Climate forcing by the on-road transportation and power generation sectors

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\textbf{Abstract}

The on-road transportation (ORT) and power generation (PG) sectors are major contributors to carbon dioxide (CO\textsubscript{2}) emissions and a host of short-lived radiatively-active air pollutants, including tropospheric ozone and fine aerosol particles, that exert complex influences on global climate. Effective mitigation of global climate change necessitates action in these sectors for which technology change options exist or are being developed. Most assessments of possible energy change options to date have neglected non-CO\textsubscript{2} air pollutant impacts on radiative forcing (RF). In a multi-pollutant approach, we apply a global atmospheric composition-climate model to quantify the total RF from the global and United States (U.S.) ORT and PG sectors. We assess the RF for 2 time horizons: 20- and 100-year that are relevant for understanding near-term and longer-term impacts of climate change, respectively. ORT is a key target sector to mitigate global climate change because the net non-CO\textsubscript{2} RF is positive and acts to enhance considerably the CO\textsubscript{2} warming impacts. We perform further sensitivity studies to assess the RF impacts of a potential major technology shift that would reduce ORT emissions by 50\% with the replacement energy supplied either by a clean zero-emissions source (S1) or by the PG sector, which results in an estimated 20\% penalty increase in emissions from this sector (S2). We examine cases where the technology shift is applied globally and in the U.S. only. The resultant RF relative to the present day control is negative (cooling) in all cases for both S1 and S2 scenarios, global and U.S. emissions, and 20- and 100-year time horizons. The net non-CO\textsubscript{2} RF is always important relative to the CO\textsubscript{2} RF and outweighs the CO\textsubscript{2} RF response in the S2 scenario for both time horizons. Assessment of the full impacts of technology and policy strategies designed to mitigate global climate change must consider the climate effects of ozone and fine aerosol particles.

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1. Introduction

The world, including the United States (U.S.), is moving towards mitigating emissions considered to be responsible for global climate change. On-road transportation (ORT) and power generation (PG) have been major contributors to the atmospheric build up of the most important long-lived well-mixed greenhouse gas (WMGHG) carbon dioxide (CO\textsubscript{2}). In addition, these human activities influence climate and air quality through the generation of radiatively-active short-lived air pollutants, the most important of which are tropospheric ozone (O\textsubscript{3}) and fine aerosol particles including sulfate, organic carbon (OC) and black carbon (BC). Technology changes and energy policy in the coming decades will be required to address these two major emitting sectors.

Like CO\textsubscript{2}, O\textsubscript{3} is a greenhouse gas that absorbs infrared terrestrial radiation as well as incoming short-wave radiation and leads to global warming. The effects of aerosol particles from ORT and PG emissions on global climate are more complex and depend on chemical composition. The direct effect of sulfate and OC is a global cooling due to scattering of sunlight to space. The direct effect on climate of BC is a warming of the atmosphere through absorption of sunlight (Jacobson, 2001). Aerosols exert additional indirect effects on Earth’s climate by modifying properties of clouds in several ways such as making the clouds brighter and longer-lived. Aerosol indirect effects are the most uncertain aspects of climate change, but likely contribute an additional global cooling (Penner et al., 2006). Since the preindustrial, the combined sum of the air pollutant (denoted ‘non-CO\textsubscript{2}’) radiative forcing (RF) may well rival that of the largest single human-made RF from CO\textsubscript{2} (Forster et al., 2007). Hence, the non-CO\textsubscript{2} air pollutant RF constituents deserve greater attention than they have received by the climate policy community (Hansen, 2002). In addition to affecting Earth’s climate, O\textsubscript{3} and fine aerosols pose serious public health problems.
Exposures to O₃ and fine aerosols have been linked in epidemiological studies to adverse health effects that include premature mortality, exacerbation of acute and chronic respiratory symptoms, and increased hospital admissions (Dockery et al., 1993; Schwartz, 1996; Pope et al., 2002; Bell et al., 2004). At present, atmospheric levels of O₃ and fine aerosol particles are controlled via air quality legislation in some regions, which usually neglects the concurrent impacts on global or regional climate. At the same time, these short-lived air pollutants are not included in international climate agreements. Regulatory action in a particular emissions sector may involve changes to all species, both short and long-lived, especially in the case of a major energy switch such as replacing one fossil fuel source with another or changes in efficiency affecting total usage. Whilst policymakers are beginning to consider the benefits of synergies between climate change, energy and air quality management policies, the climate effects of air pollutants are still overlooked (Chiu et al., 2007).

