

Response to anonymous referee #1

We first thank the very constructive comments of the reviewer. We have taken all of reviewer's comments into consideration and revised the manuscript accordingly. All the changes have been highlighted in the revised manuscript. Our detailed responses, including a point-by-point response to the reviews and a list of all relevant changes, are as follows.

General comments

“Using simulations from an atmosphere-only global climate model, the authors highlight two main results:

1. If emissions of black carbon (BC) aerosol were reduced independently from co-emitted species, then the climate system would be cooled.

2. However, if emissions of co-emitted species (sulphur and organic carbon, OC) were also simultaneously reduced with BC, then the climate system would be warmed.

The authors argue that, since “there are no effective ways to remove the BC exclusively without influencing the other co-emitted components” (p33118.19), a reduction in BC would lead to the second situation above.

The paper contributes to the literature. However, I think that the contribution would be significantly improved if the authors act on my recommendations below.”

Specific comments (major)

“1. Justification of the co-emission assumption. The authors state that “there are no effective ways to remove the BC exclusively without influencing the other co-emitted components” (p33118.19), “the emissions of sulphate and OC will be

reduced accordingly if the emission of BC is [reduced]” (33120.9), and “the emissions of some coemitted scattering aerosols and their precursor gases will be inevitably reduced when BC emission is reduced due to their homology” (p33128.6). Indeed, this assumption (phrased in three alternative ways) is key to the ultimate conclusion of the paper. However, the validity of this assumption is not discussed and references are not provided (beyond a cursory reference to Lamarque et al., 2010, at p33120.8). Due to the important role it plays, the authors should discuss the assumption in much more detail, and references should be provided.”

Reply: Because actual operational reduction in BC emission in most of severe polluted countries, like China, is often to cut the usage of coal and other fossil fuels, as well as forbid open burning to reduce biomass burning emissions, all these major measures will result in the emission reductions in BC and its co-emitted components at the same time. We have added these statements and more discussions and references to justify the validity of the co-emission assumption in section 1. The details can be found in line 96 - 112, page 5 - 6 in the revised manuscript.

“2. Decomposition of radiative flux perturbations (RFPs). The key results in the paper concern RFPs. Ghan (2013, www.atmos-chem-phys.net/13/9971/2013/) recommends that “clean-sky” CRF is used when decomposing RFPs. Do the authors have sufficient diagnostics to diagnose “clean-sky” CRF and also the surface albedo forcing? If not, then discussion of why $\Delta DRF + \Delta CRF \neq \Delta FNT$ (Table 3) is warranted. Also, decomposing the change in CRF into SW and LW components may provide further insight.”

Reply: In this study, we don’t perform additional simulations in which aerosol scattering and absorption are neglected to diagnose “clean-sky” CRF and surface albedo forcing according to the method by Ghan (2013). We have supplemented these statements and the formulas of calculating the different aerosol effects in Section 2.2

to explain why $\Delta\text{DRF} + \Delta\text{CRF} \neq \Delta\text{FNT}$ in our results. The details can be found in line 218 - 233, page 10 - 11 in the revised manuscript. In addition, we have separately presented the changes in SW and LW CRF in Table 3 in the revised manuscript.

“3. Nature of the indirect effect. Does the model contain a representation of only the albedo (first) indirect effect, or does it also contain a representation of the lifetime (second) indirect effect on stratiform clouds? This should be clearly stated, and the implications considered. If the lifetime effect is included, do the authors know which of the two indirect effects dominates in the model? Does looking at column CDNC (Fig. 4) really offer much insight for the interpretation of Fig. 5? Would it be sensible to also look at changes in cloud fraction, or CCN concentration at the surface, or maps of the SW and LW CRF RFP?”

Reply: The model contains representations of both albedo and lifetime indirect effects on stratiform clouds. This further statement has been added in Section 2.1. We don't know which of the two indirect effects dominates in the model. Therefore, we added the figures of changes in CCN concentration at the surface and shortwave and longwave cloud forcings (Fig. 4 and 6 in the revised manuscript) and the corresponding analyses in Section 3.2.2. The details can be found in line 325 - 336, page 15 - 16 and line 345 - 356, page 16 - 17 in the revised manuscript.

Specific comments (minor)

“4. Title. The title is somewhat misleading. I would recommend pointing out the co-emission assumption, by using a title along the lines of the following: “Simultaneous reduction in emission of black carbon and co-emitted species will weaken the aerosol net cooling effect”, or, if you want to keep “black carbon” at the start, “Black carbon reduction: simultaneous reduction with co-emitted species will weaken the aerosol net cooling effect” (although it is grammatically awkward).”

Reply: Accepted. We have used the title “Simultaneous reductions in emissions of black carbon and co-emitted species will weaken the aerosol net cooling effect” instead of the original.

“5. Use of “coupled”. The use of “coupled” is potentially misleading, as many readers may understand this to mean that the model contains a dynamical ocean component. To avoid confusion, I would recommend using “aerosol-climate atmosphere-only model” at p33118.9, p33120.23, p33121.3, and p33127.10. The term “prescribed-SST simulations” could also be used early in the manuscript (e.g. in the abstract and/or the final paragraph of the introduction) and in the Conclusions – of course, the acronym “SST” would need to be expanded the first time it is used.”

Reply: Accepted.

“6. Table 1. The differences between the simulations, and the interpretation of those differences, seems rather complicated on an initial read. Readability could be improved by creating separate column columns for the BC emissions and for the SO₂ and OC emissions in Table 1, and by incorporating aspects of the interpretation of the scenarios (p33123) into the table – see a modified version of Table 1 below.”

Simulation	BC emission	OC & SO ₂ emissions	Interpretation (compared to SIM1)
SIM1	year-2000	year-2000	Present-day reference scenario.
SIM2	RCP2.6 year-2100	year-2000	Maximal reduction in BC; no reductions in OC & SO ₂ .
SIM3	RCP2.6 year-2100	RCP8.5 year-2100	Maximal reduction in BC; minimal reductions in OC & SO ₂ .
SIM4	RCP2.6 year-2100	RCP2.6 year-2100	Simultaneous maximal reductions in BC, OC & SO ₂ .

etc.

Reply: Accepted. We have modified the representation of Table 1.

“7. Calculation of ratios (SIM5). Were the ratios calculated and applied for each individual grid box and month? Or were global annual means used when calculating the ratios? Please clarify this in the manuscript.”

