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Global and regional climate impacts of future aerosol mitigation in an RCP6.0-like scenario in EC-Earth

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Abstract Future changes in aerosol concentrations will influence the climate system over the coming decades. In this study we evaluate the equilibrium climate response to aerosol reductions in different parts of the world in 2050, using the global climate model EC-Earth. The aerosol concentrations are based on a set of scenarios similar to RCP6.0, developed using the IMAGE integrated assessment model and exploring stringent and weaker air pollution control. Reductions in aerosol concentrations lead to an increase in downward surface solar radiation under all-sky conditions in various parts of the world, especially in Asia where the local brightening may reach about 10 Wm^{-2}. The associated increase in surface temperature may be as high as 0.5 °C. This signal is dominated by the reduced cooling effect of sulphate which in some areas is partially compensated by the decreased warming effect of black carbon. According to our simulations, the mitigation of BC may lead to decreases in mean summer surface temperature of up to 1 °C in central parts of North America and up to 0.3 °C in northern India. Aerosol reductions could significantly affect the climate at high latitudes especially in the winter, where temperature increases of up to 1 °C are simulated. In the Northern Hemisphere, this strong surface temperature response might be related to changes in circulation patterns and precipitation at low latitudes, which can give rise to a wave train and induce changes in weather patterns at high latitudes. Our model does not include a

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parameterization of aerosol indirect effects so that responses could be stronger in reality. We conclude that different, but plausible, air pollution control policies can have substantial local climate effects and induce remote responses through dynamic teleconnections.

1 Introduction

Changes in the amount, distribution and composition of aerosols in the atmosphere over the last 150 years are mainly caused by anthropogenic activities related to energy and land use. These changes have influenced the transfer of radiation and spatial distribution of moist static energy through the atmosphere with a large impact on weather and climate (Boucher et al. 2013). Sulphate (SO_4), nitrate, and some forms of organic aerosols reflect solar radiation and thus have a cooling effect on the climate (Hansen et al. 1981; Charlson et al. 1991; Kiehl and Briegleb 1993; Mitchell et al. 1995). Black carbon (BC), on the other hand, absorbs solar radiation, thereby reducing the amount of solar energy that reaches the earth's surface. This results in a local warming of the atmosphere and a cooling of the underlying surface (Hansen et al. 2005; Bond et al. 2013). Besides these direct radiative effects, aerosols also influence the climate by changing the properties and lifetimes of clouds, and changes in diabatic heating can cause remote changes through atmospheric teleconnections. Field observations and modelling studies have shown that overall increases in aerosols have had a net cooling effect on the climate, especially at the surface (Boucher et al. 2013).

The aerosol-induced scattering and absorption of solar radiation, which results in dimming at the surface, reduces the amount of solar energy available for evaporation, thereby slowing down the hydrological cycle (Wild et al. 2005 and references therein; Hartmann et al. 2013). There are indications that this dimming has recently been reversed in some parts of the world (Wild et al. 2005), resulting in local warming that is larger than the warming of greenhouse gases alone (Van Oldenborgh et al. 2009). This could be the result of reduction of aerosol concentrations due to the implementation of stringent air pollution policy. While the implementation of air quality control measures has reduced emissions of aerosols and aerosol precursors in Europe and North America, emissions have increased in the rapidly growing economies in South Asia and East Asia. While it is expected that stronger air pollution control policies will also be implemented here, it is yet unclear how pollution levels in Asia will evolve in the decades ahead.

A number of studies have looked at the impact of aerosol mitigation on future climate using the Representative Concentration Pathways (RCPs) (Chalmers et al. 2012; Gillett and Von Salzen 2013; Rotstayn et al. 2013) and emission scenarios from the International Institute for Applied Systems Analysis (IIASA) (Kloster et al. 2010; Sillmann et al. 2013). In general, these studies show that the mitigation of aerosols and precursor emissions could result in brightening at the surface and an increase in surface temperature.

In a previous study (Chuwah et al. 2013), we explored the implications of different assumptions regarding future air quality and climate policy for air pollutant concentrations, using a set of RCP-like scenarios developed with the IMAGE integrated assessment model (Bouwman et al. 2006). The scenarios showed a wide range of aerosol concentration pathways corresponding to substantially different radiative forcings, even on a global scale. The study found that the implementation of more stringent air pollution control (compared to current legislation) in a scenario with weak climate policy (similar to RCP6.0) would lead to a global mean net positive aerosol direct radiative forcing of 0.22 Wm^{-2}, mainly due to substantial

reductions of aerosol concentrations in Asia. Among the different aerosol components, the reduction of the cooling effect of $SO_4$was found to be the strongest signal (0.64 Wm^{-2}), but that effect is partially compensated by the decline in the warming effect of BC (-0.35 Wm^{-2}).

