Impacts of air pollutant caps on climate

Could policies designed to address air pollution impact climate?

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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 aerosols[1] that are important in air pollution and climate are often highly correlated due to shared generating processes. Most important among the generating processes is combustion of fossil fuels and biomass which produces carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), carbon dioxide (CO_2), black carbon (BC) aerosols, and sulphur oxides (SO_x, comprised of some sulphate aerosols, but mostly SO_2 gas which subsequently forms reflective sulphate 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 sulphate 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 Gt 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.

Effects of pollution on climate

The climatic effects of atmospheric constituents are typically expressed by their contributions to radiative forcing, which is a measure of the imbalance between incoming solar energy and outgoing infrared energy for the Earth. We expect that air pollutant reductions will influence climate for several reasons. Specifically, 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. Capping NO_x alone also decreases OH and thus increases 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 sulphate aerosols. This causes 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. Enhanced radiative forcing by these aerosol and CH_4 changes combined leads to more warming and sea level rise.

In this article, recent exploratory calculations designed to quantify the above effects of specific global air pollutant emission caps on climate are reviewed. The key question is, could future air pollution policies help to decrease future climate change or increase it?

Integrated Global System Model

The connections between the chemistry of the atmosphere and climate are complex and require a systems modelling approach that considers urban, regional and global scales. The calculations by Prinn *et al.* (2005)[2] reviewed here utilise the MIT Integrated Global System Model (IGSM). The IGSM, as illustrated in Figure 1, consists of a set of coupled submodels of economic development and its associated emissions, natural biogeochemical cycles, climate, air pollution and natural ecosystems. It is specifically designed to address key questions in the natural and social sciences that are

[1] *Aerosols are suspended particles in air (other than water droplets or ice).*

[2] Prinn, R.G., Reilly, J., Sarofim, M., Wang, C. and Felzer, B., 2005: Effects of air pollution control on climate, MIT Joint Program on the Science and Policy of Global Change, Report 118 (http://web.mit.edu/globalchange/www/reports.html#pubs). Also to appear in *Integrated Assessment of Human-Induced Climate Change*, Cambridge University Press, 2005.

amenable to quantitative analysis and are relevant to environmental policy. Of particular importance to the calculations reviewed here, the urban air pollution submodel of the IGSM is based upon, and designed to simulate, the detailed chemical and dynamical processes in current three-dimensional urban air chemistry models. For this purpose, the emissions calculated in the economics submodel are divided into two parts: urban emissions which are processed by the pollution submodel before entering the global chemistry/climate submodel, and non-urban emissions which are input directly into the large-scale model.

IGSM runs with pollutant caps

To illustrate some of the possible impacts of controls of air pollutants on temperature and sea level, Prinn *et al.* (2005) 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.

Specifically, in five runs of the IGSM, they considered 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) were 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 sulphur 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.

The MIT Integrated Global System Model (IGSM)

