al.* [2004, 2005]). 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 8.5 where all pollutants are capped and ozone decreased by about 13% globally (Figure 8.4a). The effect is even greater when we assume that croplands receive optimal levels of nitrogen fertilizer (“with Fertilizer” case; Felzer *et al.*, 2004, 2005). The land sink (NEP) is increased by 30 to 49% or 0.6 to 0.9 Gt of

carbon (in CO_2) in 2100 through the illustrated pollution caps (Figure 8.5).

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.

8.4.3 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. But monetary damage estimates suffer from numerous shortcomings (e.g. Jacoby, 2004). Felzer *et al.* (2004, 2005) 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 Gt of carbon is only 2 to 4% of year 2100 reference projections of anthropogenic fossil CO_2 emissions (which reach nearly 25 Gt C/yr in 2100 according to Felzer *et al.* [2005]). 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 with the reference scenarios shown in Figure 8.5. The Net Present Value (NPV) cost savings through 2100 discounted to the present (2005) are \$2.5 trillion (“without Fertilizer”) to \$4.7 trillion (“with Fertilizer”) (1997 dollars; trillion = 10^{12}). These implied savings are 12 to 22% of the total NPV cost of the 550 ppm 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 additional 2000–2100 carbon uptake is 36 Gt (without Fertilizer) and 75 Gt (with Fertilizer), 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 be used later only if needed. An important caveat here is that, as shown in Felzer *et al.* (2004, 2005), 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 550 ppm carbon policy in place, leads to only a 0.1 to 0.8 Gt increase in the land sink in 2100 (compare 0.6 to 0.9 Gt in Figure 8.5) and a cumulative 2000–2100 increase of carbon uptake of 13 to 40 Gts of carbon, which is about one-half of the above increased cumulative uptake when the pollution cap occurs assuming there is no climate policy.

8.4.4 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 8.6 as percentages relative to the global-average reference case changes of 2.7°C and 0.4 meters respectively.

In the reference run, CO₂ contributes about 80% of the total 6.6 W/m² increase in radiative forcing of climate change from 1990 to 2100. Smaller or larger contributions by CO₂ will lead to larger or smaller percentage changes than those shown in Figure 8.6. Also, these illustrated changes are very significant when compared with the changes induced by the non-CO₂ forcings, including ozone and aerosols, alone (which contribute only 20% of the reference increase in radiative forcing from 1990 to 2100). The largest increases in temperature and sea level occur when SO_x alone is capped, owing 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 CH₄ increases), but decreases in the northern hemisphere (because the cooling effects of the O₃ decreases exceed the warming driven by the CH₄ increases). This result confirms the earlier conclusion of Mayer *et al.* (2000) that lowering NO_x alone has little impact on global mean temperatures because the effects of the CH₄ increases offset those of the O₃ decreases. For CO, and VOC reductions, there are small decreases in temperature driven by the accompanying aerosol increases and CH₄ 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 non-linearity in the system is evidenced by the fact that the combined effects are not simple sums of the effects from the individual caps. Ozone decreases and aerosol increases (offset only slightly by CH₄ 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 8.6 omit the cooling effects of the CO₂ reductions caused by the lessening of the inhibition of the land sink by ozone (Figure 8.5). This omission is valid if we presume that anthropogenic CO₂ 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 CO₂ reductions to occur, we show a sixth case in Figure 8.6 (“allcap + sink”) which combines the capping of all air pollutant emissions with the enhanced carbon sink from Figure 8.5. 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 8.4.3.

8.5 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 with 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 on 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 CO₂). 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 CH₄. These OH decreases and CH₄ increases are lessened (but not reversed) when there are simultaneous NO_x, CO, and VOC caps. Increases in CH₄ lead to greater radiative forcing. In this respect, the comprehensive modeling study of CH₄ by Khesghi *et al.* (1999) concluded that the most effective means of reducing CH₄ may be to raise OH by maintaining NO_x emissions while lowering CO and VOC emissions. Our results qualitatively confirm this, but the CH₄ reductions are modest in our case (Figure 8.4, CO/VOC caps). 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 CH₄ changes combined leads to more warming and sea-level rise. Hence these impacts on climate of the pollutant caps partially cancel each other.

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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 case of the NO_x cap alone, 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, whereas the opposite is true in the southern hemisphere (Figure 8.6).

We have previously emphasized (and estimated) the significant uncertainties in IGSM projections of pollutant emissions and concentrations, and resultant climatic changes (Webster *et al.*, 2002, 2003). These uncertainties apply to the six specific IGSM runs used in this study, but by expressing our results as percentage changes from the reference, the effects of many of the highly correlated uncertainties among the runs (e.g. total fossil fuel usage, radiative forcing by aerosols, sensitivity of climate to radiative forcing, heat and carbon uptake by the ocean) are minimized. While we explicitly include urban atmospheric chemistry, our use of a 2D model for the non-urban atmospheric chemistry, and for climate, needs to be tested using a 3D model (although, again, some of the uncertainties induced by use of the 2D model may be effectively minimized through our statement of results as percentages).

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 measures for climate change mitigation, 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 SO₂ and NO₂ resulting from air pollution reductions.

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