Our scenarios cover a much broader range of possible outcomes with regard to future air pollutants than the RCPs. The climate impacts have not yet been evaluated in a general circulation model. In this study, we use the global climate model EC-Earth to assess the climate impacts of aerosol reductions in the RCP6.0-like scenarios from Chuwah et al. (2013) for 2050. We thereby separate the climate impacts due to reductions in SO_4 and BC, respectively. EC-Earth is derived from a numerical weather prediction model and has a comparatively high resolution compared to other models that participated in CMIP5 (Taylor et al. 2012). As a consequence it simulates atmospheric dynamics comparatively well (e.g., Zappa et al. 2013). Our model does not include a parameterization of aerosol indirect effects. Although these are very uncertain and not well constrained by observations, responses to aerosol reductions could therefore be higher in reality, especially in the case of SO_4.

The paper is structured as follows: Section 2 describes the methodology. In Section 3 we present results on local and remote climate impacts of aerosol mitigation. A discussion and conclusions of our results are given in Section 4.

2 Methodology

2.1 Model description

In this study, we use the EC-Earth model version 2.3 which participated in the Coupled Model Intercomparison Project (CMIP5, Taylor et al. 2012). The atmosphere and land surface components in EC-Earth are simulated using the Integrated Forecasting System (IFS) from the European Centre for Medium-Range Weather Forecasts (ECMWF). In this version of EC-Earth, IFS version 31r1is used with some modifications as described by Hazeleger et al. (2012). The IFS component is configured to run at a horizontal spectral resolution of T159 (triangular truncation at wavenumber 159) and a vertical resolution of 62 layers. The ocean is simulated with the Nucleus for European Modelling of the Ocean (NEMO) version 2, with a horizontal resolution of about 1 degree and 42 vertical layers (Madec 2008). Sea ice is modelled inside NEMO using the Louvain-la-Neuve sea ice model (LIM) version 2. The ocean/sea ice and the atmosphere/land components communicate via the OASIS3 coupler (Valcke 2013). Here we used the fully coupled EC-Earth model that allows for dynamic response and feedbacks from interactions between the atmosphere, land surface, sea ice, and the ocean. It is important to note that in this version of EC-Earth the description of clouds is not coupled to changes in aerosol concentrations. Also, the impact of BC deposited on snow or ice is not accounted for. In that sense, indirect aerosol effects are not accounted for. The absorption of solar radiation by BC modifies the atmospheric temperature structure and therefore cloud distributions (semi-direct effect). In EC-Earth, the impact of changes in cloud distributions on radiation induced by this semi-direct effect is accounted for.

2.2 Emissions scenarios

From the four scenarios presented by Chuwah et al. (2013), we selected two scenarios that explore high and low aerosol forcing as a result of different levels of air pollution control.

These scenarios, developed using the IMAGE integrated assessment model (Bouwman et al. 2006), have the same greenhouse gas emissions, but different emission factors (emissions per unit activity per sector and fuel type) for air pollutants (scenarios LOW and HIGH). In terms of greenhouse gas emissions, the scenarios are similar to the original RCP6.0 (Masui et al. 2011). Thus the global radiative forcing in our scenarios gradually increases throughout the century and reaches a value of around 6.0 Wm^{-2} in 2100.

The official RCP scenarios all assume successful implementation of air pollution policy (see Van Vuuren et al. 2011). This is simulated in our scenario LOW, in which the emission factors are assumed to decline in accordance with the implementation of current and planned air pollution legislations until 2030 and thereafter as a function of income levels. In contrast, in the HIGH scenario we assume that emission factors are held constant at the 2010 levels providing a reference scenario, which enables us to systematically assess the potential impacts of future air pollution policy on aerosol concentrations and regional climate conditions by comparing the LOW and HIGH scenario. As a set, the two scenarios therefore explore the impact of air pollution emissions for a wider range than included in the RCPs. A detailed description of the underlying assumptions of the LOW and HIGH scenarios and comparison with the RCPs can be found in Chuwah et al. (2013). Some important results of the scenarios are shown in the supplementary material (Fig. S1).

2.3 Experimental setup

The climate response to the reduced aerosol concentrations is investigated using time slice simulations with EC-Earth for 2050. The initial conditions were set to the 2005 results from a CMIP5 compliant simulation of EC-Earth with prescribed historical forcings. Here, we used prescribed monthly mean aerosol fields for our simulations which is in line with simulations conducted in other studies (e.g., Teng et al. 2012). In our time slice simulations, the forcings for well-mixed greenhouse gases, ozone, volcanic aerosols, and the solar cycle were fixed to their 2050 levels irrespective of the model year. All simulations were continued for 180 years to allow the model to adjust to the imposed forcings. The output of our simulations was analysed for the last 80 years when the model's climate has reached a quasi-steady state (Fig. S2).

