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Black carbon reduction will weaken the aerosol net cooling effect

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Abstract

Black carbon (BC), a distinct type of carbonaceous material formed from the incomplete combustion of fossil and biomass based fuels under certain conditions, can interact with solar radiation and clouds through its strong light-absorption ability, thereby warming the Earth's climate system. Some studies have even suggested that global warming could be slowed down in a short term by eliminating BC emission due to its short lifetime. In this study, we estimate the influence of removing some sources of BC and other co-emitted species on the aerosol radiative effect by using an aerosol-climate coupled model BCC_AGCM2.0.1_CUACE/Aero, in combination with the aerosol emissions from the Representative Concentration Pathways (RCPs) scenarios. We find that the global annual mean aerosol net cooling effect at the top of the atmosphere (TOA) will be enhanced by 0.12 W m^{-2} compared with present-day conditions if the BC emission is reduced exclusively to the level projected for 2100 based on the RCP2.6 scenario. This will be beneficial for the mitigation of global warming. However, the global annual mean aerosol net cooling effect at the TOA will be weakened by 1.7–2.0 W m^{-2} relative to present-day conditions if emissions of BC and co-emitted sulfur dioxide and organic carbon are simultaneously reduced as the most close conditions to the actual situation to the level projected for 2100 in different ways based on the RCP2.6, RCP4.5, and RCP8.5 scenarios. Because there are no effective ways to remove the BC exclusively without influencing the other co-emitted components, our results therefore indicate that a reduction in BC emission can lead to an unexpected warming on the Earth's climate system in the future.

1 Introduction

Aerosols in the atmosphere can alter the amount of sunlight reaching the Earth by directly scattering sunlight (e.g., sulfate, organic carbon (OC) and nitrate) or absorbing it (e.g., black carbon (BC) and dust) (Boucher et al., 2013). Aerosol particles can also

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change cloud microphysical and optical properties by acting as cloud condensation nuclei (CCN) or ice nuclei (Twomey, 1977; Albrecht, 1989; DeMott et al., 1997). These changes due to aerosols will directly or indirectly affect the climate. Since the industrial era, an increase in atmospheric aerosols leads to a net cooling of the Earth's climate system (Boucher et al., 2013).

BC has a special role in the climate system, although it accounts for less than 5 % of the mass of atmospheric aerosol in most areas of the world (X. Y. Zhang et al., 2012). BC can increase the amount of solar radiation within the Earth's climate system and heat the atmosphere or surface by directly absorbing sunlight in the visible to infrared wavebands (Hansen et al., 2000; Ramanathan and Carmichael, 2008), changing the cloud amount and its brightness due to embedding into clouds (Chuang et al., 2002; Jacobson, 2012; Wang et al., 2013a), or by reducing the surface albedo due to deposition onto snow and ice surfaces (Wang et al., 2011; Lee et al., 2013). BC has even been considered as a potential cause of global warming (Hansen et al., 2000; Jacobson, 2010; Bond et al., 2013). Ramanathan and Carmichael (2008) compared the radiative forcings of greenhouse gases and BC, suggesting that the direct radiative forcing due to BC was larger than that due to any other greenhouse gases except CO_2. The radiative heating effect on the whole atmosphere due to BC was almost double that due to all greenhouse gases. By considering all the known ways that BC affects the climate system, Bond et al. (2013) gave an estimate of industrial-era climate forcing of $+1.1\,W\,m^{-2}$ due to BC with 90 % uncertainty limits of +0.17 to $+2.1\,W\,m^{-2}$. BC can therefore be considered the second most important human emission after CO_2 in the present-day atmosphere. Some studies have even suggested that global warming could be slowed down in a short term by eliminating BC emission due to its short atmospheric lifetime. For example, eliminating soot generated from fossil fuels, including BC, primary organic matter, and sulfide, was found to decrease global surface air temperature by 0.3–0.5 K in the short term (about 15 year) (Jacobson, 2010). A simultaneous decrease of short-lived BC and methane through the adoption of control measures

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could reduce projected global mean warming by about 0.5 °C by 2050 (Shindell et al., 2012).