Recent research has begun to quantify the RF of the short-lived air pollutants by emission sector (Unger et al., 2008; Fuglestvedt et al., 2008; Shindell et al., 2008). For the near future 2030 atmosphere, the global surface transportation sector contributes a large net positive non-CO₂ forcing relative to complete removal due to the sensitive amounts of O₃ and BC associated with this activity (Unger et al., 2008). Indeed, for North America and Europe, surface transportation emissions contribute the largest net positive non-CO₂ forcing of all the human activities from those regions. Conversely, the global PC sector contributes a large net negative non-CO₂ forcing due to the significant amounts of sulfate associated with this activity. For the preindustrial to present day change (1750–2005), Fuglestvedt et al. (2008) have found that of all the transportation subsectors, ORT emissions have made the largest contribution to warming with the non-CO₂ agents O₃ and BC adding around one-third to the CO₂ RF.

Several modeling studies have attempted to assess the atmospheric impacts of various technology and energy shifts in the ORT sector (e.g. Schultz et al., 2003; Jacobson et al., 2005; Electric Power Research Institute, 2007). Other studies have emphasized the importance of reducing coal use in the PG sector (e.g. Hansen et al., 2008). No study to date has quantified the non-CO₂ impacts of potential technology shifts between the ORT and PG sectors. A potential technology shift that may affect both sectors is conversion of the on-road vehicle fleet to Plug-In Hybrid Electric Vehicles (PHEVs), which may potentially become the dominant vehicle platform by the year 2020 (Romm, 2006). Conversion to a PHEV fleet will reduce ORT sector emissions but could impose increases in emissions from the PG sector as increased utilization of existing capacity or new electric capacity may be required to fuel the fleet.

Our objective is to apply a global atmospheric composition-climate model using a multi-pollutant approach to quantify the contributions of the global and U.S. ORT and PG sectors to total RF (with special focus on the non-CO₂ air pollutant RF) for the present day atmosphere. Then, we use the model to assess the RF impacts of a potential technology shift that would enable reduction of emissions from the ORT sector by 50% for two scenarios. In the first scenario, the replacement energy to supply the fleet is provided by a clean zero emission source and in the second case, the replacement energy is supplied by the PG sector in its current state.

In Section 2, we describe the experimental methodology including: the atmospheric composition-climate model (Section 2.1); emissions inventory (Section 2.2); simulations and emissions scenarios (Section 2.3); and the calculation of radiative forcing (Section 2.4). Section 3 includes discussion of the model results: contribution of the ORT and PG sectors to RF (Section 3.1); the impact of S1 and S2 scenarios on surface air quality (Section 3.3). In Section 4, we present the conclusions and a discussion of the implications of our findings for conversion of the vehicle fleet to PHEVs.

2. Experimental method

2.1. Atmospheric composition-climate model

We applied the NASA Goddard Institute for Space Studies (GISS) model for Physical Understanding of Composition-Climate Interactions and Impacts (G-PUCCINI) described in detail and comprehensively evaluated in Shindell et al. (2006). The model has been used previously to understand the role of short-lived air pollutants in climate change for past, present and future atmospheres (e.g. Unger et al., 2006a; Koch et al., 2007; Shindell et al., 2007).

Briefly, the model comprises the GISS version ModelE general circulation model (Schmidt et al., 2006) with embedded fully interactive photochemistry and aerosol modules. The version used here includes sulfate, BC, OC and sea salt. For the present study, we do not allow the atmospheric composition to feedback to the climate dynamics through the radiation scheme. We use 23 vertical layers (model top in the mesosphere) and 4° × 5° latitudinal by longitudes horizontal resolution. Chemical calculations are performed only in the troposphere in the present version of the model. We use a thermal tropopause defined by the meteorological lapse rate. Stratospheric values of O₃, NOₓ and CH₄ are prescribed according to satellite observations with seasonally varying abundances (Shindell et al., 2003). The model performance with respect to key short-lived tracers has been comprehensively evaluated for O₃, nitrogen species, and reduced carbon species (Shindell et al., 2006), CO (Shindell et al., 2005) and sulfate aerosol (Koch et al., 2006). Tropospheric O₃ is well simulated, especially in the vicinity of the tropopause, where it has the greatest effect on climate, and at the surface, where it affects air quality, with an average bias of only 6% against a comprehensive ozoneonde dataset (Shindell et al., 2006). The tropospheric chemistry version of G-PUCCINI performed well in a multi-model intercomparison involving evaluation against ozoneonde climatology, with a root-mean-square (rms) error value of 6.3 ppbv compared with a range of rms error values of 4.6–17.0 ppbv (Stevenson et al., 2006). Comparisons of the vertical profiles of NOₓ and nitric acid (HNO₃) show good agreement between the model and observations from a variety of aircraft measurements across many regions (Shindell et al., 2006). The model’s simulation of CO has been compared extensively with both surface and satellite observations (Shindell et al., 2005). It shows good agreement in both magnitude and seasonality, suggesting that the model’s hydroxyl radical fields are reasonably realistic. Monthly mean correlations against mid-tropospheric satellite observations from MOPITT (Measurements of Pollution in the Troposphere) were typically in the range of 0.8–0.9. The sulfate simulation is generally within a factor of 2 of observations using emissions from the Emissions Database for Global Atmospheric Research (EDGAR) (Koch et al., 2006). Model sulfate at remote sites is generally less than observed. In the U.S. the model sulfate tends to be deficient in the east but excessive over the west. Koch et al. (2006) attributes the bias, which is largest in summertime, to excessive advection westward over the Rocky Mountains (which have reduced elevation because of the coarse model resolution). Carbonaceous aerosols are also typically within a factor of 2 of surface concentration observations, but are underestimated by more than a factor of 5 in Southeast Asia. The model BC and OC surface concentrations agree within a factor of 2 with observations over the most of the U.S., although BC is too small in the eastern U.S. (Koch et al., 2007).
2.2. Emission inventory

