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The role of reduced aerosol precursor emissions in driving near-term warming

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Abstract
The representative concentration pathway (RCP) scenarios all assume stringent emissions controls on aerosols and their precursors, and hence include progressive decreases in aerosol and aerosol precursor emissions through the 21st century. Recent studies have suggested that the resultant decrease in aerosols could drive rapid near-term warming, which could dominate the effects of greenhouse gas (GHG) increases in the coming decades.
In CanESM2 simulations, we find that under the RCP 2.6 scenario, which includes the fastest decrease in aerosol and aerosol precursor emissions, the contribution of aerosol reductions to warming between 2000 and 2040 is around 30%. Moreover, the rate of warming in the RCP 2.6 simulations declines gradually from its present-day value as GHG emissions decrease. Thus, while aerosol emission reductions contribute to gradual warming through the 21st century, we find no evidence that aerosol emission reductions drive particularly rapid near-term warming in this scenario. In the near-term, as in the long-term, GHG increases are the dominant driver of warming.

Keywords: near-term climate change, aerosols, sulfate

1. Introduction

Anthropogenic aerosols drive a net cooling of the climate, but have many negative effects on human health and the environment. Because of these effects, in recent decades legislation has been put in place to reduce emissions of aerosol precursors, in particular SO_2, and such legislation has already led to a substantial reduction in SO_2 emissions since the 1970s (figure 1(a)) [1]. Sulfate aerosol is currently very likely the aerosol component with the largest radiative forcing [2], though uncertainties in aerosol forcing are large [2–4] and recent estimates suggest that black carbon aerosol forcing may be larger than previously thought [5]. While reconstructed emissions of black carbon and organic carbon continue to increase (although these estimates have large uncertainties), emissions of SO_2 and ammonia are now stable or decreasing [6]. The set of emissions scenarios underpinning the fifth Coupled Model Intercomparison Project (CMIP5) [7] and underpinning the forthcoming IPCC Fifth Assessment Report, are known as representative concentration pathways (RCPs). They all assume ongoing and increasingly stringent emissions controls on aerosols and most aerosol precursors, even in the most fossil-fuel intensive RCP 8.5 scenario [8], although ammonia emissions are projected to increase. This leads to a gradual decline in SO_2 emissions (figure 1(a)) and most other aerosol precursor emissions through the 21st century to close to preindustrial levels by 2100, with broadly similar SO_2 emissions in all the RCP scenarios. This contrasts for example, with the IPCC SRES scenarios [9] which all assume considerably higher SO_2 emissions, with increases in the near-term in all but the SRES B2 scenario (figure 1(a)). This difference is explained by considerably higher emissions in the SRES scenarios in the period between 1990 and the present than those which actually occurred, and the more stringent emissions controls on aerosols assumed in all RCP