The aerosol fields used in EC-Earth version 2.3 for CMIP5 are based on simulations with the chemistry-climate models CAM3.5 (Lamarque et al. 2010). The CAM aerosols consist of hydrophobic and hydrophilic BC and OC, SO_4, sea salt and mineral dust. In order to account for the aerosol direct radiative effects according to the HIGH and LOW scenarios for 2050, we scale the CAM mixing ratios of BC, OC, and SO_4 using the vertically integrated burdens from the atmospheric chemistry and transport model TM5, used by Chuwah et al. (2013). Note that the TM5 future aerosol concentrations were calculated using present-day (2005) meteorological fields from ERA-Interim reanalysis (Dee et al. 2011) of the European Centre for Medium-Range Weather Forecasts (ECMWF). To use our TM5 aerosol fields in EC-Earth, we apply scaling ratios for SO_4, BC, and OC to the corresponding aerosol fields for 2005 computed in CAM. Thus, the mixing ratios X_i of the various aerosol components i used in our simulations are given by

$$X_i\left(\underline{r}, 2050\right) = \frac{B_i^{\mathrm{TM5}}\left(\underline{x}, 2050\right)}{B_i^{\mathrm{TM5}}\left(\underline{x}, 2005\right)} \times X_i^{\mathrm{CAM}}\left(\underline{r}, 2005\right)$$

where B_i denote the vertically integrated burdens for the different aerosol components, and $\underline{r}$ and $\underline{x}$ are the 3-D and 2-D coordinates.

We performed four different simulations with different aerosol concentrations as shown in Table 1. The first two simulations correspond to the LOW and HIGH scenarios respectively. To assess the individual contributions of BC and SO_4 to the simulated climate response we performed two additional experiments: BC-LOW and SO_4-LOW. In these experiments the HIGH scenario is assumed, but with concentrations of BC and SO_4, respectively, from the LOW scenario. The data presented in this study represent averages over the last 80 years of our simulations. Statistical significance of the differences in climate response between our scenarios is evaluated using student's *t*-test at a significance level of 0.05.

3 Results

3.1 Impacts of aerosol reductions on radiation

The top panels of Fig. 1 show the differences in annual mean downward surface solar radiation (SSRD) under all-sky conditions between the LOW and HIGH pollution scenarios (left) and the contribution from reductions in SO_4 aerosols only (SO_4-LOW compared to HIGH) (right). While the air pollution control policies assumed in the LOW scenario strongly reduce air pollution levels, they also lead to a significant brightening at the surface, most notably in the Northern Hemisphere (NH) subtropics and mid-latitudes. The largest changes, with an increase in annual mean SSRD reaching 9.9 Wm^{-2}, are found in India and China, where aerosol concentrations are projected to increase strongly in the HIGH scenario and pollution control is most effective in reducing absolute concentrations levels. Significant changes in annual mean SSRD due to aerosol reductions can also be seen in most parts of the United States (US), Mexico and Europe, and in some parts of the Middle East and Northern Africa. Comparison with the SSRD differences due to changes in SO_4 only reveals that the SSRD increases are dominated by the scattering effect of SO_4, with the contributions from reductions in other aerosol components being much smaller.

The reduction of aerosol concentrations by air pollution policy as assumed in the LOW scenario leads to increases in annual mean net solar radiation at the top of the atmosphere (TSR) under clear-sky conditions (Fig. 1, bottom panels), especially in eastern China where increases of around 3 Wm^{-2} are estimated. Here, the reduced upward scattering by SO_4 dominates the calculated increase in the clear-sky TSR, which is partially compensated by a decrease in BC absorption. However, under all-sky conditions we see a decrease in annual mean TSR, especially in parts of eastern China where we simulate decreases of up to 7 Wm^{-2}.

Table 1 Overview of the EC-Earth simulations performed in this study

Simulation	BC concentrations	OC concentrations	SO_4 concentrations
LOW	Low	Low	Low
HIGH	High	High	High
LOW-BC	Low	High	High
LOW-SO_4	High	High	Low