Reducing the emissions of absorptive aerosols (e.g., BC) would decrease the absorption of solar radiation by atmospheric aerosols, thereby enhancing the aerosol net cooling effect. However, BC, OC, sulfate, and some other aerosols have many common emission sources (e.g., in the emission sectors of transportation, industrial, residential, and commercial energy consumption, etc.), and they are generally co-emitted into the atmosphere (Lamarque et al., 2010). Sulfate, BC, and OC are the main aerosol species in the atmosphere, and the emissions of sulfate and OC will be reduced accordingly if the emission of BC is tried to remove from its sources. Both sulfate and OC are strongly scattering and hygroscopic aerosols, and they can cool the climate system by directly scattering solar radiation and increasing the cloud albedo and lifetime by acting as CCN (Boucher et al., 2013). Therefore, would the global warming be slowed down necessarily by reducing BC emission in the future? This is the point of this study.

Focusing on the issue mentioned above, the impact of removing some BC sources and other co-emitted species on the aerosol radiative effects was studied in this paper by using an aerosol-climate coupled model BCC_AGCM2.0.1_CUACE/Aero (Atmospheric General Circulation Model of Beijing Climate Center, BCC_AGCM2.0.1, coupled with the aerosol model of China Meteorological Administration Unified Atmospheric Chemistry Environment for Aerosols, CUACE/Aero), in combination with the Representative Concentration Pathways (RCPs) emission scenarios underpinning the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5). In Sect. 2, we introduce the aerosol–climate coupled model and simulation details. In Sect. 3, we present the effects of reducing only BC emission and then of the simultaneous reduction of BC and other co-emitted aerosol emissions on aerosol direct, semi-direct and indirect, and net radiative effects. Finally, our conclusions are presented in Sect. 4.

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2 Model and simulation

2.1 Model description

We use the aerosol-climate coupled model BCC_AGCM2.0.1_CUACE/Aero developed by Zhang et al. (2012a), and improved by Jing and Zhang (2013), Zhang et al. (2014), and Wang et al. (2014) in this study. The aerosol direct, semi-direct, and indirect effects have been included in BCC_AGCM2.0.1_CUACE/Aero. The model has been used to study the impact of aerosol direct radiative effect on East Asian climate (Zhang et al., 2012a), direct radiative forcing of anthropogenic aerosols (Bond et al., 2013; Myhre et al., 2013), climate response to the presence of BC in cloud droplets (Wang et al., 2013a), effect of non-spherical dust aerosol on its direct radiative forcing (Wang et al., 2013b), anthropogenic aerosol indirect effect (Wang et al., 2014), and direct effect of dust aerosol on arid and semi-arid regions (Zhao et al., 2014).

A detailed description of BCC_AGCM2.0.1 was given by Wu et al. (2010). The model employs a horizontal resolution of T42 (approximately $2.8^{\circ} \times 2.8^{\circ}$) and a 26 layer hybrid sigma-pressure coordinate system in the vertical direction, with a rigid lid at 2.9 hPa. The time step is 20 min. However, the cloud overlap, radiation, and cloud microphysical schemes were improved in the model. The cloud overlap scheme of the Monte Carlo independent column approximation (McICA) (Pincus et al., 2003) and the Beijing Climate Center RADiation transfer model (BCC_RAD) developed by Zhang et al. (2003, 2006a, b) were used instead of the old schemes in the model (Jing and Zhang et al., 2013). These schemes have improved the accuracy of the subgrid cloud structure and its radiative transfer process (Zhang et al., 2014). A two-moment bulk cloud microphysical scheme to predict both the mass and number concentrations of cloud droplets and ice crystals was implemented into the model instead of the old one-moment bulk cloud microphysical scheme (Wang et al., 2014). The scheme of Abdul-Razzak and Ghan (2000) has been adopted for the activation of cloud droplets.

The aerosol model CUACE/Aero is a comprehensive module incorporating emission, gaseous chemistry, transport, removal, and size-segregated multi-component aerosol

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algorithms based on the Canadian Aerosol Module developed by Gong et al. (2002, 2003). A detailed description of CUACE/Aero was given by Zhou et al. (2012). The mass concentrations of the main five aerosols in troposphere that include sulfate, BC, OC, dust, and sea salt can be calculated. Each aerosol type is divided into 12 bins as a geometric series for a radius between 0.005 and 20.48 µm. Aerosol optical properties from Wei and Zhang (2011) and Zhang et al. (2012b) were calculated based on the Mie theory. The refractive indices of aerosols were adopted from d'Almeida (1991). Hygroscopic growth was considered for sulfate, OC, and sea salt (Zhang et al., 2012a).