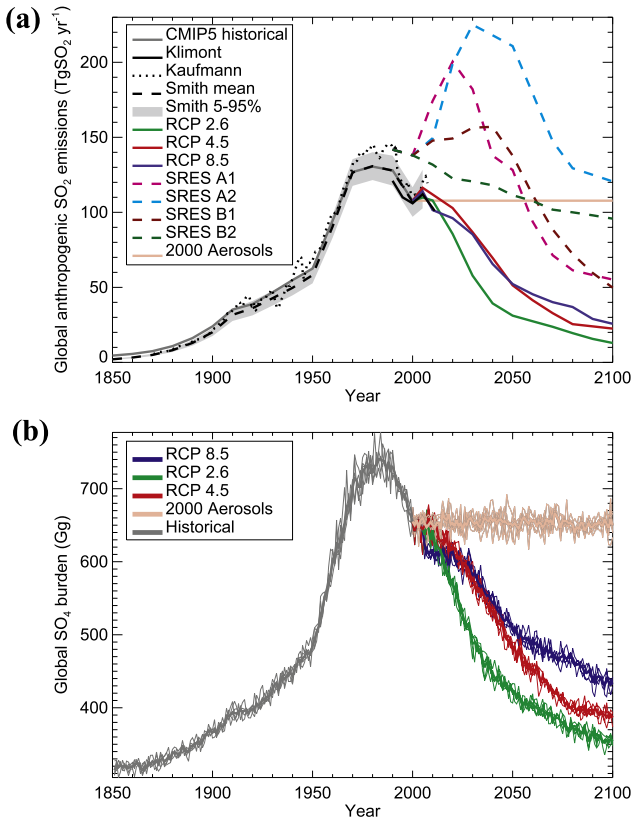

Figure 1. Panel (a) compares SO_2 emissions prescribed over the historical period in the CMIP5 simulations (solid grey) with three inventory-based estimates of historical emissions [1, 10, 11]. Note that, unlike the other estimates shown, the Klimont *et al* [11] estimates exclude emissions from open burning from grasslands, savannahs, forests and deforestation, though this contribution is relatively small. SO_2 emissions over the 21st century specified in the RCP 2.6, 4.5 and 8.5 scenarios [8] (solid coloured lines) are compared with those specified in the SRES A1, A2, B1 and B2 scenarios [9] (dashed coloured lines). The pink line shows the emissions in the simulation with fixed 2000 aerosol emissions. Panel (b) shows the simulated global atmospheric burden of SO_4 in the historical simulations (grey), RCP simulations (colours), and RCP 4.5—2000 aerosols simulations (pink).

scenarios, leading to SO_2 emissions lying at the low end of other projections in the literature [8]. Note that the RCP SO_2 emissions were set equal to inventory-based estimates in 2000 [6]. Although there was an increase in SO_2 emissions between 2000 and 2005 (figure 1(a)) [10], estimated SO_2 emissions have since decreased (figure 1(a)) and were below those in RCP 2.6 and RCP 4.5 in 2010 [11] . There is thus no evidence that differences in SO_2 emissions explain the reduced rate of warming in the observations compared to the CMIP5 simulations over the past decade [10]: in fact the higher SO_2 emissions in the RCP 4.5 scenario should have caused slightly less warming in the RCP 4.5 simulations than the observations over this period, though any difference in temperature response to sulfate aerosols is likely to be small compared to internal variability.

The large reduction in aerosol and aerosol precursor emissions through the 21st century in the RCP scenarios is expected to lead to a warming effect on climate [12–14]. Based on equilibrium simulations with the ECHAM5-HAM model, Kloster *et al* [12] find that maximum feasible emissions reductions in aerosols (including SO_2 and black carbon), compared to constant year 2000 emissions, would lead to almost 1 °C warming between 2000 and 2030. The reduction in SO_2 emissions which they specify of approximately ∼80 $TgSO_2$ yr^{-1} is large even compared to the ∼50 $TgSO_2$ yr^{-1} emissions reduction in the RCP 2.6 scenario between 2000 and 2030. However, even considering this large reduction in SO_2 emissions, their estimate of warming is relatively large, given observationally constrained estimates of present-day temperature response attributable to anthropogenic forcings other than well-mixed greenhouse gases of −0.25 °C (5–95% range of −0.6–0.1 °C) [15], and a present-day aerosol cooling of ∼0.5 °C simulated in CanESM2 (figure 2). This may partly be explained by the use of equilibrium simulations by Kloster *et al* [12] rather than transient simulations, and partly by a particularly strong aerosol forcing in their model: they simulate a reduction in aerosol forcing between 2000 and 2030 of 1.13 W m^{-2} which is considerably greater than the total aerosol forcing in 2000 in CanESM2 of −0.89 W m^{-2}. However, given the large uncertainties in aerosol forcing and in equilibrium climate sensitivity, their estimate, though high, may not be inconsistent with observational constraints.

Levy *et al* [14] compare RCP 4.5 simulations from GFDL-CM3 with a parallel set of simulations in which aerosol and aerosol precursor emissions are fixed at 2005 levels. They focus on long-term impacts of aerosol emissions reductions and find a relatively large warming impact of ∼1 °C by 2100. This estimate of warming is larger than an estimate of observationally constrained present-day cooling attributable to anthropogenic forcings other than greenhouse gases [15], which is consistent with their suggestion that the total aerosol effect in the model is too strong. Although it is not the focus of their study, their figures show negligible impact of aerosol changes relative to 2005 on global mean temperature prior to 2030 in RCP 4.5 (their figure 4).