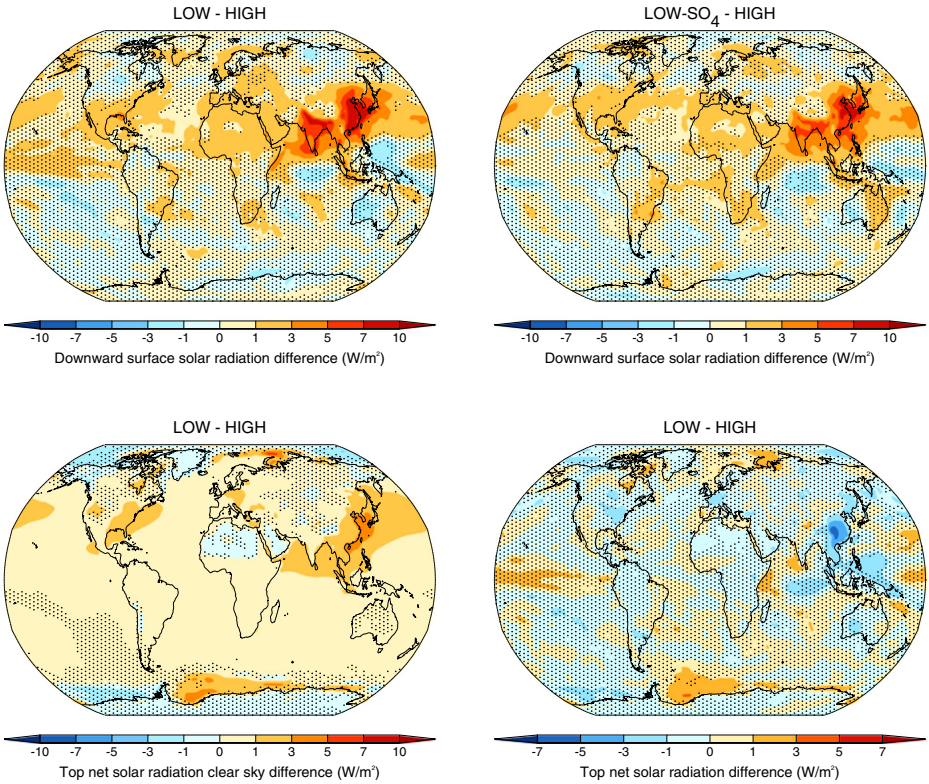

Fig. 1 Differences in annual mean downward surface solar radiation under all-sky conditions between the LOW and the HIGH scenario (top left panel) and the contributions from reductions in SO_4 aerosols only (top right panel). The bottom panels show the corresponding differences in annual mean top of atmosphere net solar radiation under clear-sky (left) and all-sky (right) conditions. The stippled areas show regions where the differences are not significant at the 5 % level, and this applies to all the other figures as well

Further analysis indicates that the aerosol-induced brightening at the surface increases the amount of potential convective energy, thereby enhancing the development of convective clouds, which increases the upward scattering effect of clouds. This is evident in the increase in the computed annual mean liquid water path (Fig. S4, bottom left) and in convective precipitation, especially during the boreal summer (Fig. S4, bottom right). The mitigation of aerosols result in an increase in precipitation of up to 1 mm per day over China which is similar to the findings of Levy et al. (2013). This computed increase in available potential convective energy and convection is consistent with previous studies (see Persad et al. 2012; Kim et al. 2014) and demonstrates how aerosol direct radiative effects can have an impact on clouds and the hydrological cycle. In contrast, Niemeier et al. (2013) found that the hydrological sensitivity is decreased by solar radiation management, especially for aerosol-based techniques such as artificial sea salt emissions.

3.2 Local impacts of aerosol reductions on climate

Our results indicate that the impact of air pollution policy on surface temperature could be significant, especially in South and East Asia (Fig. 2). The abatement of aerosols in the LOW