2.2 Simulation details

Six simulations were run in this study. In all simulations, the model settings were the same, whereas aerosol emissions were different. All simulations kept greenhouse gases fixed at present-day values in order to obtain the effect of change in aerosol emissions exclusively. Table 1 gives the emission setups in all simulations. As a base case, the first simulation (SIM1) used emissions of sulfur dioxide (SO_2), BC, and OC for the year 2000, representing the aerosol effect for present-day conditions. In the second simulation (SIM2), BC emission in 2100 under the RCP2.6 scenario was used, but the emissions of SO_2 and OC were the same as those in SIM1. In the third simulation (SIM3), BC emission in 2100 under the RCP2.6 scenario was also used, but the emissions of SO_2 and OC used were those for 2100 under the RCP8.5 scenario. In the fourth simulation (SIM4), the emissions of SO_2, BC, and OC for 2100 under the RCP2.6 scenario were used. In the fifth simulation (SIM5), BC emission in 2100 under the RCP2.6 scenario was used, but the emissions of SO_2 and OC used corresponded to the 2100 emission of BC under the RCP2.6 scenario by multiplying them with the ratios of the emissions of SO_2 and OC with BC in 2000. In the sixth simulation (SIM6), the emissions of SO_2, BC, and OC in 2100 under the RCP4.5 scenario were used. Aerosol emission inventories for the year 2000 given by Lamarque et al. (2010) were used. The emission dataset of RCPs scenarios were obtained from http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Actionhtmlpage&pageabout. The

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National Centers for Environmental Prediction (NCEP) reanalysis climatological data on a Gaussian grid was used as the initial field. Data for the prescribed annual cycle of monthly mean sea surface temperature and sea ice from the Hadley Centre were used in these simulations. Each simulation was run for 20 years, and the simulation data for the last 10 years were averaged and analyzed.

The difference between SIM2 and SIM1 shows the impact on aerosol radiative effects (AREs) of reducing only BC emission maximally in the four RCPs scenarios. The difference between SIM3 and SIM1 indicates the effect of maximally reducing the emission of absorbing BC, combined with the least reduction in the emissions of precursor (SO_2) of scattering sulfate and OC on AREs. The differences between SIM4 and SIM1, between SIM5 and SIM1, and between SIM6 and SIM1 show the effects of a simultaneous reduction of SO_2, BC, and OC emissions under the RCP2.6 scenario, a reduction of the BC emission with a simultaneous reduction of the emissions of SO_2 and OC (in terms of their ratios with BC), and a simultaneous reduction in the emissions of SO_2, BC, and OC under the RCP4.5 scenario (representing the most likely future situation), on AREs, respectively. The aerosol direct effect was obtained by calling radiation routine two times (Ghan et al., 2012). The combination of the semi-direct and indirect effects of aerosol was estimated by the change in cloud radiative forcing (CRF), and the aerosol net effect was assessed by the change in net radiation flux at the top of the atmosphere (TOA) (Gettelman and Chen, 2013).

3 Results

3.1 Aerosol optical depth for present-day conditions

The simulation performance of BCC_AGCM2.0.1_CUACE/Aero has been given by Wang et al. (2014) in detail. They demonstrated that the model has a good ability to simulate aerosols, cloud properties, and meteorological fields. However, we replace the aerosol emission from AeroCom with those given by Lamarque et al. (2010) for

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present-day conditions in this work. Thus, a comparison of simulated annual mean aerosol optical depth (AOD) with satellite retrievals is shown in Fig. 1. The simulated AODs range from 0.3 to 0.6 over the Sahara Desert and are from 0.15 to 0.3 in nearby Arabian areas due to the large dust loading. The AODs are mainly between 0.2 and 0.4 in eastern China, and exceed 0.15 in eastern North America and West Europe due to the large emissions of anthropogenic aerosols. The AODs are above 0.1 over most subtropical oceans because of the contribution of sea salt and sulfate. The model generally reproduces the geographical distribution of AOD well, but it significantly underestimates the AODs over South Asia, eastern China, and tropical oceans.