Chalmers *et al* [13] compare simulations forced with RCP 2.6 emissions to simulations forced with RCP 4.5 emissions from the HadGEM2-ES model. They show that even though GHG concentrations were higher in the RCP 4.5 simulation over the period 2018–2037, the RCP 2.6 simulation was warmer, which they attribute to the more rapid decline in SO_2 emissions in that scenario (figure 1(a)). They argue that their results provide strong evidence that rapid warming between 2010 and 2025 in HadGEM2-ES RCP 2.6 simulations is a result of a rapid decrease in sulfate aerosol load. However, since they do not have simulations with GHG or aerosol changes only, they cannot quantify the contribution of aerosols to the temperature change, and they suggest that a simulation with aerosol emissions fixed at 2005 levels is needed to do this. We carry out such simulations using CanESM2, and quantify the contribution of reductions in aerosol emissions to projected near-term warming.

2. Model and simulations

We use simulations from CanESM2, the Earth System Model used for CMIP5 by the Canadian Centre for Climate

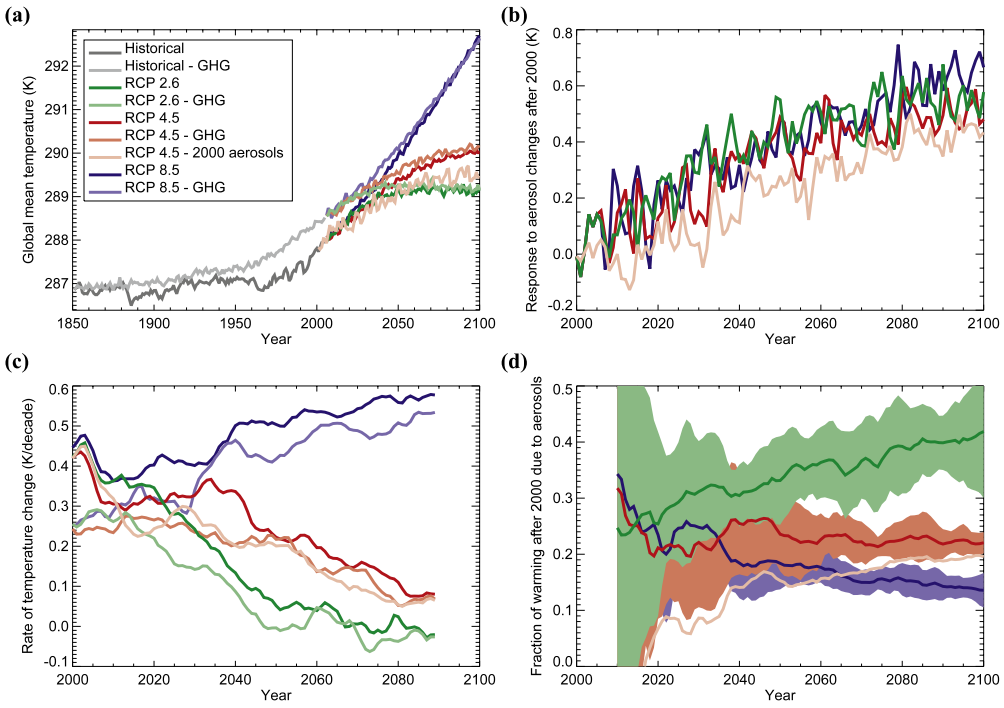

Figure 2. Panel (a) shows ensemble mean global mean near-surface air temperature in historical and RCP simulations from CanESM2. Pale lines labelled 'GHG' show global mean temperature in simulations with well-mixed GHG changes only. The pink line labelled 'RCP 4.5—2000 aerosols' shows simulations with fixed 2000 aerosol and aerosol precursor emissions and all other forcings following RCP 4.5. Panel (b) shows an estimate of the aerosol contribution to temperature change since 2000 derived by subtracting the temperature anomaly relative to 1995–2005 in the simulations with GHG changes only (dark coloured lines) or 2000 aerosols simulations (light pink line) from the anomaly in the RCP simulations. Panel (c) shows the rate of temperature change in each of the simulations, calculated from a difference in mean temperature between the following and preceding 11-year periods for each year. The warming rate in 2000 is higher than in any previous year of the historical simulations. Panel (d) shows an estimate of the ratio of the aerosol-induced temperature changes to the total temperature change relative to the year 2000 for each RCP. Dark lines show ratios derived from the difference between the RCP simulations and the GHG-only simulations, and the light pink line shows the ratio derived from the difference between the RCP 4.5 and RCP 4.5—2000 aerosols simulations. All temperatures were smoothed with an 11-year running mean prior to calculating this ratio. Shaded bands show estimates of the 5–95% uncertainty ranges in the ensemble mean ratios, derived by taking the standard deviation of the ratio from each of the five independent pairs of simulations with and without aerosol changes, dividing by the square root of five (the ensemble size), and multiplying by a Student-*t* statistic with a cutoff value of 0.05 and four degrees of freedom (one less than the ensemble size). All values shown are five-member ensemble means.