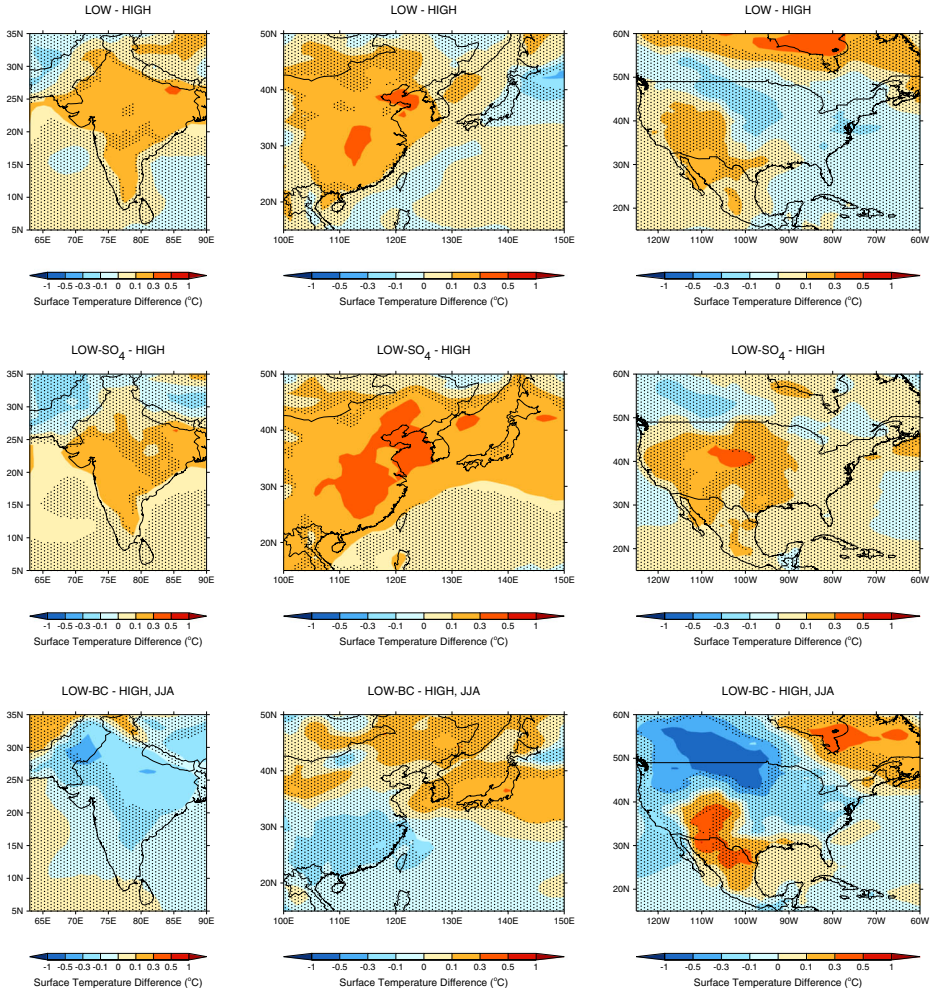

Fig. 2 Differences in annual mean temperature over India (left panels), China (middle panels) and the United states (right panels) between the LOW and the HIGH scenario (upper panels), the contributions from reductions in sulphate only (second row panels) and the effects of reductions in BC in the summer (JJA, third row panels)

vs. HIGH scenario results in an increase of up to 0.5 °C in surface temperature in parts of North America, India and China. The significant changes in surface temperature that we find over the US appear qualitatively similar to results reported in Mickley et al. (2012). Our results also show that the reduced scattering effect of SO_4 (SO_4-LOW compared to HIGH) explains most of the estimated increases in surface temperature especially in most parts of eastern China and central US, with a maximum increase of up to 0.5 °C. Levy et al. (2013) also found that the temperature response to aerosol changes in RCP4.5 is dominated by sulphate in their model. On the other hand, a 0.3 °C decrease in surface temperature due to the effect of reductions in BC (BC-LOW with respect to HIGH) in the northern parts of India during the boreal summer is also visible (Fig. 2, third row, left panel). Also, we find a significant decrease in summer mean surface temperature of up to 1 °C in parts of central North America (Fig. 2, bottom right) as a result of the mitigation of BC. Teng et al. (2012) found qualitatively similar temperature

changes over the United States in response to changes in carbonaceous aerosol concentrations over Asia. Interestingly, we find that BC reductions lead to surface warming in parts of the US and a region stretching from the Sea of Japan to the east, which may be related to the simulated surface brightening. In Europe the changes in surface temperature are less significant.

3.3 Remote impacts of aerosol reductions on climate

Although most of the aerosol changes occur in the subtropics and NH mid-latitudes, a substantial climate response is found in the Arctic and Antarctic (Fig. 3). In the Arctic the