3.2 The effect of aerosol reductions

3.2.1 Global mean statistics

Tables 2 and 3 show the global emission amounts and annual mean column burdens of aerosols in all simulations and differences in AREs among them. The global emission amount of BC is reduced from 7.8 $\mathrm{Tg\,yr^{-1}}$ at present to 3.3 $\mathrm{Tg\,yr^{-1}}$ at the end of this century under the RCP2.6 scenario due to the operation of various control measures. The global annual mean of simulated BC burden is decreased from 0.17 $\mathrm{mg\,m^{-2}}$ in SIM1 to 0.08 $\mathrm{mg\,m^{-2}}$ in SIM2, assuming that only BC emission is reduced under the RCP2.6 scenario (Table 2). The reduction in the mass concentration of atmospheric BC results in less direct absorption of solar radiation by atmospheric aerosols, thereby causing the global annual mean aerosol direct radiative effect at the TOA to be enhanced by 0.07 $\mathrm{W\,m^{-2}}$. The reduction in the BC concentration also weakens the aerosol semi-direct effect, resulting in an increase of 0.11 $\mathrm{W\,m^{-2}}$ in the absolute value of the global annual mean net CRF due to a reduction in cloud evaporation (Table 3). However, the slight decrease in the sulfate mass concentration in SIM2 partially offsets the net cooling effect caused by the decrease in BC emission compared with SIM1. Consequently, the global annual mean aerosol net cooling effect at the TOA is enhanced by 0.12 $\mathrm{W\,m^{-2}}$ compared with present-day conditions when just BC emission is reduced

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to the level projected for the end of this century under the RCP2.6 scenario (Table 3). The change in global annual mean surface air temperature caused by the reduction of only BC emission is close to zero due to the small non-homogeneous perturbation in the radiation fluxes.

There are several common sources of SO_2, BC, and OC (Lamarque et al., 2010). SO_2 and OC emissions are likely to be reduced proportionally when BC emission is decreased, as there is no effective way of removing BC exclusively without influencing the other co-emitted components. Therefore, we considered four different ways to simultaneously reduce the emissions of SO_2, BC, and OC to the levels projected for the end of this century under the RCP2.6, RCP4.5, and RCP8.5 scenarios, and calculated the effect of a reduction in the emission of all these aerosols on radiation fluxes in SIM3 to SIM6. It can be seen from Table 2 that the global emissions of SO_2, BC, and OC are decreased to 12.9–25.7 $Tg\,yr^{-1}$, 3.3–4.3 $Tg\,yr^{-1}$, and 20.0–25.3 $Tg\,yr^{-1}$ under these three scenarios, respectively. Thus, the global annual mean burdens of sulfate, BC, and OC are reduced by different levels (63–72, 51–55, and 25–31 %, respectively). The concurrent reductions in scattering sulfate and OC burdens weaken the global annual mean aerosol direct radiative effect at the TOA by 0.25–0.3 $W\,m^{-2}$, although the absorbing BC burden is also significantly reduced in SIM3 to SIM6. Additionally, sulfate and OC particles can act as CCN due to their hygroscopicity, so any decrease in their emissions would decrease CCN concentrations and cloud albedo. As can be seen from our results, the absolute values of global annual mean net CRF are decreased by 0.8–1.1 $W\,m^{-2}$ in SIM3 to SIM6 compared with SIM1, which even exceed the changes in the aerosol direct radiative effect. This is consistent with results obtained by Chen et al. (2010), who reported that a reduction in BC emission would dampen aerosol indirect forcing. Finally, the global annual mean aerosol net cooling effect at the TOA is weakened by 1.7–2.0 $W\,m^{-2}$, and the global annual mean surface air temperature is increased by 0.06–0.1 °C when the emissions of SO_2, BC, and OC are simultaneously reduced to the levels projected for the end of this century based on three different RCP scenarios (Table 3). It should be noted that the temperature response to aerosol forcing

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is caused only by rapid adjustments of radiation, clouds, and land surface due to the impact of aerosols, but does not include any feedbacks associated with sea surface temperature changes induced by aerosol forcing. The latter may play a more important role in the total equilibrium temperature response (Bala et al., 2009; Andrew et al., 2010).

3.2.2 Global distributions

Figure 2 shows the global distributions of simulated annual mean sulfate, BC, and OC burdens under all six simulations. As can be seen from Fig. 2a, the BC column burdens are significantly decreased in areas with high BC emission such as East Asia, South Asia, central Africa and South America, eastern North America, and Western Europe compared with present-day conditions when only the BC emission is reduced. Changes in other aerosol burdens are not obvious. The reduction in the BC concentration weakens the direct absorption of solar radiation by atmospheric aerosols, leading to a cooling effect at the TOA in these regions. The largest cooling exceeds $1\,W\,m^{-2}$ in China, Europe, and eastern North America (Fig. 3a). The decrease in the absorption ability of aerosols also weakens the cloud evaporation and increases cloud droplet number concentrations (CDNCs). The maximum increase in annual mean column CDNCs are about $0.6 \times 10^{-10}\,m^{-2}$ over eastern China, northern India, and Mediterranean regions (Fig. 4a). Finally, only the reduction of BC emission result in an increase of more than $2\,W\,m^{-2}$ in the annual mean aerosol net cooling effect at the TOA over most regions with large BC emission (Fig. 5a).