Reply: Yes, the ratios were calculated and applied for each individual grid box and month. We have added this in Section 2.2. The details can be found in line 192 - 193, page 9 in the revised manuscript.

“8. Sensitivity to BC inventory. If present-day BC emissions have been substantially underestimated (Cohen and Wang, 2014, doi:10.1002/2013JD019912), how may this affect the conclusions? This would be worthy of discussion.”

Reply: Accepted. We have added this discussion in Section 4. The details can be found in line 395 - 402, page 18 - 19 in the revised manuscript.

“9. Limitation of not including SST feedbacks. The limitation of using prescribed-SST simulations when looking at temperature (and, for that matter, other important climate variables such as rainfall) is noted at p33125.29–p33126.5. This should also be highlighted elsewhere in the manuscript (e.g. in the Conclusions, and maybe also Section 2.2). Alternatively, the temperature results in Table 3 could be removed from the paper (or relegated to Supplementary Material) to avoid confusion.”

Reply: Accepted. We have removed the temperature results from the paper.

Technical corrections/suggestions

“- p33118.5 - ‘in a short term’ to ‘in the short term’.”

Reply: Done.

“- p33118.14 - The sentence starting “However” is long, devoid of punctuation, and not very fluid. I would suggest re-writing it, thinking carefully about the order of ideas, seeking to improve fluidity. The more accessible your abstract is, the more likely it will be that readers will continue reading the rest of your paper.”

Reply: Accepted. We have re-written this sentence. Please see line 37 - 42, page 2 in the revised manuscript.

“- p33119.3 - ‘Since the industrial era, an increase in atmospheric aerosols leads to’ to ‘Since the start of the industrial era, an increase in atmospheric aerosol emissions has likely led to’.”

Reply: Done.

“- p33119.17 - ‘greenhouse gases’ to ‘greenhouse gas’.”

Reply: Done.

“- p33119.21 - I would question whether the sentence starting ‘BC can therefore...’ is true, due to the generality of the claim. I would advise that the authors make the sentence more specific, clarifying that the claim about the importance of carbon dioxide and BC is in relation to global warming (as opposed to e.g. health, stratospheric chemistry, or atmospheric circulation). For

example, the authors could make the claim that BC is the second most important anthropogenic positive radiative forcing agent instead.”

Reply: Accepted. We have revised this sentence. Please see line 76, page 4 in the revised manuscript.

“- p33119.24 - ‘in a short term’ to ‘in the short term’.”

Reply: Done.

“- p33119.26 - ‘sulfide’ to ‘sulfate’ (or ‘sulphate’, the British English spelling, as ACP is a European journal - the copyeditors should be able to advise on this).”

Reply: Done.

“- p33119.27 - ‘K’ to ‘^oC’, for consistency with e.g. p33120.1.”

Reply: Done.

“- p33120.10 - ‘tried to remove from its sources’ to ‘reduced’.”

Reply: Done.

“- p33120.13 - ‘would the global warming be slowed down necessarily by’ to ‘would global warming necessarily be slowed down by’.”

Reply: Done.

“- p33121.25 - Have I understood correctly that the two-moment cloud microphysics scheme is a modified version of Morrison and Gettelman (2008,

doi:10.1175/2008JCLI2105.1)? If so, then it may be helpful to also include this reference, as MG08 will be familiar to users of another commonly-used atmosphere model (CAM5).”

Reply: Yes, it is the version of Morrison and Gettelman (2008). We have added this reference in line 161, page 8 in the revised manuscript.

“- p33122.28 - When I click on the URL, I land on a webpage that says “docs under construction”. Is the URL up-to-date, or have symbols been omitted from the URL when typesetting? Can a more reliable URL be provided? (The problem may be that equals signs have been dropped from the URL when typesetting. <http://tntcat.iiasa.ac.at:8787/RcpDb/>, a shorter version, may be effective.)”

Reply: Accepted. We have revised the URL.

“- p33123.16 - Start a new paragraph before ‘The aerosol direct effect...’.”

Reply: Done.

“- p33125.29 - Start a new paragraph before ‘It should be noted...’.”

Reply: This part has been removed.

Response to anonymous referee #2

We first thank the very constructive comments of the reviewer. We have taken all of reviewer's comments into consideration and revised the manuscript accordingly. All the changes have been highlighted in the revised manuscript. Our detailed responses, including a point-by-point response to the reviews and a list of all relevant changes, are as follows.

General comments

“This is an interesting paper which shows single-model results of the net climate effect of reducing black carbon (BC) aerosol emissions, both with and without reducing co-emitted compounds. I recommend publication of the paper, but I do have some concerns which need to be addressed first. In particular, no quantification or discussion of the model uncertainty is given, the co-emission assumption should be further justified, and analysis of surface temperature change is confusing since the model has been run with prescribed sea-surface temperatures. Please see below for details.”

Reply: We have addressed all the comments in the revised manuscript. Please see below for the detailed responses.

Specific comments

“Introduction. Semi-direct aerosol effect is not mentioned in the introduction. It is important for BC, and should be explained briefly. You could refer to e.g., Koch and Del Genio (2010).”

Reply: Accepted. This has been added in line 53 - 55, page 3 in the revised manuscript.

“Page 33119, line 20-21. It is good that the uncertainty limits from Bond et al. are mentioned, but I think that this huge uncertainty in climate forcing of BC, and the associated ongoing debate should be emphasized more in the introduction. Other studies, such as Myhre et al. (2013, ACP), have much lower estimate of the direct aerosol effect of BC, which is reflected in the best estimate in the latest IPCC report (Boucher et al., 2013; Myhre et al., 2013). Recent literature also suggests that the climate effect of BC may be overestimated due to overestimation of its lifetime, and this might be worth mentioning (see e.g., Hodnebrog et al., 2014; Samset et al., 2014; Wang et al., 2014).”

Reply: Accepted. These have been supplemented. The details can be found in line 84 - 90, page 4 - 5 in the revised manuscript.

“Page 33120, line 17-21. An overall reference to the model used, and also to the RCP scenarios (van Vuuren et al., 2011) would be appropriate here.”

Reply: Accepted. These references have been added. Please see line 126 - 128, page 6 in the revised manuscript.

“Page 33122, line 12. Please specify which year GHG concentrations are from.”

Reply: Done. Please see line 180, page 9 in the revised manuscript.