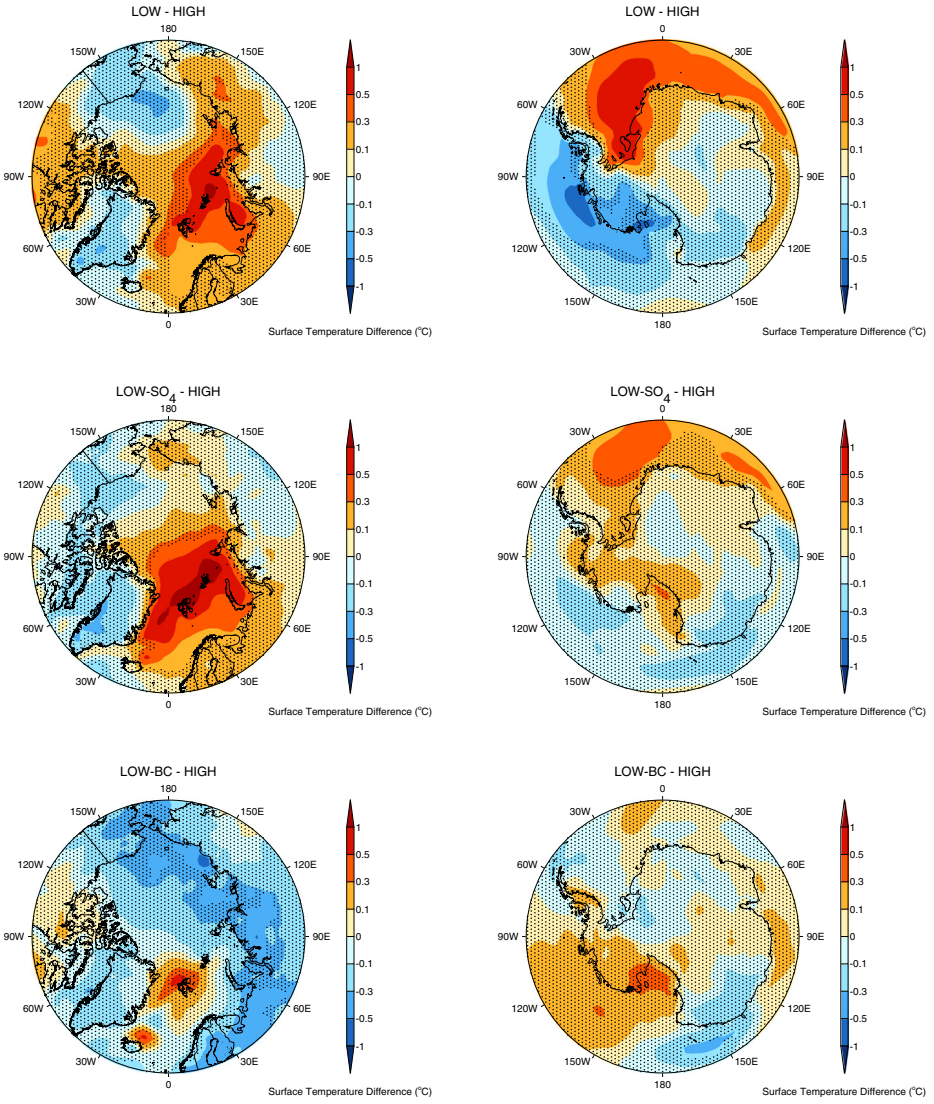

Fig. 3 Differences in annual temperature in the Arctic (left panels) and Antarctic (right panels) between the LOW and the HIGH scenario (upper panels), and the contributions from reductions in SO_4 (middle panels) and BC (bottom panels) only

annual mean surface temperature increases by about 0.5 °C due to aerosol reductions. This surface temperature increase is higher in winter (up to 1 °C).

Results from the SO_4-LOW and BC-LOW compared to the HIGH scenario show that BC and SO_4 can have opposite effects on surface temperature in the Arctic. For example, decreases in SO_4 concentrations increase annual mean surface temperatures in the Arctic by up to1°C. On the contrary, reductions in BC tend to lead to surface cooling of the Arctic. Locally, this contribution can be as high as 0.5 °C in the annual mean and 1 °C in winter.

The reduction of aerosol concentrations results in a decrease in annual mean surface temperature by 1 °C in parts of the Weddell Sea. At the same time, increases in annual mean surface temperature of up to 1 °C can be seen in small parts of the Ross Sea and in large parts of the Southern Ocean to the west of the Ross Sea. The changes found in the high latitudes may be caused by remote responses induced by changes in aerosol concentrations through teleconnections. However, the region where such responses are simulated is rather small. It is important to reiterate that most of the aerosols reductions take place in the NH mid-latitudes and the tropics. This suggests that the overall climate response at high latitudes is strengthened by processes described below.

Previous studies have shown that Arctic temperatures are strongly influenced by NH mid-latitude forcings (e.g., Shindell 2007; Shindell et al. 2010; Sand et al. 2013; Rotstayn et al. 2014). Part of the strong surface temperature response that we find in the winter at the poles is linked to the local ice albedo feedback carried over from the summer (see Screen and Simmonds 2010, and references therein). Here, the reduced sea ice cover in the summer enhances the warming of the surface ocean, which further harnesses sea ice loss and more energy uptake by the ocean. The additional heat stored in the ocean is released in the winter, thereby hampering the expansion of winter sea ice. In the Arctic, the largest temperature changes are found in the Barentsz and Kara Seas, which have been noted to have very large climate variability and strong local feedbacks (Kim et al. 2014). However, there are important differences between the externally mixed aerosols used in our model and the internally mixed representation in Kim et al. (2014), which might limit the comparison of our results to their findings.

Nonlocal effects through atmospheric teleconnections likely play a role as well. In Fig. 4 we present changes in zonal mean precipitation and the meridional overturning mass stream function for boreal summer under the LOW and SO_4-LOW scenarios relative to the HIGH scenario. Increases in zonal mean precipitation of up to about 0.07 mm per day are found, with the strongest responses in the tropics and NH mid-latitudes. The precipitation changes are dominated by changes in convective precipitation, especially in the tropics. Also, we see changes in the Hadley cell circulation pattern which is strongly related to precipitation at low latitudes (Yoshimori and Broccoli 2008). Previous studies (Rotstayn et al. 2014 and references therein) have indicated that higher aerosol forcings in the NH result in the enhancement of the Hadley cell circulation, an increase in precipitation in the SH and a decrease in the NH tropics. Our results show a weakening of the ascending and descending branches of the Hadley cell circulation, especially during the boreal summer (Fig. 4, bottom panels).