Figure 2b–e shows that there are different levels of reduction in the annual mean sulfate, BC, and OC burdens in SIM3 to SIM6, with decreases of up to 2.0–5.0 $mg\,S\,m^{-2}$, 0.2–1.0 $mg\,m^{-2}$ and 2.0–6.0 $mg\,m^{-2}$ in most of areas, respectively, when all aerosol emissions are reduced. The combined reduction in scattering and absorbing aerosols weakens the aerosol direct radiative effect at the TOA by over $1\,W\,m^{-2}$ for most of the Northern Hemisphere (NH) compared with SIM1 (Fig. 3b–e). Correspondingly, the CDNCs are significantly decreased due to the reduction in hygroscopic sulfate and OC.

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The largest decreases in annual mean column CDNCs exceed 5×10^{-10} m^{-2} in Western Europe, North America, and eastern China (Fig. 4b–e). Finally, the annual mean aerosol net cooling effect at the TOA is weakened over a range of 2.0–10.0 W m^{-2} due to the changes in emissions of all aerosols over most regions of the NH that have large anthropogenic aerosol emissions.

4 Conclusions

It has been argued that eliminating BC emission would be an effective measure to slow down global warming and environmental pollution. In this study, we assess the impact of removing some sources of BC and other co-emitted species on aerosol radiative effects by using an aerosol-climate coupled model BCC_AGCM2.0.1_CUACE/Aero, in combination with the RCP scenarios. Compared with the aerosol effect for present-day conditions, the global annual mean aerosol net cooling effect at the TOA is enhanced by 0.12 W m^{-2} due to a decrease in the direct absorption of solar radiation and cloud evaporation when BC emission is reduced exclusively to the level projected for the end of this century under the RCP2.6 scenario. The annual mean aerosol net cooling effect at the TOA is enhanced by more than 2.0 W m^{-2} in eastern China, northern India, and Mediterranean regions. Therefore, a reduction of BC emission alone could ideally mitigate global warming.

However, our results suggest that associating with the reduction of net cooling effects directly from aerosols, the aerosol indirect effect is also weakened when emissions of SO_2, BC, and OC are simultaneously reduced in different ways to the levels projected for the end of this century under the RCP2.6, RCP4.5, and RCP8.5 scenarios. Relative to the aerosol effect for present-day conditions, the total global annual mean aerosol net cooling effect at the TOA is weakened by 1.7–2.0 W m^{-2} with the reduction according to potential actual conditions in the emission of all these aerosols (i.e., BC and the major co-emitted species). The main cooling regions are over East Asia, Western Europe, eastern North America, and central Africa, with the largest change exceeding

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10.0 W m^{-2}. This is somewhat consistent with the results given by Gillett and Salzen (2013) and Levy et al. (2013), who also reported that the reduction in atmospheric aerosols will weaken the aerosol cooling effect in the future.

This study highlights that reducing only BC emission could play a positive role in mitigating global warming and environmental pollution, and would be beneficial to human health. However, the emissions of some co-emitted scattering aerosols and their precursor gases will be inevitably reduced when BC emission is reduced due to their homology. Therefore, reducing BC emission could lead to unexpected warming on the Earth's climate in the future, unless certain technical advances in emission reduction technology are available for removal of the BC exclusively without influencing the other co-emitted components.

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Table 1. Simulation setups.

Simulations	Aerosol emissions
SIM1	SO_2, BC, and OC in 2000
SIM2	BC in 2100 under RCP2.6, SO_2 and OC in 2000
SIM3	BC in 2100 under RCP2.6, SO_2 and OC in 2100 under RCP8.5
SIM4	SO_2, BC, and OC in 2100 under RCP2.6
SIM5	BC in 2100 under the RCP2.6, SO_2 and OC equal to BC in 2100 under the RCP2.6 by multiplying them with the ratios of SO_2 and OC with BC in 2000
SIM6	SO_2, BC, and OC in 2100 under RCP4.5

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Table 2. Global amounts of aerosol emissions and annual means of aerosol burdens.