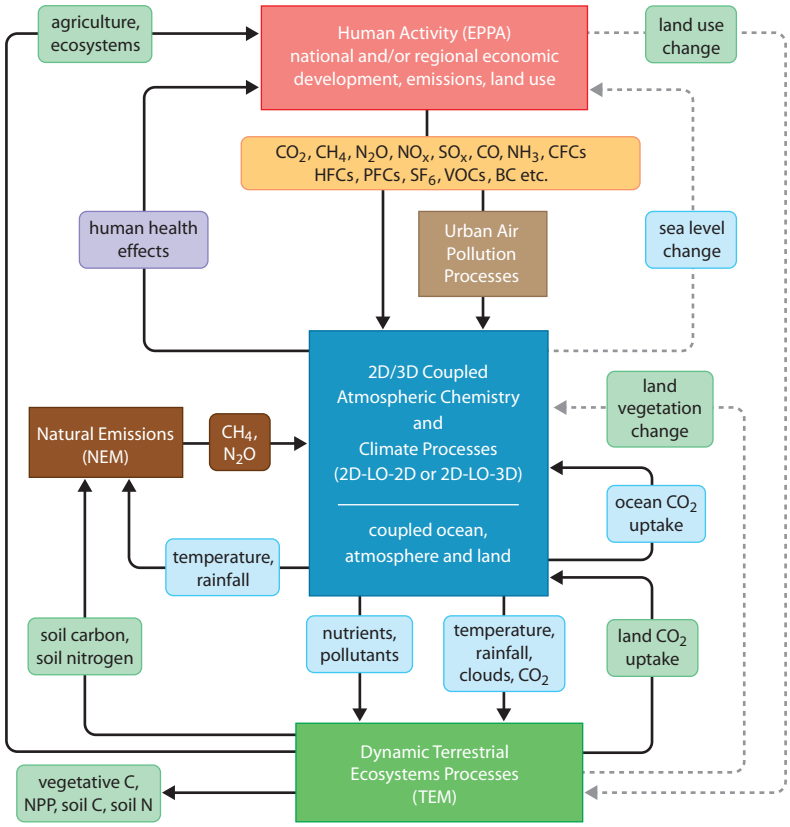

Figure 1
Schematic illustrating the framework, submodels and processes in the MIT Integrated Global System Model (IGSM). Feedbacks between the component models that are currently included, or proposed for inclusion in later versions, are shown as solid or dashed lines respectively.

In interpreting their results, it is important to note that they 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).

The ratios of the emissions of NO_x, CO/VOCs, and SO_x in the year 2100 to the reference case in 2100 are about 1/3, 1/2 and 3/5 respectively, when their emissions are capped at 2005 levels. For calibration, the reference global emissions of NO_x, CO/VOCs, and SO_x in 2100 are about 4, 2.5, and 1.5 times their 2000 levels. Because these chemicals are short-lived (hours to several days for NO_x, VOCs, and SO_x, a few months for CO), the effects of

Table 1 Sign of the changes from the reference of O_3, OH, CH_4 and sulphate aerosol levels in 2100 in the 5 capping cases

Effect	Cap SO_x	Cap NO_x	Cap CO/VOC	Cap 3-cap	Cap all cap
O_3	0	–	+	–	–
OH	+	–	+	–	0
CH_4	–	+	–	+	+
sulphates	–	–	+	0	_

their emissions are largely restricted to the hemispheres in which they are emitted (and, for the shortest-lived pollutants, restricted to their source regions).

As summarised in Table 1, the major global effects of capping SO_x are to decrease sulphate 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 sulphate (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 sulphate 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. The northern hemisphere contributes the most to the global averages and therefore responds similarly. Because methane has a long lifetime (about 9 years) relative to the interhemispheric mixing time (about 1–2 years), its global concentrations are influenced by OH changes in either hemisphere alone, or in both.

Caps on air pollutants significantly affect the land ecosystem sink for carbon due to reductions in ozone-induced plant damage. The land sink, which is the difference between plant photosynthesis and the sum of plant respiration and soil respiration plus decay, increases when ozone decreases. This is evident in the case where all pollutants are capped, causing an ozone decrease of 13% globally, and a land sink increase of 30–49% or 0.6–0.9 Gt of carbon (in CO_2) in 2100 (the range of these values depends on assumptions about managed land fertilisation).

The Prinn *et al.* (2005) ecosystem calculations do not include the additional positive effects on the land sink 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 of decreasing nutrient nitrate and possibly sulphate deposition that also arise from these caps.

Effects of caps on climate

The effects of these pollutant caps on global and hemispheric mean surface temperature and sea level changes from 2000–2100 are shown in Figure 2 (Prinn *et al.* 2005) as percentages relative to the global average reference case changes of 2.7°C and 0.4 metres respectively. The largest increases in temperature and sea level occur when SO_x alone is capped due to the removal of reflecting (cooling) sulphate 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 decreases in O_3 exceeding the warming driven by the increases in CH_4). For CO and VOC reductions, there are small decreases in temperature driven by the accompa-

nying 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.

The nonlinearity in the system is evidenced by the fact that the combined effects in the '3 cap' case are not simple sums of the effects from the individual caps. Ozone 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 than, but qualitatively similar to, the case where only SO_x is capped. However, 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.

The calculations for the five capping cases in Figure 2 omit the cooling effects of the CO_2 reductions caused by the lessening of the inhibition of the land sink by ozone. 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 is the basis for the economic analysis discussed below. To illustrate the lowering of climate impacts if the sink-related CO_2 reductions actually occur, Prinn *et al.* (2005) considered a sixth case ('allcap+sink') which combined the capping of all air pollutant emissions with the enhanced carbon sink (Figure 2). The enhanced sink is sufficient for the sign of the warming and sea level rise seen in the 'allcap' case to be reversed in the 'allcap+sink' case. If this lowering of climate impacts could be valued, it would provide an alternative to the economic analysis discussed below.

To summarize, the study by Prinn *et al.* (2005) showed that the impacts on climate of 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.