“Page 33122, line 15. Year 2000 is already 15 years ago, so I would not call this “present-day conditions”. Alternatively you could call it “recent past”.”

Reply: Done.

“Page 33122, line 16-28. No references are given to the RCP scenarios – this is needed. Only a web address is given, and this does not even work.”

Reply: We have added the reference and revised the URL. The details can be found in line 196 - 198, page 9 in the revised manuscript.

“Page 33122, line 26-27. What about biomass burning emissions? Were they kept constant at year 2000 levels or are they also changed when using RCP scenarios?”

Reply: The biomass burning emissions are also changed when using RCP scenarios. We have added the explanation in Section 2.2. Please see line 198 - 199, page 9 - 10 in the revised manuscript.

“Page 33123, line 1-4. Which year(s) are these data representing? Do you have any reference to the data?”

Reply: We have added the year and reference on SST data. The initial fields have no specific time and are only a climatological data, which can be downloaded from the website <http://www.cesm.ucar.edu/models/atm-cam/download/>. We have added this. The details can be found in line 201 - 205, page 10 in the revised manuscript.

“Page 33123, line 4-5. I am not convinced that 10 years are enough for the analysis. The paper does not give any information about uncertainties in the results and the year-to-year variability. Usually when running climate models, even with prescribed SSTs, natural variability can be very large and long simulations are needed (at least 30 years, but this depends on the size of the forcing). This is particularly important for the semi-direct and indirect aerosol effects, which depends on the cloud cover, while the quantification of the direct aerosol effect varies less from year to year. Please justify that 10 years are enough to derive radiative fluxes that are within reasonable accuracy.”

Reply: We have added the standard deviations of different aerosol effects in Table 3

to show the uncertainties in the results. Please see the revised manuscript.

“Page 33123, line 15. What is the argument for RCP4.5 representing the most likely future situation?”

Reply: RCP4.5 represents a medium-low emission pathway. We have changed this.

“Page 33123, line 17-20. In principle, when running with prescribed SSTs, the sum of the semi-direct and indirect aerosol effects should not deviate too far from the difference between the change in net radiation flux at TOA and the direct aerosol effect. However, results in Table 3 show that this difference is rather large. Is estimation of change in cloud radiative forcing (CRF) an appropriate way of quantifying the semi-direct and indirect aerosol effects? In Ghan et al. this is done differently for the shortwave. As indicated above, I am also curious how large the inter-annual variation is, especially for CRF.”

Reply: In this study, we don't perform additional simulations in which aerosol scattering and absorption are neglected to exclusively diagnose indirect aerosol effect according to the method by Ghan et al., because we finally focus on change in net radiation flux (NRF). The change in cloud radiative forcing (CRF) is used as an approximate way of quantifying the semi-direct and indirect aerosol effects. The change in CRF could be affected by the aerosol direct effect (ADE) in our results (Ghan et al., ACP, 2013). Thus, the sum of ΔADE and ΔCRF is not equal to the change in net radiation flux. These statements have been supplemented in Section 2.2. In addition, we have decomposed the change in CRF into shortwave and longwave components in Table 3. The details can be found in line 218 - 233, page 10 - 11 in the revised manuscript.

“Page 33124, line 8-9. Any reasons for the underestimation? Is this a known

problem.”

Reply: The underestimation could be caused by a variety of factors such as uncertainty in the aerosol sources, coarse model resolution, and the uncertainties of physical processes in the model, and the absence of nitrate and ammonium aerosols and secondary organic aerosol in the model (Zhang et al., Clim. Dyman., 2012). We have added these. The details can be found in line 250 - 253, page 12 in the revised manuscript. This problem also exists in most of models.

“Page 33124, line 20-21. Specify that it is a net cooling effect that is enhanced.”

Reply: Done. Please see line 266 - 267, page 13 in the revised manuscript.

“Page 33124, line 18-21. Given the strong emission reduction for BC, the change in direct aerosol effect of 0.07 W m^{-2} is quite small. As far as I can see from the multi-model comparison in Myhre et al. (2013, ACP), the BCC model has much lower normalized radiative forcing for BC than most of the other models. I think this is worth mentioning.”

Reply: Accepted. This has been added in Section 3.2.1. The details can be found in line 267 - 270, page 13 in the revised manuscript.

“Page 33124, line 22. This implies that the semi-direct aerosol effect for BC in this model is positive and larger than the direct aerosol effect of BC. The IPCC AR5 indicates that the BC semi-direct effect is negative, although this is uncertain, with a best estimate of -0.1 W m^{-2} and a range from -0.3 to $+0.1 \text{ W m}^{-2}$ (Boucher et al., 2013). Some justification of this strong positive semi-direct effect would be useful, e.g., a plot of the change in cloud cover between SIM1 and SIM2?”

Reply: Here, the increase of 0.11 W m^{-2} in CRF is not due to only BC semi-direct effect but due to a combined effect of decrease in cloud evaporation and increase in cloud cover caused by BC reduction, changes in other aerosol concentrations due to quick adjustment of the atmosphere to BC reduction, and the resulting changes in cloud properties. We have added these explanations in Section 3.2.1. The details can be found in line 274 - 277, page 13 in the revised manuscript.

“Page 33124, line 23. BC also changes the stability of the atmosphere, and this could also lead to a change in cloud cover, in addition to the changes in cloud evaporation (which is caused by changes in relative humidity) (see e.g., Hansen et al., 1997; Cook and Highwood, 2004; Johnson et al., 2004).”

Reply: Accepted. This has been supplemented in line 275, page 13 in the revised manuscript.

“Page 33124, line 24. What is the cause of the decrease in sulphate mass concentration? Emissions of SO₂ are the same in the two simulations.”

Reply: Due to changes in meteorological fields caused by declining BC. This has been supplemented in line 278 - 279, page 13 in the revised manuscript.

“Page 33125, line 2-4. This is probably mostly due to the fact that prescribed SSTs have been used. Therefore, the global mean surface air temperature would not change much. I do not understand the point of including the surface temperature analysis in Table 3 and the discussion, and suggest removing it from the paper.”

Reply: Accepted. This has been removed from the paper.

“Page 33125, line 5-8. Since this is a very important point of the paper, this needs to be further justified and referenced, rather than just stating that “SO₂ and OC emissions are likely to be reduced proportionally when BC emission is decreased...”. Furthermore, co-emissions of other compounds, such as CO₂, might be more important than SO₂ and OC, and this should be mentioned/discussed (see e.g., Rogelj et al., 2014).”