We used anthropogenic CO, NOx, NMVOCs and SO2 emissions from EDGAR3.2 for the year 1995 (Olivier and Berdowski, 2001). BC and OC emissions are not available in the EDGAR3.2 database and we used values from another global inventory for the year 1996 (Bond et al., 2004). The emissions include all anthropogenic fossil fuel, biofuel and biomass sources and are partitioned into several sectors including explicit representation of ORT and PG emissions (Table 1). Natural precursor and aerosol emissions are prescribed according to conventional estimates detailed elsewhere (Unger et al., 2006b). In the present study, CH4 concentrations are averaged that were generated in previous simulations with the same model but using a fully interactive CH4 cycle including climate sensitive emissions from wetlands (Unger et al., 2006b). Northern hemisphere CH4 is fixed at 1802 ppbv and southern hemisphere CH4 is fixed at 1802 ppbv and OC emissions are not available in the EDGAR3.2 database and are partitioned into several cycles including climate sensitive emissions from wetlands (Unger et al., 2006b). BC emissions were reduced by 50% in the U.S. (S2_US) and globally (S2_GLO) and we assume that the replacement energy to supply the fleet is provided by PG sector in its current state. Hence, the additional demand to fuel 50% of the U.S. ‘light-duty’ vehicle mileage accounts for the largest fraction (~80%) of the total ORT emissions in the U.S. (United States Environmental Protection Agency, 2006). The electricity consumption of light-duty category PHEVs ranges from 0.3 to 0.5 kWh/mile \(^{-1}\) (Electric Power Research Institute, 2007). Therefore an additional 390–650 billion kWh year\(^{-1}\) of electricity would be required. In the U.S. around 4000 billion kWh year\(^{-1}\) of electricity is currently produced (United States Department of Energy-Energy Information Administration, 2006). Hence, the additional demand to fuel 50% of the U.S. ‘light-duty’ vehicle mileage represents around 10–20% of the present production. In S2, we explore the upper limit and apply a concurrent increase of 20% in PG emissions for both the U.S. and global cases (assuming that U.S. ORT/GC emissions ratio is also approximately applicable to the whole world as indicated in Table 1). The RF impacts of the examined emissions perturbations in the ORT and PG sectors are determined by taking the difference between the relevant sensitivity simulation (e.g. S1_US) and the ExpC simulation. Absolute changes in emissions for each perturbation scenario are shown in Table 3.

All the simulations were run for 7 model years; the first 2 years of the simulations are discarded as spin-up and the remaining 5 years are averaged for analysis.

2.3. Simulations and emissions scenarios

A control simulation is performed (named ExpC) using the 1995 emissions inventory described in Section 2.2 that is meant to reflect present day conditions. In addition, we performed a number of sensitivity experiments. Firstly, in order to assess the total RF attributable to each emissions sector, we selectively removed ORT and PG emissions from the entire world region and from the U.S. region in a total of 4 model sensitivity runs. The contributions to RF by the individual emissions sectors are isolated by taking the difference between the ExpC simulation and the relevant sensitivity simulation.