Effects of five air pollution capping cases on average temperature and global sea level between 2000 and 2100

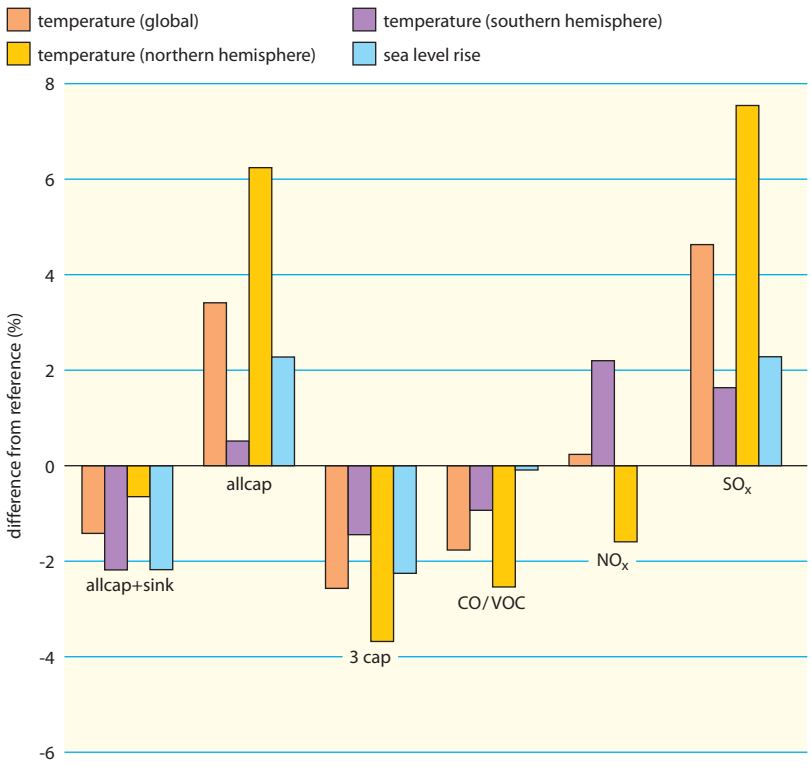

Figure 2
Impacts of air pollution caps in the five capping cases on the global, northern hemispheric and southern hemispheric average temperature increases, and the global sea level rise, between 2000 and 2100 are shown as percent changes from their average values (global or hemispheric) in the reference case from Prinn et al. *(2005). Also shown are the percent changes for the case where the enhanced sink due to the ozone cap is included along with the caps on all pollutants. For this case, they assume the average of the computed range of sink enhancements.*

Economic consequences

One approach to estimating some of the economic effects of air pollutant caps is to value the above increases in carbon storage in ecosystems in terms of the avoided costs of fossil fuel CO_2 reductions needed to achieve an atmospheric stabilisation target. The above extra annual carbon uptake (due to avoided ozone damage) of 0.6–0.9 Gt of carbon is only 2–4% of year 2100 reference projections of anthropogenic fossil CO_2 emissions (which reach nearly 25 Gt C/year in 2100). However, this small level of additional uptake can have a surprisingly large effect on the cost of achieving a climate policy goal. Prinn *et al.* (2005) used a 5% discount rate, and adopted the policy costs associated with 550 ppm CO_2 stabilisation, to estimate the policy cost savings that would result from the increased carbon

uptake through 2100 in the 'allcap' compared to the 'ref' scenarios. The savings are $2.5 to $4.7 trillion (1997 dollars). These implied savings are 12 to 22% of the total cost of a 550 ppm stabilisation policy. There are two reasons for the large economic value of the additional carbon uptake. One reason is that the fossil carbon reduction savings are cumulative; the total additional 2000–2100 carbon uptake is 36 to 75 Gt, or about 6–13 years of fossil carbon emissions at current annual rates. The second reason is that the additional uptake avoids the highest marginal cost options.

Concluding remarks

To further check on the validity of the Prinn *et al.* (2005) 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 (there are multiple, regionally variable and partially-offsetting effects of black carbon on absorption and reflection of sunlight, reflectivity of clouds and the strength of lower tropospheric convection); and

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

Nevertheless, the Prinn *et al.* (2005) calculations suggest that, while urban air pollution policies are obviously beneficial for human health and downwind ecosystems, they 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 beneficial in economic terms as they may take the place of the highest cost climate change mitigation measures, i.e. those occurring at the margin.