	SIM1	SIM2	SIM3	SIM4	SIM5	SIM6
Emission (Tg yr^{-1})						
SO_2	107.4	107.4	25.7	12.9	19.8	22.2
BC	7.8	3.3	3.3	3.3	3.3	4.3
OC	35.8	35.8	23.9	25.3	24.9	20.0
Burden (mg m^{-2})						
Sulfate	3.5	3.4	1.3	0.98	1.1	1.2
BC	0.17	0.079	0.078	0.077	0.078	0.084
OC	1.6	1.6	1.2	1.2	1.2	1.1
Dust	39.9	39.9	39.9	40.6	42.7	42.8
Sea salt	14.2	14.2	14.0	14.0	14.0	14.1

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Table 3. Global annual mean differences of aerosol direct, semi-direct and indirect, and net effect at the TOA (positive values mean incoming, units: $W\,m^{-2}$) and 2 m air temperature (unit: °C) in different simulations*.

	SIM1	ΔSIM2	ΔSIM3	ΔSIM4	ΔSIM5	ΔSIM6
DRF	−2.01	−0.07	+0.27	+0.28	+0.25	+0.3
CRF	−21.2	−0.11	+0.8	+1.1	+0.91	+0.88
FNT	−0.66	−0.12	+1.7	+2.0	+1.8	+1.8
$T_{2\,m}$	286.5	~ 0.0	+0.1	+0.09	+0.08	+0.06

* DRF, CRF, FNT and $T_{2\,m}$ in the SIM1 column are aerosol direct radiative forcing, net cloud radiative forcing, net radiation flux at the TOA (units: $W\,m^{-2}$), and $T_{2\,m}$ in SIM1, respectively. Values in the ΔSIM2–ΔSIM6 columns represent the changes of corresponding variables in these simulations vs. those in SIM1.

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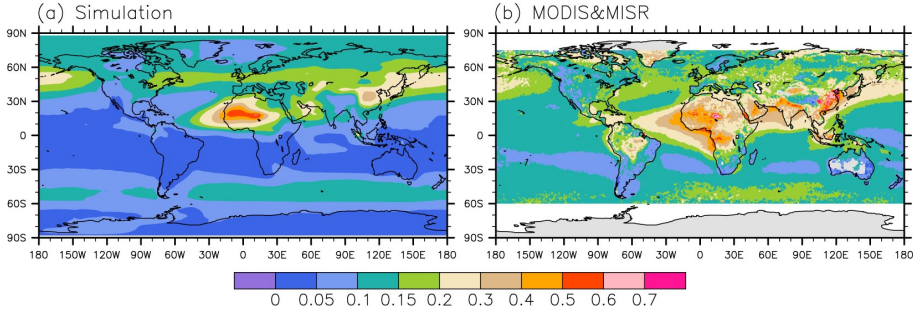

Figure 1. Global distributions of simulated and observed annual mean AOD at 550 nm. **(a)** Simulation and **(b)** MODIS&MISR (van Donkelaar et al., 2010).

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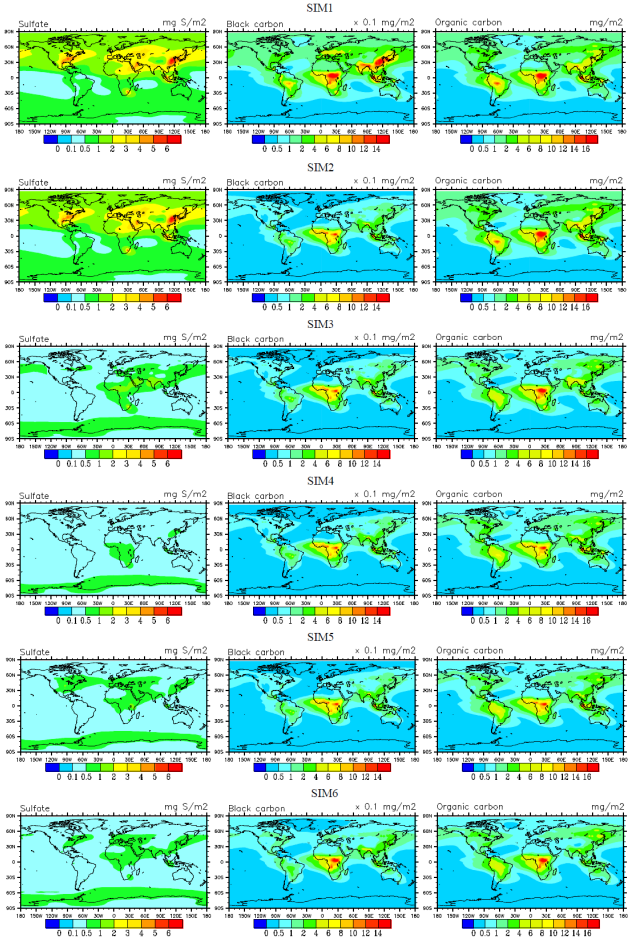

Figure 2. Global distributions of simulated annual mean aerosol column burdens (units: $mg\,m^{-2}$).