In order to assess the RF response from a major technology shift in the ORT sector, we performed 4 further sensitivity experiments described in Table 2. In the first scenario (S1), ORT emissions were reduced by 50% in the U.S. (S1_US) and globally (S1_GLO) and we assume that the replacement energy to supply the fleet is provided by a clean zero emission source. In the second scenario (S2), ORT emissions were reduced by 50% in the U.S. (S2_US) and globally (S2_GLO) and we assume that the replacement energy to supply the fleet is provided by the PG sector in its current state. Here, we perform a simple calculation to determine the additional electricity demand to fuel 50% of the U.S. ‘light-duty’ vehicle mileage that accounts for the largest fraction (~80%) of the total ORT emissions in the U.S. (United States Environmental Protection Agency, 2006). The electricity consumption of light-duty category PHEVs ranges from 0.3 to 0.5 kWh/mile\(^{-1}\) (Electric Power Research Institute, 2007). Therefore an additional 390–650 billion kWh year\(^{-1}\) of electricity would be required. In the U.S. around 4000 billion kWh year\(^{-1}\) of electricity is currently produced (United States Department of Energy-Energy Information Administration, 2006). Hence, the additional demand to fuel 50% of the U.S. ‘light-duty’ vehicle mileage represents around 10–20% of the present production. In S2, we explore the upper limit and apply a concurrent increase of 20% in PG emissions for both the U.S. and global cases (assuming that U.S. ORT/GC emissions ratio is also approximately applicable to the whole world as indicated in Table 1). The RF impacts of the examined emissions perturbations in the ORT and PG sectors are determined by taking the difference between the relevant sensitivity simulation (e.g. S1_US) and the ExpC simulation. Absolute changes in emissions for each perturbation scenario are shown in Table 3.

All the simulations were run for 7 model years; the first 2 years of the simulations are discarded as spin-up and the remaining 5 years are averaged for analysis.

2.4. Calculation of radiative forcing (RF)

The direct instantaneous top-of-the-atmosphere (TOA) RF by the short-lived pollutants (O3, sulfate, BC and OC) is calculated internally within the climate model’s radiation scheme (Schmidt et al., 2006). The aerosols are assumed to be externally mixed. Additional details on optical and radiative schemes are provided in Koch et al. (2006). Since the atmosphere will have no memory of the short-lived air pollutant precursor emissions from one year to

Table 1

<table>
<thead>
<tr>
<th>Precursor</th>
<th>Global total anthropogenic emission</th>
<th>Global ORT</th>
<th>Global PG</th>
<th>U.S. total anthropogenic emission</th>
<th>U.S. ORT</th>
<th>U.S. PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (Tg CO year(^{-1}))</td>
<td>846.7</td>
<td>195.0</td>
<td>1.8</td>
<td>102.1</td>
<td>76.3</td>
<td>0.5</td>
</tr>
<tr>
<td>NOx (Tg N year(^{-1}))</td>
<td>33.2</td>
<td>8.4</td>
<td>7.2</td>
<td>6.3</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>NMVOC (Tg C year(^{-1}))</td>
<td>131.8</td>
<td>30.0</td>
<td>0.3</td>
<td>18.4</td>
<td>7.9</td>
<td>0.1</td>
</tr>
<tr>
<td>SO2 (Tg S year(^{-1}))</td>
<td>73.4</td>
<td>2.0</td>
<td>26.1</td>
<td>10.3</td>
<td>0.2</td>
<td>6.2</td>
</tr>
<tr>
<td>BC (Tg BC year(^{-1}))</td>
<td>8.2</td>
<td>1.3</td>
<td>0.03</td>
<td>0.4</td>
<td>0.2</td>
<td>0.007</td>
</tr>
<tr>
<td>OC (Tg OC year(^{-1}))</td>
<td>4.2</td>
<td>1.0</td>
<td>0.03</td>
<td>1.2</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>CO2 (Tg year(^{-1}))</td>
<td>26 939</td>
<td>3761</td>
<td>7744</td>
<td>5576</td>
<td>1343</td>
<td>2045</td>
</tr>
<tr>
<td>CH4 (Tg year(^{-1}))</td>
<td>301.95</td>
<td>0.77</td>
<td>0.11</td>
<td>39.79</td>
<td>0.25</td>
<td>0.03</td>
</tr>
</tbody>
</table>

\(^{a}\) CO\(_2\) and CH4 are not included dynamically in the model but the emissions are shown for comparison.
produced is 9.21 Tg year$^{-1}$ and gas production is 44.5 Tg year$^{-1}$. It is challenging to attribute these upstream energy production CH$_4$ emissions to the ORT and PG sectors without further information and thus we do not include them in this analysis.

O$_3$ precursor emissions impact CH$_4$ RF indirectly through changing the CH$_4$ lifetime. CO emissions tend to reduce atmospheric oxidation capacity and thus increase the CH$_4$ lifetime and RF (Daniel and Solomon, 1998) whereas NO$_x$ emissions tend to increase atmospheric oxidation capacity and thus decrease the CH$_4$ lifetime and RF (Wild et al., 2001). The short-lived precursor emissions induced changes in CH$_4$ will also feedback to affect O$_3$ on the longer timescale of the CH$_4$ lifetime. We estimate these indirect effects on CH$_4$ and the secondary effects through CH$_4$ on O$_3$ for the examined emissions perturbations based on the model-determined initial change in CH$_4$ lifetime following the method described in Bernsten et al. (2005). This indirect CH$_4$ forcing, including the secondary O$_3$ effect, is denoted 1–CH$_4$.