Reply: Accepted. These are further justified, referenced, and discussed in Section 1 and Section 4. The details can be found in line 96 - 112, page 5 - 6 and line 402 - 408, page 19 in the revised manuscript.

“Page 33125, line 20. Is only the cloud albedo effect included or is the lifetime indirect effect also included? This is not clear from the method section and should be specified.”

Reply: The model includes both cloud albedo and lifetime effects. This has been added in the method section. The details can be found in line 141 - 142, page 7 in the revised manuscript.

“Page 33126, line 8. In Fig. 2, labels a, b, c, etc. seem to be missing.”

Reply: This has been added.

“Page 33126, line 16. See earlier comment on cloud evaporation and atmospheric stability changes.”

Reply: Done.

“Page 33127, line 14. See above. Perhaps better to use semi-direct aerosol effect instead of cloud evaporation?”

Reply: Accepted.

“Table 2. I assume these emission numbers include biomass burning in addition to fossil fuel and biofuel emissions? It would be good to specify this.”

Reply: Yes, these emission numbers include biomass burning emissions. This has been specified in Section 2.2. Please see line 198 - 199, page 9 -10 in the revised manuscript.

“Table 3. As mentioned before, it would be useful to show some uncertainty values. E.g., you could include standard deviations representing the inter-annual variation of the different radiative effects. Again, I suggest removing the T_{2m} results to avoid confusion.”

Reply: Accepted. We have added the values of standard deviations and removed the T_{2m} results in Table 3.

Technical corrections

“Page 33119, line 8. I suggest inserting “absorbed” after “radiation”.”

Reply: Accepted.

“Page 33122, line 3-4. This sentence is a bit strange. I think there are some commas missing. Please fix or rephrase.”

Reply: We have revised this sentence. The details can be found in line 170, page 8 in the revised manuscript.

“Page 33126, line 24. Replace “in most of areas” with “in most areas”.”

Reply: Done.

“Table 3. Please insert “(DRT)” after “direct”, “(CRF)” after “semi-direct and indirect”, and “(FNT)” after “net effect at the TOA”.”

Reply: Done.

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1 **Simultaneous reductions in emissions of black carbon and co-emitted species will**
2 **weaken the aerosol net cooling effect**

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Abstract

23

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

45 an unexpected warming on the Earth's climate system in the future.

46

47 **1 Introduction**

48 Aerosols in the atmosphere can alter the amount of sunlight reaching the Earth
49 by directly scattering sunlight (e.g., sulphate, organic carbon (OC) and nitrate) or
50 absorbing it (e.g., black carbon (BC) and dust) (Boucher et al., 2013). Aerosol
51 particles can also change cloud microphysical and optical properties by acting as
52 cloud condensation nuclei (CCN) or ice nuclei (Twomey, 1977; Albrecht, 1989;
53 DeMott et al., 1997). Absorbing aerosols such as BC or dust absorb incoming solar
54 radiation, perturb the temperature structure of the atmosphere, and influence cloud
55 cover (Koch and Del Genio, 2010). These changes due to aerosols will directly or
56 indirectly affect the climate. Since the start of the industrial era, an increase in
57 atmospheric aerosol emissions has likely led to a net cooling of the Earth's climate
58 system (Boucher et al., 2013).

59 BC has a special role in the climate system, although it accounts for less than 5%
60 of the mass of atmospheric aerosol in most areas of the world (X. Y. Zhang et al.,
61 2012). BC can increase the amount of solar radiation absorbed within the Earth's
62 climate system and heat the atmosphere or surface by directly absorbing sunlight in
63 the visible to infrared wavebands (Hansen et al., 2000; Ramanathan and Carmichael,
64 2008), changing the cloud amount and its brightness due to embedding into clouds
65 (Chuang et al., 2002; Jacobson, 2012; Wang et al., 2013a), or by reducing the surface
66 albedo due to deposition onto snow and ice surfaces (Wang et al., 2011; Lee et al.,

67 2013). BC has even been considered as a potential cause of global warming (Hansen
68 et al., 2000; Jacobson, 2010; Bond et al., 2013). Ramanathan and Carmichael (2008)
69 compared the radiative forcings of greenhouse gases and BC, suggesting that the
70 direct radiative forcing due to BC was larger than that due to any other greenhouse
71 gas except CO₂. The radiative heating effect on the whole atmosphere due to BC was
72 almost double that due to all greenhouse gases. By considering all the known ways
73 that BC affects the climate system, Bond et al. (2013) gave an estimate of
74 industrial-era climate forcing of +1.1 W m⁻² due to BC with 90% uncertainty limits of
75 +0.17 to +2.1 W m⁻². BC can therefore be considered the second most important
76 anthropogenic positive radiative forcing agent after CO₂ in the present-day
77 atmosphere. Some studies have even suggested that global warming could be slowed
78 down in the short term by eliminating BC emission due to its short atmospheric
79 lifetime. For example, eliminating soot generated from fossil fuels, including BC,
80 primary organic matter, and sulphate, was found to decrease global surface air
81 temperature by 0.3–0.5 °C in the short term (about 15 year) (Jacobson, 2010). A
82 simultaneous decrease of short-lived BC and methane through the adoption of control
83 measures could reduce projected global mean warming by about 0.5 °C by 2050
84 (Shindell et al., 2012). However, there is a huge uncertainty and an ongoing debate in
85 climate forcing of BC. Other studies, such as Myhre et al. (2013a), have much lower
86 estimate of the direct radiative forcing from BC, which is reflected in the best estimate
87 in the latest IPCC report (Boucher et al., 2013; Myhre et al., 2013b). Recent literature
88 also suggests that the climate effect of BC may be overestimated due to

89 overestimation of its lifetime (e.g., Hodnebrog et al., 2014; Samset et al., 2014; Q.
90 Wang et al., 2014).