The simulated increases in precipitation in the tropics can cause anomalies in high-level wind divergence which acts as a Rossby wave source (Hoskins and Karoly 1981). For instance, Yuan and Martinson (2000), using Pacific precipitation as an indicator of tropical climate variability, showed that there is a link between the Antarctic sea ice extent and changes in Pacific precipitation. It is possible that the increase in convection as highlighted by an increase in convective precipitation in the tropics induced by aerosol reductions might affect the sea ice cover and the climate in the polar regions. The anomalies in geopotential height

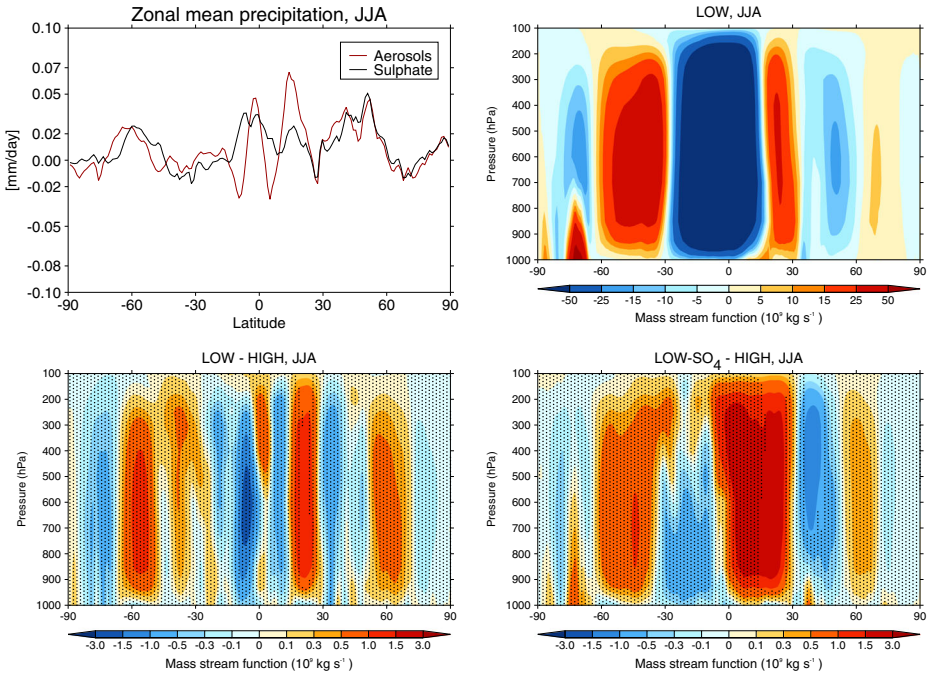

Fig. 4 Zonally integrated precipitation (top left panel) and mass stream function (top right panel) in boreal summer (JJA), and the corresponding differences in mass stream function between the LOW and the HIGH scenario (bottom left panel), and the contribution from reductions in SO_4 only (bottom right panel)

indicate a Pacific-North American (PNA) response and a North Atlantic Oscillation-like response in the Northern Hemispheric during the winter. (Fig. 5, top panels). These teleconnection patterns are known to be driven by anomalous divergence in the Pacific warm pool region. However, the Pacific South American-like response appears less significant in austral winter. While our results indicate that some of the climate responses simulated in the Arctic might be driven by climatic changes in the tropics, it is not clear from our findings if the climate responses seen in the Antarctic are related to the changes in circulation patterns and precipitation at low latitudes, as demonstrated by Yuan and Martinson (2000). While our findings are consistent with previous research (Kloster et al. 2010; Chalmers et al. 2012), additional research is needed to better comprehend the mechanisms responsible for the aerosol induced climatic responses simulated in the Antarctic.

4 Discussion and conclusions

This study has assessed the impacts of reduction of aerosol and aerosol precursor emissions (as a result of air pollution policies) on climate using the ocean–atmosphere coupled general circulation model EC-Earth (Hazeleger et al. 2012). EC-Earth has a relatively high spatial resolution and well represents atmospheric dynamics. We performed long equilibrium simulations with fixed boundary conditions for 2050. In total, we completed four simulations based on two concentration scenarios, describing a contrasting LOW and HIGH trajectory of aerosol concentrations for an RCP6.0-type of scenario (Chuwah et al. 2013). These scenarios are used

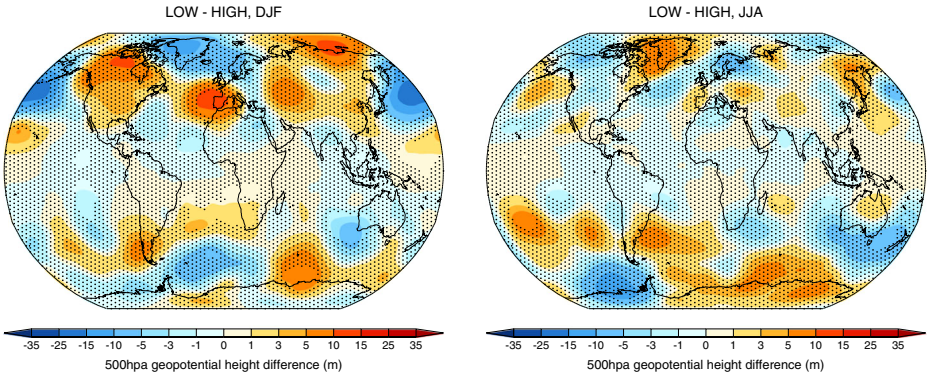

Fig. 5 Differences in boreal winter (DJF) and summer (JJA) geopotential height anomaly with respect to the zonal mean, between the LOW and the HIGH scenario

to estimate the combined climate impact of reductions in SO_4, BC, and OC. Also, we compute the climate impact of reducing BC and SO_4 separately. By comparing the different simulations, we are able to assess possible climate impacts of aerosols mitigation and the separate contributions of SO_4 and BC.