The effect of aerosols on cloud albedo (aerosol indirect effect, AIE) is usually dominated by sulfate aerosol since that has the largest mass of the anthropogenic particulates. We use a semi-quantitative approach to estimate the RF from the AIE by scaling the simulated direct sulfate RF by the ratio of the indirect forcing to direct sulfate forcing from the latest IPCC estimate ($-0.70$ W m$^{-2}$, $-0.40$ W m$^{-2}$ = 1.75) (Forster et al., 2007). In the present study, we do not consider the indirect effects of BC snow concentration on snow albedo.

3. Results

3.1. Contribution of ORT and PG sectors to RF

The contributions of the ORT and PG sectors to total RF for emissions from the U.S. region and worldwide are shown in Table 4 and Fig. I. As indicated in Table 1, the ORT sector is associated with large emissions of O$_3$ precursors (CO and NO$_x$) and BC, both key non-CO$_2$ warming agents. In contrast, the PG sector is associated with large emissions of SO$_2$, the sulfate aerosol precursor, but is not a significant source of CO, BC or OC. Global and U.S. ORT emissions result in a positive net non-CO$_2$ RF due to substantial contributions from O$_3$ and BC, and in the case of U.S. ORT from indirect CH$_4$ effects. The net non-CO$_2$ RF from the global and U.S. PG sector is negative due to the large amount of reflective sulfate aerosol and associated aerosol–cloud effects produced from this activity. NO$_x$ emissions tend to increase atmospheric oxidation capacity and therefore decrease CH$_4$ lifetime, in contrast to the effects of CO and NMVOC emissions. Consequently, both global and U.S. PG sector emissions contribute a negative RF from indirect CH$_4$ effects. On the other hand, for the U.S. ORT sector, the effects on CH$_4$ lifetime of the CO emissions dominate over the NO$_x$ emissions.

Table 4

<table>
<thead>
<tr>
<th>Forcing agent</th>
<th>Global ORT</th>
<th>Global PG</th>
<th>U.S. ORT</th>
<th>U.S. PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_3$</td>
<td>+39</td>
<td>+12</td>
<td>+10</td>
<td>+3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-7</td>
<td>-101</td>
<td>+2</td>
<td>-19</td>
</tr>
<tr>
<td>BC</td>
<td>+51</td>
<td>+1</td>
<td>+7</td>
<td>+0.2</td>
</tr>
<tr>
<td>OC</td>
<td>-4</td>
<td>-0.1</td>
<td>-0.3</td>
<td>-0</td>
</tr>
<tr>
<td>AIE</td>
<td>-12</td>
<td>-177</td>
<td>+3</td>
<td>-33</td>
</tr>
<tr>
<td>I–CH$_4$</td>
<td>-4</td>
<td>-22</td>
<td>9</td>
<td>-6</td>
</tr>
<tr>
<td>NET non-CO$_2$</td>
<td>-63</td>
<td>-287</td>
<td>+31</td>
<td>-55</td>
</tr>
<tr>
<td>CH$_4$ (20-year)</td>
<td>+97</td>
<td>+198</td>
<td>+35</td>
<td>+53</td>
</tr>
<tr>
<td>CH$_4$ (100-year)</td>
<td>+284</td>
<td>+576</td>
<td>+102</td>
<td>+156</td>
</tr>
</tbody>
</table>
emissions resulting in a positive indirect CH$_4$ RF that is about the same magnitude as the direct O$_3$ RF from this regional sector. Similarly, U.S. ORT emissions are responsible for a small positive RF from sulfate that is also a result of CO-driven reductions in oxidation capacity. In the global ORT case, the NO$_x$ effects are dominant yielding only a small negative RF from indirect CH$_4$ effects. Emissions from the U.S. regional sectors represent around half the total global non-CO$_2$ RF from ORT but only around 20% of total global non-CO$_2$ RF from PG.