Modelling and Analysis [16, 17]. The model includes interactive cycles of sulfur, organic and black carbon, mineral dust and sea salt and represents their direct radiative effects [17]. Effects of sulfate aerosols on cloud albedo (the first indirect effect) in the model are based on a semi-empirical parameterization of cloud droplet number concentration, while cloud-lifetime effects are not included. The model accounts for the evaporation of cloud droplets from absorption of solar radiation by black carbon (the semi-direct effect), but effects of black carbon on snow albedo are not accounted for in this version of the model. Aerosol mass concentrations are simulated in the model based on prognostic parameterizations for emissions, dry and wet deposition, and sulfur chemistry. Sulfur oxidation processes are calculated using fixed annually repeating specified monthly mean oxidant concentrations in the atmosphere, so changes in oxidant concentrations do not contribute to aerosol changes in these simulations. The model's diagnosed total aerosol effective radiative forcing in 2000 of -0.89 W m^{-2} (with a sulfate aerosol contribution of -0.96 W m^{-2}) is consistent with other model-based estimates to within uncertainties (Shindell *et al* [18] report a 5–95% range of -0.71 to -1.44 W m^{-2} in the ACCMIP models). Ozone in the troposphere and stratosphere is specified for radiative transfer calculations using the transient, three-dimensional ozone fields recommended for CMIP5 [19]. A zonally averaged version of the CMIP5 tropospheric ozone was used. No changes in stratospheric water vapour were prescribed.

We use output from a preindustrial control simulation and five-member ensembles of each of the following: a historical simulation with all major anthropogenic and natural forcings including specified anthropogenic changes in land cover (1850–2005), a historical simulation with natural forcings only, a historical simulation with GHG forcings only, RCP 2.6, RCP 4.5 and RCP 8.5 simulations from 2006 to 2100, corresponding simulations in which concentrations of well-mixed greenhouse gases followed the RCP scenarios but all other forcings were held fixed at preindustrial levels [16, 20], and a new simulation with all aerosol and aerosol precursor emissions fixed at 2000 levels, but all other forcings following RCP 4.5 (2000 aerosols). Note that aerosol and aerosol precursor emissions are generally specified at 10-yr intervals in the RCP scenarios, and were interpolated between these values for intervening years in our simulations.

3. Results

Figure 2(a) shows the near-surface air temperature simulated in response to the RCP 2.6, 4.5 and 8.5 scenarios in CanESM2. Consistent with Chalmers *et al* [13], we find that the RCP 2.6 simulation is warmer than the RCP 4.5 simulation over the 2018–2037 period by 0.06 K (significant at the 10% level based on a two-tailed test). When the aerosol response is isolated by subtracting the simulated response to GHG changes only (figure 2(b)), the RCP 2.6 simulation is warmer by 0.10 K over this period, which is also statistically significant. This is consistent with the RCP 2.6 simulation also having lower GHG forcing during this period [13]. However, by comparing figures 2(a) and (b) it is also clear that the temperature response to aerosols in the RCP simulations is relatively small compared to the total temperature response. Figure 2(d) shows the ratio of temperature change due to aerosols and other non-GHG forcings to the temperature change due to all forcings relative to the year 2000 for each scenario. Consistent with Chalmers *et al* [13], aerosol changes are responsible for a larger fraction of warming in RCP 2.6 than in RCP 4.5. However, in the CanESM2 RCP 2.6 simulations the aerosol-driven warming is around 30% of the total warming throughout the period prior to 2040, thus aerosols are not the dominant driver of warming in this period in our simulations, and unlike Chalmers *et al* [13] we do not find a period of particularly rapid warming between 2010 and 2025 that 'is a result of a rapid decrease in sulfate aerosol load'. Over much of Asia and parts of the North Pacific, aerosol changes drive more than 50% of the simulated warming by 2031–2040 in RCP 2.6, while driving smaller fractions of warming in RCP 4.5 and 8.5 (figure 3). Our finding that the aerosol contribution to projected warming has a maximum over central Asia, but is weaker and non-significant over the Arctic, is consistent with previous studies [12, 14]. By the end of the century the aerosol-driven fraction of warming in RCP 2.6 is approximately 40% (figure 2(d)), thus aerosol-driven warming under this scenario is more important in the longer term than in the near-term.