The equilibrium climate responses presented in this study take into account the direct and semi-direct radiative effects of the imposed aerosol changes, and the subsequent response of the climate system. Other studies (Kloster et al. 2010; Levy et al. 2013; Rotstayn et al. 2013) have taken into account aerosol effects on cloud albedo and cloud lifetime. This could make the sulphate effects relatively more important. For instance, Levy et al. (2013) found that both temperature and precipitation show much stronger responses when aerosol indirect effects are included. In addition, the use of prescribed monthly mean aerosol fields ignores correlations introduced by synoptic variability, for example related to wet removal and interactions with clouds. This tends to reduce the simulated aerosol direct radiative effects under clear-sky conditions, and in the case of BC above clouds.

In addition, we did not account for changes in nitrate aerosols in our simulations. The impact of nitrate on future climate will become relatively more important as concentrations of other aerosol components will decrease (Bellouin et al. 2011; Shindell et al. 2013). Bellouin et al. (2011) indicated that nitrate aerosols are likely to become the dominant species in Europe and Asia and decelerate the decrease in global mean aerosol forcing. They estimated that increases in nitrate aerosols could make aerosol radiative forcing 2 to 4 times stronger by 2100, depending on the RCP. However, it is important to note that nitrate concentrations are quite difficult to model, especially with global models, because of its semi-volatile character and the strongly localized pattern of ammonia emissions.

The climate impacts have been evaluated in terms of changes in the solar radiation budget, surface temperature and elements of the hydrological cycle. The results show that the reductions in aerosol concentrations will lead to a substantial increase in SSRD under all-sky conditions on regional and continental scales, especially in Asia. This increase is mainly caused by reduced scattering by sulphate. The direct radiative effects of aerosols also have an impact on clouds. This can be seen in the computed TSR over eastern China, where the increase in clear-sky downward surface solar radiation results in more convective clouds, precipitation and a decrease in simulated TSR. Also, it has been shown that the reduced absorption of incoming solar radiation by BC has a semi-direct effect on clouds and climate

(Boucher et al. 2013) by cooling the surrounding atmosphere and reducing the evaporation of cloud droplets.

A decrease in both scattering and absorbing aerosols leads to a change in surface temperature in some parts of the world by up to 1 °C. The surface temperature response is qualitatively similar to the effect of declining aerosols on climate reported in the global modelling studies of Rotstayn et al. (2013) and Levy et al. (2013) and the regional modelling study for the US by Mickley et al. (2012). For instance, some of the strongest surface temperature responses are found at high latitudes, where the changes in aerosol concentrations are small. This indicates the sensitivity of this region to changes in the tropics and mid-latitudes. Other studies (Shindell and Faluvegi 2009; Screen and Simmonds 2010; Kim et al. 2014) have also shown that the climate response in the Arctic is correlated with mid-latitude forcing, notably outside the summer season, as a result of the large-scale dynamics influencing the climate of this region.

A decrease in sulphate concentrations alone results in surface warming, while decreases in BC concentrations might decrease or increase the local surface temperature depending on the location. It has been demonstrated in previous studies (Shindell and Faluvegi 2009; Sand et al. 2013; Yang et al. 2014) that increases in BC at mid-latitudes may contribute substantially to surface warming in the Arctic, through increased transport of heat into the Arctic which leads to a decrease in sea ice. However, it is important to note that we do not take into account the direct role of BC in producing surface warming when it is deposited on ice or snow. Previous studies (e.g., Hazeleger et al. 2005; Bond et al. 2013 and references therein) have shown that BC deposited on snow or ice decreases the reflectivity of these surfaces, resulting in an increase in solar radiation absorption, and may play an important role in Arctic warming. Here, we also find a substantial surface temperature response in the Antarctic. This could be related to increased convection in the Western Pacific, which propagates in a wave train modulating the westerlies over the South Pacific and thereby influencing the variations of Antarctic sea ice over the Pacific and Atlantic sectors (Trenberth et al. 2007). Further research is needed to analyse these nonlocal effects in more detail.

This study clearly shows that there are continental and regional scale climate impacts following the implementation of aerosol mitigation measures. Our analysis indicates that the warming induced by sulphate mitigations dominate under the 6.0 Wm^{-2} scenario considered in this study and are therefore representative of scenarios with similar climate policy assumptions. However, under a scenario with stronger climate policies such as the 2.6 Wm^{-2} scenario similar to RCP2.6 discussed in Chuwah et al. (2013), the climate effects induced by BC reductions through air pollution control measures are expected to become more important as a lot of sulphate precursor emissions are already phased out by climate policies, while BC aerosol emissions could be much less affected by this.

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