Globally, the non-CO$_2$ RF from ORT (+63 mW m$^{-2}$) is as large as around 2/3 of the CO$_2$ RF for the 20-year time horizon (+97 mW m$^{-2}$) and about 1/5 for the 100-year time horizon (+284 mW m$^{-2}$). Globally the non-CO$_2$ RF from PG is large due to sulfate direct and indirect effects (−287 mW m$^{-2}$) and dominates the CO$_2$ RF for the 20-year time horizon (+198 mW m$^{-2}$). Despite uncertainties in the AIE, our model results suggest that PG emissions likely exert a net cooling influence on climate in the short-term. However, the negative non-CO$_2$ RF from PG is out-weighed by the positive CO$_2$ RF for the 100-year time horizon (+576 mW m$^{-2}$). For the ORT and PG sectors in the U.S. region, the net non-CO$_2$ and CO$_2$ RF are of equal magnitudes for the 20-year time horizon whilst the non-CO$_2$ RF is around 1/3 of the CO$_2$ RF for the 100-year time horizon (the net non-CO$_2$ having opposite sign for the PG sector) demonstrating the important role of short-lived air pollutants in global climate change. As a result the sum of non-CO$_2$ and CO$_2$ (20-year) forcings for the U.S. ORT sector is substantial (+66 mW m$^{-2}$) but only tiny for the PG sector (−2 mW m$^{-2}$).

The individual component RFs from the global ORT sector found in this study are broadly consistent to those determined in a previous study using a different model (Fuglestvedt et al., 2008). The only exception is the BC RF from global ORT, which is considerably higher here (+51 mW m$^{-2}$ versus +23 mW m$^{-2}$ reported in the Fuglestvedt et al. study) due to the use of different BC emissions from this sector (1300 Gg for the year 1995 versus 969 Gg for the year 2000). There are well known (but less well understood) uncertainties in aerosol emission inventories, especially for carbonaceous aerosols, that are the focus of ongoing research.

Despite these uncertainties, it is evident that ORT is an attractive target sector in the U.S. and worldwide to mitigate global climate change because the net non-CO$_2$ RF is positive and acts to enhance the CO$_2$ warming impacts. Therefore emissions controls in this sector would have a beneficial effect on climate in the short-term through O$_3$ and BC effects (and in the case of U.S. controls only, on indirect CH$_4$ effects) and in the long-term through CO$_2$ effects. According to our model results, the PG sector exerts a substantial cooling effect through sulfate direct and indirect effects that dominates the CO$_2$ warming in the short-term (20-year time horizon) on global scales.

3.2. Impact of S1 and S2 scenarios on RF

Table 5 and Fig. 2 present the resultant global annual mean RF response from a 50% reduction in ORT emissions in the U.S. and globally for the scenarios that we explore in which there are no compensatory changes to other fossil fuel sources (S1) and in which there is concurrent 20% increase to PG emissions (S2). The net non-CO$_2$ and CO$_2$ RF for each scenario and each time frame examined is indicated, indicating a cooling effect on global climate in the short and long terms. However, the relative roles of non-CO$_2$ and CO$_2$ forcing agents depend on how the replacement energy is supplied.

A global reduction of 50% in ORT emissions with no change to PG emissions yields a total RF (including CO$_2$ and non-CO$_2$ effects) of −82 mW m$^{-2}$ for the 20-year time horizon (40% due to non-CO$_2$ effects) and −176 mW m$^{-2}$ for the 100-year time horizon (25% due to non-CO$_2$ effects) and could contribute to global warming mitigation as part of a multi-pronged strategy (Pacala and Socolow, 2004). For the global S1 scenario, the non-CO$_2$ cooling effects are dominated by reductions in O$_3$ and BC. Similarly, for emissions changes in the U.S. (S1_US), the total RF is −33 mW m$^{-2}$ for the 20-year time horizon (50% due to non-CO$_2$ effects) and −68 mW m$^{-2}$ for the 100-year time horizon (40% due to non-CO$_2$ effects).

Reduction of ORT emissions in the U.S. also imposes a negative indirect CH$_4$ RF that is of the same magnitude as the O$_3$ RF response. In the short-term, for a 50% reduction in U.S. ORT emissions, the non-CO$_2$ and CO$_2$ agents play an equal role in the climate forcing impacts.

As we have seen in the previous section, the PG sector is a large source of both CO$_2$ emissions and scattering sulfate aerosol formed from SO$_2$ emissions released during coal burning. Hence, when the replacement energy is supplied by the PG sector, and there is a concurrent 20% increase in PG emissions, the CO$_2$ benefit of the 50% reduction in ORT emissions is greatly offset by increases in CO$_2$ emissions from the PG sector resulting in only small resultant CO$_2$ RF impacts. Moreover, additional sulfate is generated from the increased PG emissions yielding a negative RF from both direct and indirect aerosol effects. Thus, the net non-CO$_2$ RF becomes more negative if the replacement energy is supplied by the PG sector. The
source of BC and OC from PG is negligible and thus their RF impacts are the same across all scenarios regardless of concurrent changes to the PG emissions. The total RF (including CO2 and non- CO2 effects) for the global scenario (S2_GLO) is $-146 \text{ mW m}^{-2}$ for the 20-year time horizon (94% due to non-CO2 effects) and $-162 \text{ mW m}^{-2}$ for the 100-year time horizon (85% due to non-CO2 effects). For the U.S. case (S2_US), the total sum of non-CO2 and CO2 (20-year) RF is the same for both scenarios S1 and S2 ($-33 \text{ mW m}^{-2}$) since in S2 the reduced CO2 impacts are compensated for by increased sulfate impacts. However, although the additional sulfate imparts a cooling effect on climate, increases in these aerosols will have severely detrimental effects on air quality that are discussed in the next Section 3.3. The CO2 RF response is dwarfed by the non-CO2 forcing response in both the U.S. and global cases. Hence, for a potential technology shift scenario, where ORT emissions can be reduced with the replacement energy supplied by the PG sector in its current state, our results indicate that the non-CO2 RF effects are substantially more important than CO2 and will control the overall climate impacts of the shift.