91 Reducing the emissions of absorptive aerosols (e.g., BC) would decrease the
92 absorption of solar radiation by atmospheric aerosols, thereby enhancing the aerosol
93 net cooling effect. However, BC, OC, sulphate, and some other aerosols have many
94 common emission sources (e.g., in the emission sectors of transportation, industrial,
95 residential, and commercial energy consumption, etc.), and they are generally
96 co-emitted into the atmosphere (Lamarque et al., 2010). A technology-based global
97 emission inventory of BC and OC showed that BC and primary OC particles were
98 co-emitted from combustion including fossil fuels, biofuels, open biomass burning,
99 and urban waste burning (Bond et al., 2004). An inventory of air pollutant emissions
100 in Asia supporting the Intercontinental Chemical Transport Experiment-Phase B
101 showed that sulfur dioxide (SO₂), BC, and OC all were emitted from power, industry,
102 residential, and transportation sources (Zhang et al., 2009). A spatially resolved
103 biomass burning data set also indicated that BC, OC, and SO₂ were proportionally
104 emitted from biofuel and forest fire sources (Reddy and Venkataraman, 2002). The
105 analyses of aerosol emission trends from some important source regions showed that
106 there were same trends for BC, OC, and SO₂ separately emitted from fossil fuel,
107 biofuel, and biomass burning sources from 1980 to 2009 (Chin et al., 2014), which
108 indirectly suggested the co-emissions of BC with some other aerosols. Moreover,
109 actual operational reduction in BC emission in most of severe polluted countries, like
110 China, is often to cut the usage of coal and other fossil fuels, as well as forbid open

111 burning to reduce biomass burning emissions. All these major measures will result in
112 the emission reductions in BC and its co-emitted components at the same time.

113 Sulphate, BC, and OC are the main aerosol species in the atmosphere, and the
114 emissions of sulphate and OC will be reduced accordingly if the emission of BC is
115 reduced. Both sulphate and OC are strongly scattering and hygroscopic aerosols, and
116 they can cool the climate system by directly scattering solar radiation and increasing
117 the cloud albedo and lifetime by acting as CCN (Boucher et al., 2013). Therefore,
118 would global warming necessarily be slowed down by reducing BC emission in the
119 future? This is the point of this study.

120 Focusing on the issue mentioned above, the impact of removing some BC sources
121 and other co-emitted species on the aerosol radiative effects was studied in this paper
122 by using an aerosol-climate atmosphere-only model
123 BCC_AGCM2.0.1_CUACE/Aero (Atmospheric General Circulation Model of
124 Beijing Climate Center, BCC_AGCM2.0.1, coupled with the aerosol model of China
125 Meteorological Administration Unified Atmospheric Chemistry Environment for
126 Aerosols, CUACE/Aero) (Wang et al., 2014) with prescribed sea surface temperature
127 (SST) and sea ice cover (SIC), in combination with the Representative Concentration
128 Pathways (RCPs) emission scenarios (van Vuuren et al., 2011) underpinning the Fifth
129 Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5).
130 In Sect. 2, we introduce the aerosol-climate model and simulation details. In Sect. 3,
131 we present the effects of reducing only BC emission and then of the simultaneous
132 reduction of BC and other co-emitted aerosol emissions on aerosol direct, semi-direct

133 and indirect, and net radiative effects. Finally, our conclusions and discussions are
134 presented in Sect. 4.

135

136 **2 Model and Simulation**

137 **2.1 Model description**

138 We use the aerosol-climate atmosphere-only model
139 BCC_AGCM2.0.1_CUACE/Aero developed by Zhang et al. (2012a), and improved
140 by Jing and Zhang (2013), Zhang et al. (2014), and Wang et al. (2014) in this study.

141 The aerosol direct, semi-direct, and indirect effects (albedo and lifetime indirect
142 effects on stratiform clouds) have been included in BCC_AGCM2.0.1_CUACE/Aero.

143 The model has been used to study the impact of aerosol direct radiative effect on East
144 Asian climate (Zhang et al., 2012a), direct radiative forcing of anthropogenic aerosols
145 (Bond et al., 2013; Myhre et al., 2013a), climate response to the presence of BC in
146 cloud droplets (Wang et al., 2013a), effect of non-spherical dust aerosol on its direct
147 radiative forcing (Wang et al., 2013b), anthropogenic aerosol indirect effect (Wang et
148 al., 2014), and direct effect of dust aerosol on arid and semi-arid regions (Zhao et al.,
149 2014).

150 A detailed description of BCC_AGCM2.0.1 was given by Wu et al. (2010). The
151 model employs a horizontal resolution of T42 (approximately $2.8^\circ \times 2.8^\circ$) and a 26
152 layer hybrid sigma-pressure coordinate system in the vertical direction, with a rigid lid
153 at 2.9 hPa. The time step is 20 min. However, the cloud overlap, radiation, and cloud
154 microphysical schemes were improved in the model. The cloud overlap scheme of the

155 Monte Carlo independent column approximation (McICA) (Pincus et al., 2003) and
156 the Beijing Climate Center RADiation transfer model (BCC_RAD) developed by
157 Zhang et al. (2003, 2006a, b) were used instead of the old schemes in the model (Jing
158 and Zhang et al., 2013). These schemes have improved the accuracy of the subgrid
159 cloud structure and its radiative transfer process (Zhang et al., 2014). A two-moment
160 bulk cloud microphysical scheme to predict both the mass and number concentrations
161 of cloud droplets and ice crystals (Morrison and Gettelman, 2008) was implemented
162 into the model instead of the old one-moment bulk cloud microphysical scheme
163 (Wang et al., 2014). The scheme of Abdul-Razzak and Ghan (2000) has been adopted
164 for the activation of cloud droplets.

165 The aerosol model CUACE/Aero is a comprehensive module incorporating
166 emission, gaseous chemistry, transport, removal, and size-segregated
167 multi-component aerosol algorithms based on the Canadian Aerosol Module
168 developed by Gong et al. (2002, 2003). A detailed description of CUACE/Aero was
169 given by Zhou et al. (2012). The mass concentrations of the main five aerosols in
170 troposphere, i.e., sulphate, BC, OC, dust, and sea salt, can be calculated. Each aerosol
171 type is divided into 12 bins as a geometric series for a radius between 0.005 and 20.48
172 μm . Aerosol optical properties from Wei and Zhang (2011) and Zhang et al. (2012b)
173 were calculated based on the Mie theory. The refractive indices of aerosols were
174 adopted from d'Almeida (1991). Hygroscopic growth was considered for sulphate,
175 OC, and sea salt (Zhang et al., 2012a).