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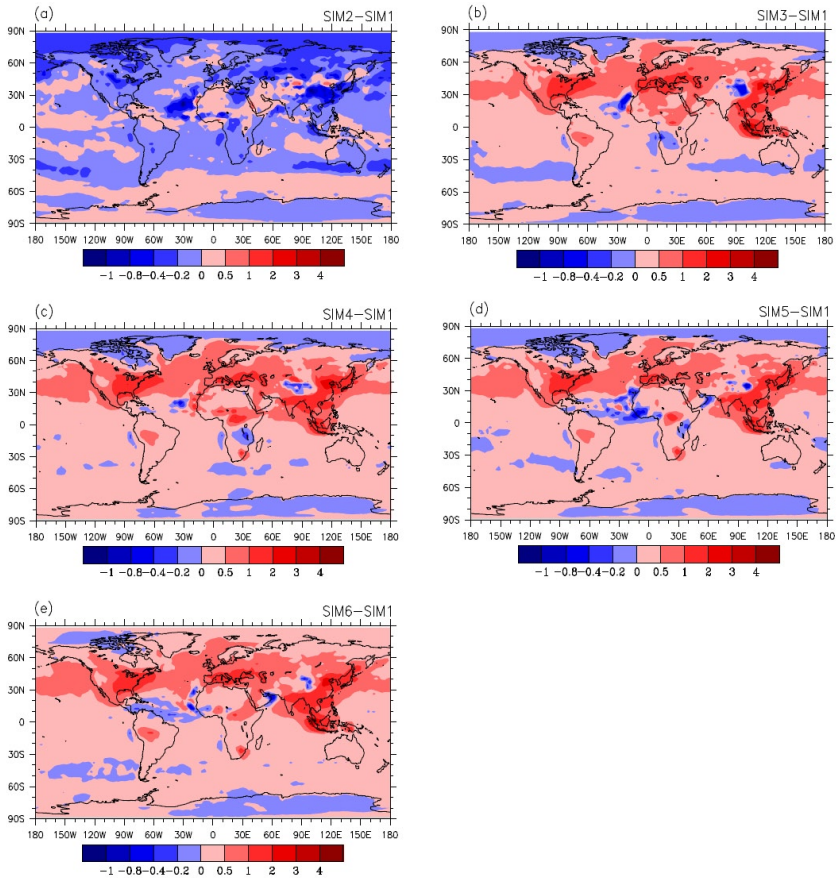

Figure 3. Global distributions of difference in simulated annual mean aerosol direct effect (units: $W\,m^{-2}$). **(a)** SIM2 – SIM1, **(b)** SIM3 – SIM1, **(c)** SIM4 – SIM1, **(d)** SIM5 – SIM1, and **(e)** SIM6 – SIM1.