Identification of the aerosol response by comparing the RCP simulations with corresponding greenhouse gas only simulations is not perfect since the effects of ozone changes, land-use change and the solar cycle are also included with the aerosol response, as is the effect of changes in aerosol emissions prior to the year 2000. To isolate the effects of changes in aerosol emissions after the year 2000, we show results from a further set of simulations. The pale pink line in figure 2(a) shows the ensemble mean temperature in simulations in which aerosol and aerosol precursor emissions are fixed at year 2000 values, and all other forcings are specified as in RCP 4.5. The sulfate aerosol load in this ensemble remains near-constant at its year 2000 value (figure 1(b)), while it declines in the RCP 4.5 ensemble. When evaluated by differencing the RCP 4.5 and RCP 4.5—2000 aerosols ensembles, the temperature response after 2000 is somewhat smaller than when evaluated by differencing the RCP 4.5 and RCP 4.5—GHG ensembles (figure 2(b)),

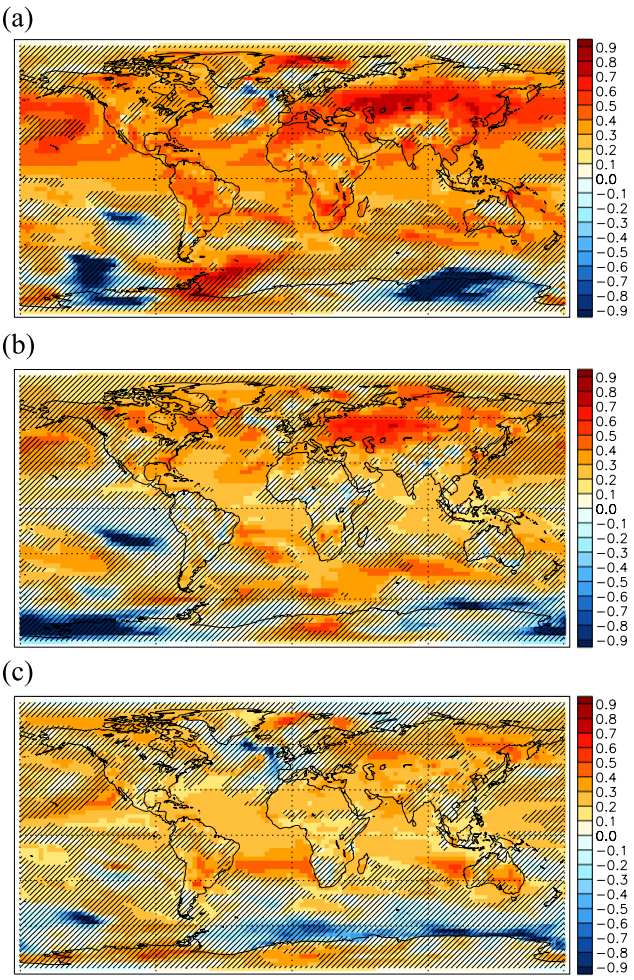

Figure 3. Ratio of aerosol-induced to total simulated near-surface air temperature change in each RCP scenario between 2005 and 2035. Aerosol-induced temperature changes are inferred from the difference between mean temperature changes in the RCP scenario simulations between 2031–2040 and 2001–2010 and mean temperature changes in the corresponding GHG-only simulations between the same periods. The inferred aerosol response therefore also includes the response to land-use, solar irradiance and ozone changes over this period, but responses to these forcings are expected to be relatively small. Hatching indicates where the ensemble mean aerosol response is not significant at the 10% level.