The small global mean RF values belie larger regional forcings shown in Fig. 3. Reducing ORT emissions by 50% in the U.S. leads to a total non-CO2 RF of $-50$ to $-80 \text{ mW m}^{-2}$ across the region with long-range effects across the Atlantic Ocean and Europe of up to $-30 \text{ mW m}^{-2}$. Compensating increases in emissions from PG sector increase the negative forcing further due to enhanced scattering sulfate loading. For a concurrent $+20\%$ increase in PG emissions, local RF over the U.S. is $-100$ to $-200 \text{ mW m}^{-2}$. Similarly, the long-range effects across the Atlantic and Europe increase to $-50$ to $-80 \text{ mW m}^{-2}$ for S2_US. Reducing ORT emissions globally by 50% has a profound influence on regional forcing in the Northern Hemisphere (S1_GLO). The negative forcing exceeds $-100 \text{ mW m}^{-2}$ across the polluted source regions of North America, Europe and East Asia and, importantly, the remote Arctic region. Moreover, comparing the results for the S1_US and S1_GLO scenarios, it is clear that the negative regional forcing over the U.S. is enhanced by a factor of 2 when ORT emissions are reduced globally versus locally, emphasizing the critical importance of multi-lateral agreements in actions to solve climate change problems. A previous study using the same model that investigated future climate impacts of short-lived air pollutants found that the ensemble-mean surface temperature response, despite being related to the short-lived pollutant RF on hemispheric scales, showed little regional correlation with the spatial pattern of RF, suggesting that oceanic and atmospheric mixing generally overwhelms the effect of even large localized forcings (Shindell et al., 2007). More research is needed to understand the climate impacts of these localized forcings.

3.3. Impact of S1 and S2 scenarios on global air quality

Changes in emissions from the ORT and PG sectors will affect surface air quality. The RF calculations that are the main focus of this study necessitated use of the coarse resolution global model that restricts our analysis to global surface air quality impacts. We recognize that there would be considerable local and urban scale air quality and human health impacts from the technology shifts under investigation that can only be meaningfully quantified using a higher resolution model.

The impact of scenarios S1_GLO and S2_GLO on annual average surface O3 and sulfate concentrations is shown in Fig. 4(a) and the impact of S1_GLO on annual average BC and OC concentrations is shown in Fig. 4(b). Since the PG sector is a negligible source of BC and OC, the same surface response is achieved for these pollutants regardless of the compensating emissions changes from the PG sector. A global 50% reduction in ORT emissions (S1_GLO) would yield substantial improvements to surface O3 and aerosol air quality over populated areas in the U.S., Europe, East Asia and South Asia. Annual average surface O3 is reduced by around 5–10% across large regions of the globe, especially the polluted subtropical regions, with reductions of 2–3 ppbv in the southwestern and southeastern U.S., the Middle East and South Asia (Fig. 4(a)). There would be dramatic improvements in BC air quality with reductions of 0.05–0.1 $\mu$g m$^{-3}$ (20–40%) in populated regions (Fig. 4(b)). OC would be reduced by around 0.1 $\mu$g m$^{-3}$ (20–10%) across large regions of the world and sulfate would be reduced by up to 0.1–0.2 $\mu$g m$^{-3}$ (2–5%) in regions that use sulfur-containing fuels.

Compensatory increases in emissions from the PG sector would detrimentally impact surface sulfate aerosol and O3 (Fig. 4(a)). In scenario S2_GLO, there is a substantial degradation in sulfate air quality with annual mean increases of up to 1 $\mu$g m$^{-3}$ across large areas of the U.S., Europe and North Africa and more than 2 $\mu$g m$^{-3}$ (40%) in the vicinity of power plants. Surface O3 changes are more modest than for S1_GLO due to counteracting increases in NOx emissions from the PG sector. There are even increases in annual mean O3 (1–2 ppbv) in some regions. A recent study suggests that the surface aerosol response to emissions changes in different composition-climate models is generally robust, whilst the surface O3 response shows greater model dependence (Shindell et al., 2008).