176

177 2.2 Simulation details

178 Six simulations were run in this study. In all simulations, the model settings were
179 the same, whereas aerosol emissions were different. All simulations kept greenhouse
180 gases concentrations fixed in year 2000 in order to obtain the effect of change in
181 aerosol emissions exclusively. Table 1 gives the emission setups in all simulations. As
182 a base case, the first simulation (SIM1) used emissions of SO₂, BC, and OC for the
183 year 2000, representing the aerosol effect for recent past. In the second simulation
184 (SIM2), BC emission in 2100 under the RCP2.6 scenario was used, but the emissions
185 of SO₂ and OC were the same as those in SIM1. In the third simulation (SIM3), BC
186 emission in 2100 under the RCP2.6 scenario was also used, but the emissions of SO₂
187 and OC used were those for 2100 under the RCP8.5 scenario. In the fourth simulation
188 (SIM4), the emissions of SO₂, BC, and OC for 2100 under the RCP2.6 scenario were
189 used. In the fifth simulation (SIM5), BC emission in 2100 under the RCP2.6 scenario
190 was used, but the emissions of SO₂ and OC used corresponded to the 2100 emission
191 of BC under the RCP2.6 scenario by multiplying them with the ratios of the emissions
192 of SO₂ and OC with BC in 2000. The ratios were calculated and applied for each
193 individual grid box and month. In the sixth simulation (SIM6), the emissions of SO₂,
194 BC, and OC in 2100 under the RCP4.5 scenario were used. Aerosol emission
195 inventories from fossil fuel, biofuel, and biomass burning for the year 2000 given by
196 Lamarque et al. (2010) were used. The emission dataset of RCPs scenarios were
197 described by van Vuuren et al. (2011) and can be obtained from
198 <http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=about>. The biomass

199 burning emissions are also changed when using RCPs scenarios. The National Centers
200 for Environmental Prediction (NCEP) reanalysis climatological data on a Gaussian
201 grid was used as the initial field (downloaded from
202 <http://www.cesm.ucar.edu/models/atm-cam/download/>). Data for the prescribed
203 annual cycle of monthly mean SST and SIC based on the 21-year (1981–2001)
204 climatology from the Hadley Centre (Hurrell et al., 2008) were used in these
205 simulations. Each simulation was run for 20 years, and the simulation data for the last
206 10 years were averaged and analyzed.

207 The difference between SIM2 and SIM1 shows the impact on aerosol radiative
208 effects (AREs) of reducing only BC emission maximally in the four RCPs scenarios.
209 The difference between SIM3 and SIM1 indicates the effect of maximally reducing
210 the emission of absorbing BC, combined with the least reduction in the emissions of
211 precursor (SO₂) of scattering sulphate and OC on AREs. The differences between
212 SIM4 and SIM1, between SIM5 and SIM1, and between SIM6 and SIM1 show the
213 effects of a simultaneous reduction of SO₂, BC, and OC emissions under the RCP2.6
214 scenario, a reduction of the BC emission with a simultaneous reduction of the
215 emissions of SO₂ and OC (in terms of their ratios with BC), and a simultaneous
216 reduction in the emissions of SO₂, BC, and OC under the RCP4.5 scenario
217 (representing a medium-low emission pathway), on AREs, respectively.

218 The aerosol direct effect (ADE) was obtained by calling radiation routine two
219 times (Ghan et al., 2012):

$$220 \Delta ADE = \Delta(F - F_{\text{clean}}), \quad (1)$$

221 where F is the radiative flux at the top of the atmosphere (TOA) and F_{clean} is the flux
222 calculated as a diagnostic with aerosol scattering and absorption excluded; Δ is the
223 difference between 2000 and 2100. The change in cloud radiative forcing (CRF) was
224 used as an approximate way of quantifying the change in combination of the aerosol
225 semi-direct and indirect effects:

$$226 \quad \Delta\text{CRF} = \Delta(F - F_{\text{clear}}), \quad (2)$$

227 where F_{clear} is the flux calculated as a diagnostic with clouds neglected. The change in
228 aerosol net effect was assessed by the change in net radiation flux at the TOA (ΔF)
229 (Ghan et al., 2012). We didn't perform additional simulations in which aerosol
230 scattering and absorption were neglected to exclusively diagnose the effect of aerosols
231 on CRF according to the method by Ghan et al. (2012) and Ghan (2013). Thus, the
232 difference in aerosol net effect is not equal to the sum of ΔADE and ΔCRF in this
233 study.

234

235 **3 Results**

236 **3.1 Aerosol optical depth for present-day conditions**

237 The simulation performance of BCC_AGCM2.0.1_CUACE/Aero has been given
238 by Wang et al. (2014) in detail. They demonstrated that the model has a good ability
239 to simulate aerosols, cloud properties, and meteorological fields. However, we replace
240 the aerosol emission from AeroCom with those given by Lamarque et al. (2010) for
241 present-day conditions in this work. Thus, a comparison of simulated annual mean
242 aerosol optical depth (AOD) with satellite retrievals is shown in Figure 1. The

243 simulated AODs range from 0.3 to 0.6 over the Sahara Desert and are from 0.15 to 0.3
244 in nearby Arabian areas due to the large dust loading. The AODs are mainly between
245 0.2 and 0.4 in eastern China, and exceed 0.15 in eastern North America and West
246 Europe due to the large emissions of anthropogenic aerosols. The AODs are above 0.1
247 over most subtropical oceans because of the contribution of sea salt and sulphate. The
248 model generally reproduces the geographical distribution of AOD well, but it
249 significantly underestimates the AODs over South Asia, eastern China, and tropical
250 oceans. These errors could be caused by several factors such as uncertainties in the
251 aerosol sources, coarse model resolution, the uncertainties of physical processes in the
252 model, and the absence of nitrate, ammonium and secondary organic aerosols in the
253 model (Zhang et al., 2012a).