particularly in the early 21st century. This may be because the former calculation omits warming due to tropospheric ozone increases and a possible contribution of committed warming due to reductions in sulfate aerosol prior to 2000 (figure 1). This translates into a reduced contribution of aerosols to near-term warming in RCP 4.5 when evaluated using the 2000 aerosols simulation (figure 2(d)). We do not have an RCP 2.6 simulation with fixed 2000 aerosols, but these results suggest that the fraction of near-term warming in RCP 2.6 due to aerosol changes since 2000 is likely to be smaller than that shown in figure 2(d).

Lastly we examine the rate of warming to test whether the near-term reduction in aerosol and aerosol precursor emissions in RCP 2.6 gives rise to a particularly rapid rate of warming. Figure 2(c) shows that while the warming rate is slightly higher in RCP 2.6 than in RCP 4.5 in the period

prior to 2025, consistent with Chalmers *et al* [13], it is lower than the warming rate in RCP 8.5. The warming rate in RCP 2.6 declines gradually through the 21st century, while it increases in RCP 8.5, and in all cases greenhouse gas changes are the dominant driver of near-term warming. These simulations indicate that under the RCP 2.6 scenario, the rate of warming is projected never to exceed that simulated over the past decade, with no indication of particularly rapid warming in the near future [13]. Note that the warming rate in the period between 2000 and 2005 is considerably higher than that simulated through most of the 20th century and is likely due in part to a recovery from Pinatubo: the warming rate is calculated from a difference in temperatures between the preceding and following 11-year periods.

4. Conclusions

Consistent with previous studies we find that projected decreases in aerosol and aerosol precursor emissions under the RCP scenarios will drive gradual warming through the 21st century. In the near-term, this aerosol-induced warming is largest in RCP 2.6, which has the most rapid decrease in SO_2 emissions [8, 13]. However, compared to the total warming simulated under these scenarios, the aerosol-driven warming is modest: In the RCP 2.6 scenario aerosol emission changes contribute around 30% of the global mean warming over the period up to 2040 considered by Chalmers *et al* [13], though the contribution is larger in some regions. Thus, while projected aerosol emissions changes are a significant contributor to future warming, and while results may be model-dependent, we consider it unlikely that a period of rapid warming between 2010 and 2025 in the HadGEM2-ES RCP 2.6 simulations is primarily 'a result of a rapid decrease in sulfate aerosol load', as Chalmers *et al* [13] concluded. In our simulations, warming over this period is mainly driven by GHG increases. Our results also disagree with those of Kloster *et al* [12], who find that rapid reductions in aerosol and aerosol precursor emissions could drive a warming of $\sim$1 K by 2030. Even by the end of the 21st century, by which time aerosol and aerosol precursor emissions are at close to preindustrial levels in the RCP scenarios, the associated warming in CanESM2 is only 0.4–0.7 K, which is also considerably less than that reported in simulations from the GFDL-CM3 model [14].

CanESM2 has a Transient Climate Response of 2.4 K, which is among the highest of the CMIP5 models [15]. Its total aerosol forcing in 2000 is -0.89 W^{-2}, which is consistent with other model estimates [18]. Perhaps in part due to its high Transient Climate Response, a detection and attribution analysis indicated that its response to aerosols should be scaled down in order to best match observations [20]. In addition, all the RCP scenarios include an increase in emissions of ammonia over the next few decades which is expected to lead to enhanced nitrate aerosol and a compensating cooling effect, neglected in our simulations. Based on these considerations, we suggest that our estimates of the 21st century warming due to aerosol changes may lie towards the upper end of likely values, though we emphasize that there are substantial uncertainties in the future evolution of aerosol radiative forcing and the associated climate response. Overall we conclude that while aerosol emissions changes under the RCP scenarios make a significant contribution to 21st century warming, GHGs are the dominant driver of warming both in the near-term and long-term. We do not expect aerosol reductions to drive a period of particularly rapid near-term warming, but rather to contribute a gradual warming over the 21st century.

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