4. Discussion and conclusions

We have examined the impacts of a 50% reduction in ORT emissions. There are a number of potential technology options for converting the vehicle fleet and reducing ORT emissions large-scale. Recent attempts have been made using advanced models of the electric and transportation sectors to simulate expected changes to ORT and PG emissions for large penetration of PHEVs into the U.S. fleet (Electric Power Research Institute, 2007; Hadley and Tsvetkova, 2008; Huo et al., 2009). The projections are highly dependent on the assumptions made including power level,
timing and duration of the PHEV connection to the grid, and future air emissions regulations. Hence, the different studies give somewhat conflicting results about the impact of a PHEV fleet on greenhouse gas and air pollutant precursor emissions. None of these studies has considered the non-CO2 short-lived air pollutant RF impacts of conversion to a PHEV fleet. Detailed transportation sector modeling indicates that the U.S. PHEV average fraction of vehicle miles traveled using battery electricity would be about 20% (Electric Power Research Institute, 2007). Thus, a 50% reduction in ORT emissions may not be possible to achieve even with complete conversion of the current U.S. fleet to PHEV. However, as battery technology improves, allowing longer trips on a single charge, this situation may no longer be the case. There is also the possibility of the development of vehicles that run entirely on battery electricity such as those produced by Toyota, Honda, Ford and General Motors in the 1990s, which were hampered by a low mileage range (60–90 miles between charges) and withdrawn from the market. There are complex uncertainties in quantifying the consequences of adding load from PHEVs onto the electric grid in the U.S. (Hadley and Tsvetkova, 2008). Depending on when and where the vehicles are plugged in, the PHEV fleet could require the addition of new electric capacity and increase the utilization of existing capacity with resultant increases in emissions from the PG sector. In a simple calculation, we found that the additional electricity demand to fuel 50% of the U.S. mileage represents around 10–20% of the present production. Additional consideration of heavy-duty vehicles would lead to a higher value. Yet, penetration of a large number of PHEVs into the fleet would occur over a number of years in the future alongside other demand increases. Electricity use is expected to grow on the order of 50% by 2030 (Energy Information Administration, 2006), which the Edison Electric Institute claims is equivalent to 250–500 new power plants (Edison Electric Institute, 2006). On the other hand, significant PHEV use may lead to a variety of alternative approaches for producing power, including building new plants and reducing reliance on older plants. There is also the possibility that in the future power plant emissions may actually decrease as cleaner power is brought on-line.

Until higher confidence estimates of the impacts of various technology change options (including a large PHEV fleet) on the ORT and PG sectors are obtained in the future, our results may be interpreted to serve as a guide to their climate impacts. In the specific case of a PHEV fleet, the development of an adequate battery that would allow the widespread introduction of PHEVs or fully electric vehicles is yet to come. However, the manufacturers remain committed to the development of advanced battery technology. The positive impacts on climate via non-CO2 and CO2 effects revealed in this study from ORT emission reduction demonstrate that is a worthwhile commitment.

There are some limitations to the present study. The central focus of this study is to understand non-CO2 RF impacts. Technology and energy changes that affect emissions from the ORT and PG sectors will have other critical environmental consequences such as influencing human health, land use and water supply (Jacobson, 2009). Some of these impacts are best examined with higher resolution models than the tool used here, which is more appropriate for large-scale RF assessments. In the U.S., SO2 emissions from the PG sector are capped. Thus, even with increases in generation, there will be no overall increases in SO2 released and utilities instead will either have to scrub more SO2 out or switch to lower sulfur fuels to keep the total constant. However, SO2 emissions from the PG sector are not capped in many other key emitting regions of the world. The aerosol indirect effect is highly uncertain and accordingly we have used a crude method to estimate the cloud RF response due to the

**Fig. 3.** Net non-CO2 annual average instantaneous TOA RF by short-lived air pollutants due to emissions perturbation scenarios S1–S2 relative to the control simulation ExpC (mW m$^{-2}$). Values include the direct forcing from O3, sulfate, BC and OC, but not indirect aerosol or chemical effects through CH4.
sulfate aerosol changes. In future work, we will use an interactive scheme (Menon and Rotstayn, 2006).

Nevertheless, this study does demonstrate the critical importance of considering climate effects of O3 and fine aerosol particles in mitigation strategies and environmental policy. Our model results indicate that full assessment of the environmental impacts of technology and policy changes designed to counter global climate change must consider the climate effects of O3 and aerosol air pollution that may outweigh CO2 effects depending on the replacement energy source.

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References