254

255 **3.2 The effect of aerosol reductions**

256 **3.2.1 Global mean statistics**

257 Tables 2 and 3 show the global emission amounts and annual mean column
258 burdens of aerosols in all simulations and differences in AREs among them. The
259 global emission amount of BC is reduced from 7.8 Tg yr⁻¹ at present to 3.3 Tg yr⁻¹ at
260 the end of this century under the RCP2.6 scenario due to the operation of various
261 control measures. The global annual mean of simulated BC burden is decreased from
262 0.17 mg m⁻² in SIM1 to 0.08 mg m⁻² in SIM2, assuming that only BC emission is
263 reduced under the RCP2.6 scenario (Table 2). The reduction in the mass concentration
264 of atmospheric BC results in less direct absorption of solar radiation by atmospheric

265 aerosols, thereby causing the global annual mean aerosol direct radiative effect at the
266 TOA to be enhanced by 0.07 W m^{-2} . This indicates that the net cooling effect is
267 enhanced. The multi-model comparison showed that our model had much lower
268 normalized radiative forcing for BC than most of the other models (Myhre et al.,
269 2013a). Thus, the change in aerosol direct radiative effect is quite small when giving
270 the strong emission reduction for BC. The reduction in the BC concentration also
271 weakens the aerosol semi-direct effect, resulting in an increase of 0.11 W m^{-2} in the
272 absolute value of the global annual mean net CRF (Table 3). Of which, the shortwave
273 cloud forcing (SWCF) and longwave cloud forcing (LWCF) are enhanced by 0.14 and
274 0.03 W m^{-2} , respectively. It is noted that the change in CRF is a combined effect of
275 decrease in cloud evaporation and increase in cloud cover caused by declining BC,
276 changes in other aerosol concentrations due to adjustment of the atmosphere to BC
277 reduction, and the resulting changes in cloud properties. However, the slight decrease
278 in the sulphate mass concentration in SIM2 due to changes in meteorological fields
279 caused by BC reduction partially offsets the net cooling effect caused by the decrease
280 in BC emission compared with SIM1. Consequently, the global annual mean aerosol
281 net cooling effect at the TOA is enhanced by 0.12 W m^{-2} compared with recent past
282 levels when just BC emission is reduced to the level projected for the end of this
283 century under the RCP2.6 scenario (Table 3).

284 Many previous studies mentioned in Sect. 1 have indicated that there are several
285 common sources of SO_2 , BC, and OC (Reddy and Venkataraman, 2002; Zhang et al.,
286 2009; Lamarque et al., 2010; Chin et al., 2014). SO_2 and OC emissions are likely to

287 be reduced proportionally when BC emission is decreased, as there is no effective
288 way of removing BC exclusively without influencing the other co-emitted
289 components. Therefore, we considered four different ways to simultaneously reduce
290 the emissions of SO₂, BC, and OC to the levels projected for the end of this century
291 under the RCP2.6, RCP4.5, and RCP8.5 scenarios, and calculated the effect of a
292 reduction in the emission of all these aerosols on radiation fluxes in SIM3 to SIM6. It
293 can be seen from Table 2 that the global emissions of SO₂, BC, and OC are decreased
294 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
295 scenarios, respectively. Thus, the global annual mean burdens of sulphate, BC, and
296 OC are reduced by different levels (63–72, 51–55, and 25–31 %, respectively). The
297 concurrent reductions in scattering sulphate and OC burdens weaken the global annual
298 mean aerosol direct radiative effect at the TOA by 0.25–0.3 W m⁻², although the
299 absorbing BC burden is also significantly reduced in SIM3 to SIM6. Additionally,
300 sulphate and OC particles can act as CCN due to their hygroscopicity, so any decrease
301 in their emissions would decrease CCN concentrations, then decreasing cloud lifetime
302 and albedo, thereby weakening the SWCF. As can be seen from Table 3, the global
303 annual mean SWCF are weakened by 0.87–1.3 W m⁻² due to simultaneous reductions
304 in emissions of SO₂, BC, and OC. The quick adjustment of the atmosphere to aerosol
305 effects leads to changes in LWCF, causing the longwave cooling by 0.07–0.2 W m⁻² in
306 SIM3 to SIM6 compared with SIM1. It partly compensates the shortwave warming.
307 The absolute values of global annual mean net CRF are decreased by 0.8–1.1 W m⁻²
308 in SIM3 to SIM6 compared with SIM1, which greatly exceed the changes in the

309 aerosol direct radiative effect. This is consistent with results obtained by Chen et al.
310 (2010), who reported that a reduction in BC emission would dampen aerosol indirect
311 forcing. Finally, the global annual mean aerosol net cooling effect at the TOA is
312 weakened by 1.7–2.0 W m⁻² when the emissions of SO₂, BC, and OC are
313 simultaneously reduced to the levels projected for the end of this century based on
314 three different RCP scenarios (Table 3).

315

316 **3.2.2 Global distributions**

317 Figure 2 shows the global distributions of simulated annual mean sulphate, BC,
318 and OC burdens under all six simulations. As can be seen from Figure 2b, the BC
319 column burdens are significantly decreased in areas with high BC emission such as
320 East Asia, South Asia, central Africa and South America, eastern North America, and
321 Western Europe compared with recent past levels when only the BC emission is
322 reduced. Changes in other aerosol burdens are not obvious. The reduction in the BC
323 concentration weakens the direct absorption of solar radiation by atmospheric aerosols,
324 leading to a cooling effect at the TOA in these regions. The largest cooling exceeds 1
325 W m⁻² in China, Europe, and eastern North America (Fig. 3a). The numbers of
326 activated sulphate, OC, and dust are increased over East and South Asia,
327 Mediterranean regions, North America and Africa due to the fast adjustment in
328 meteorological fields caused by declining BC (figure not shown), which leads to the
329 increase in CCN concentration (Fig. 4a). Higher CCN concentrations can produce
330 more cloud droplet numbers, with the maximum increase in annual mean column

331 cloud droplet number concentrations (CDNCs) being up to $0.6 \times 10^{10} \text{ m}^{-2}$ (Fig. 5a).
332 This enhances the SWCF over those regions (Fig. 6a). In addition, the decrease in the
333 absorption ability of aerosols weakens the cloud evaporation and increases the cloud
334 fraction, which further enhances the SWCF over the regions with high BC emission
335 and some oceans (Fig. 6a). However, the LWCF is also increased over most areas with
336 enhanced SWCF (Fig. 6a), which can partly offsets the shortwave cooling. Finally,
337 only the reduction of BC emission result in an increase of more than 2 W m^{-2} in the
338 annual mean aerosol net cooling effect at the TOA over most regions with large BC
339 emission (Fig. 7a).