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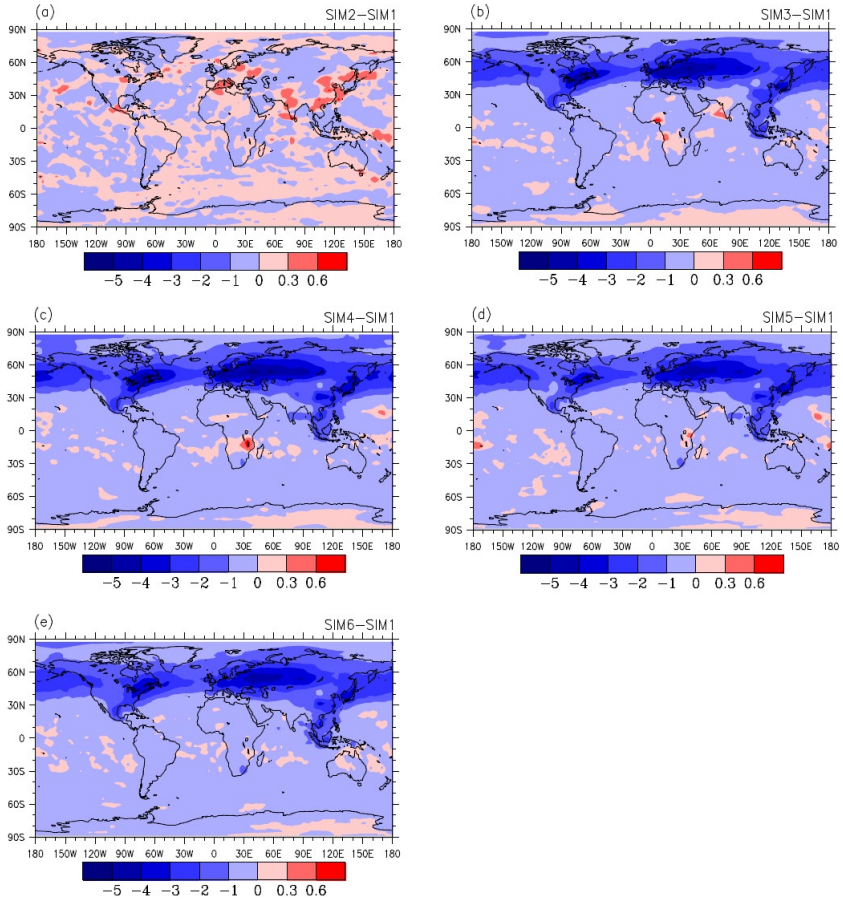

Figure 4. Global distributions of difference in simulated annual mean column cloud droplet number concentration (units: 10^{-10} m^{-2}). **(a)** SIM2 – SIM1, **(b)** SIM3 – SIM1, **(c)** SIM4 – SIM1, **(d)** SIM5 – SIM1, and **(e)** SIM6 – SIM1.

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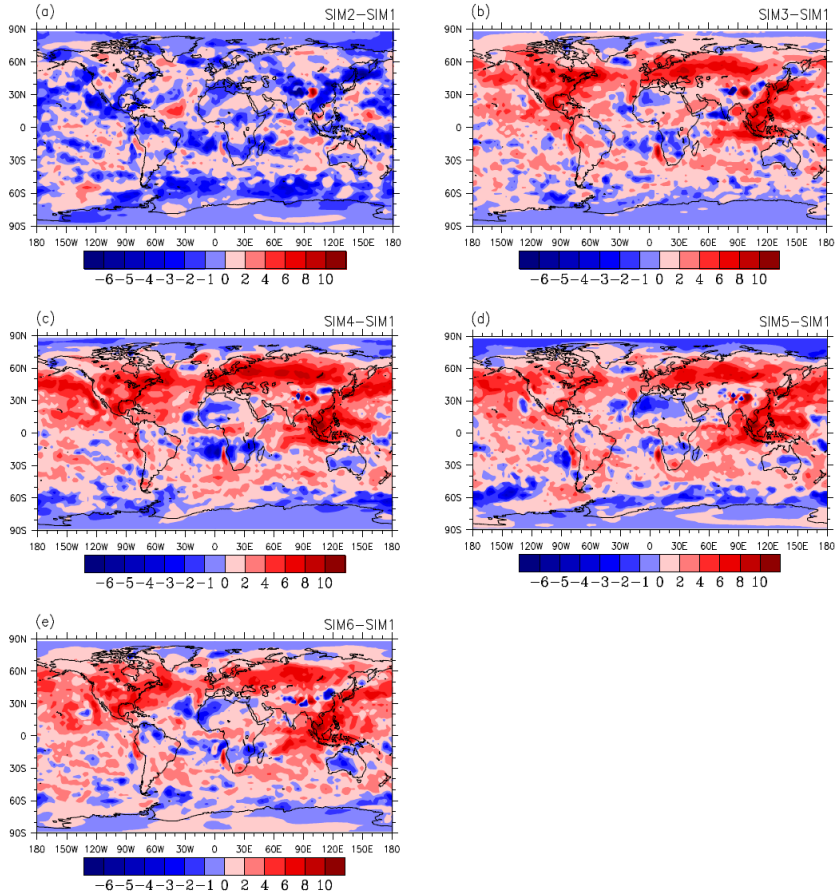

Figure 5. Global distributions of difference in simulated annual mean aerosol net effect (units: $W\,m^{-2}$). **(a)** SIM2 – SIM1, **(b)** SIM3 – SIM1, **(c)** SIM4 – SIM1, **(d)** SIM5 – SIM1, and **(e)** SIM6 – SIM1.

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