340 Figures 2c–f show that there are different levels of reduction in the annual mean
341 sulphate, BC, and OC burdens in SIM3 to SIM6, with decreases of up to 2.0–5.0 mg S
342 m^{-2} , 0.2–1.0 mg m^{-2} and 2.0–6.0 mg m^{-2} in most areas, respectively, when all aerosol
343 emissions are reduced. The combined reduction in scattering and absorbing aerosols
344 weakens the aerosol direct radiative effect at the TOA by over 1 W m^{-2} for most of the
345 Northern Hemisphere (NH) compared with SIM1 (Fig. 3b–e). The CCN
346 concentrations are greatly decreased over globe except individual regions mainly due
347 to the emission reductions in hygroscopic sulphate and OC, especially over the middle
348 latitudes of the NH (Fig. 4b–e). Correspondingly, the CDNCs are significantly
349 decreased in SIM3 to SIM6 compared with SIM1. The largest decreases in annual
350 mean column CDNCs exceed $5 \times 10^{10} \text{ m}^{-2}$ in Western Europe, North America, and
351 eastern China (Fig. 5b–e). Decreased CDNCs can decrease the cloud albedo and
352 lifetime and weaken the SWCF in the regions with high anthropogenic aerosol

emissions such as North America and Europe (Fig. 6b–e). The SWCFs are enhanced due to the increase in low cloud fraction over most of South and East Asia, though the CCNs are clearly decreased. The shortwave warmings (coolings) are also compensated by the longwave coolings (warmings) over most regions (Fig. 6b–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 (Fig. 7b–e).

360

361 **4 Conclusions and discussions**

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 atmosphere-only model BCC_AGCM2.0.1_CUACE/Aero with prescribed SST and SIC, in combination with the RCP scenarios. Compared with the aerosol effect for recent past, 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 aerosol semi-direct effect 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.

375 However, our results suggest that associating with the reduction of net cooling
376 effects directly from aerosols, the aerosol indirect effect is also weakened when
377 emissions of SO₂, BC, and OC are simultaneously reduced in different ways to the
378 levels projected for the end of this century under the RCP2.6, RCP4.5, and RCP8.5
379 scenarios. Relative to the aerosol effect for recent past, the total global annual mean
380 aerosol net cooling effect at the TOA is weakened by 1.7–2.0 W m⁻² with the
381 reduction according to potential actual conditions in the emission of all these aerosols
382 (i.e., BC and the major co-emitted species). The main cooling regions are over East
383 Asia, Western Europe, eastern North America, and central Africa, with the largest
384 change exceeding 10.0 W m⁻². This is somewhat consistent with the results given by
385 Gillett and Salzen (2013) and Levy et al. (2013), who also reported that the reduction
386 in atmospheric aerosols will weaken the aerosol cooling effect in the future.

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

395 There exists large uncertainty in BC radiative forcing (Boucher et al., 2013;
396 Myhre et al., 2013a, 2013b). One reason for the uncertainty is from the biases of

397 current emission inventories of BC, mostly obtained from the so-called bottom-up
398 approach (Cohen and Wang, 2014). Cohen and Wang (2014) provided a global-scale
399 top-down estimation of BC emissions, a factor of more than 2 higher than commonly
400 used global BC emissions data sets, by using a Kalman Filter method. If present-day
401 BC emissions have been substantially underestimated, increase in aerosol net cooling
402 effect may be larger due to only reduction in BC emission. Furthermore, co-emissions
403 of other compounds with BC, such as CO₂, might be more important than SO₂ and
404 OC (Rogelj et al., 2014). The reduction in CO₂ can mitigate global warming when
405 reducing BC. However, it is very difficult to fully obtain the ratios of BC with its
406 co-emitted components due to the complexity of emission sources and diversity of
407 energy structure in different regions. These bring about large uncertainties
408 for the relevant research.

409

410 *Acknowledgments.* This work was supported by the National Basic Research Program
411 of China (2011CB403405), National Natural Science Foundation of China
412 (41205116), Public Meteorology Special Foundation of MOST (GYHY201406023),
413 MOST (2014BAC16B01), and CAMS Basis Research Project (2012Y003).

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Table 1. Simulation setups.

Simulation	BC emission	OC & SO ₂ emissions	Interpretation (compared to SIM1)
SIM1	year-2000	year-2000	Recent past reference emissions.
SIM2	RCP2.6 year-2100	year-2000	Maximal reduction in BC; no reductions in OC & SO ₂ .
SIM3	RCP2.6 year-2100	RCP8.5 year-2100	Maximal reduction in BC; minimal reductions in OC & SO ₂ .
SIM4	RCP2.6 year-2100	RCP2.6 year-2100	Simultaneous maximal reductions in BC, OC & SO ₂ .
SIM5	RCP2.6 year-2100	RCP2.6 year-2100 BC by multiplying the ratios of the emissions of OC & SO ₂ with BC in 2000	Maximal reduction in BC; simultaneous reductions of OC & SO ₂ in terms of their ratios with BC in recent past
SIM6	RCP4.5 year-2100	RCP4.5 year-2100	Medium-low reductions in BC, OC & SO ₂ .

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677 **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)						
Sulphate	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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694 **Table 3.** Global annual mean differences of aerosol direct (DRF), semi-direct and
 695 indirect (CRF), and net effect at the TOA (FNT) (Positive values mean incoming,
 696 units: $W m^{-2}$) in different simulations* .

	SIM1	Δ SIM2	Δ SIM3	Δ SIM4	Δ SIM5	Δ SIM6
DRF	-2.01	-0.07 \pm 0.05	+0.27 \pm 0.03	+0.28 \pm 0.05	+0.25 \pm 0.03	+0.3 \pm 0.02
SWCF	-49.0	-0.14 \pm 0.2	+0.87 \pm 0.3	+1.3 \pm 0.14	+1.1 \pm 0.17	+1.02 \pm 0.2
LWCF	+27.8	+0.03 \pm 0.09	-0.07 \pm 0.08	-0.2 \pm 0.1	-0.19 \pm 0.08	-0.14 \pm 0.1
CRF	-21.2	-0.11 \pm 0.17	+0.8 \pm 0.3	+1.1 \pm 0.1	+0.91 \pm 0.11	+0.88 \pm 0.18
FNT	-0.66	-0.12 \pm 0.28	+1.7 \pm 0.2	+2.0 \pm 0.19	+1.8 \pm 0.14	+1.8 \pm 0.21

697 * DRF, SWCF, LWCF and CRF, and FNT in the SIM1 column are aerosol direct radiative forcing, shortwave, longwave and net
 698 cloud radiative forcing, and net radiation flux at the TOA (units: $W m^{-2}$) in SIM1, respectively. Values in the Δ SIM2 – Δ SIM6
 699 columns represent the changes of corresponding variables in these simulations vs. those in SIM1.

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715 **Figure captions:**

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

718 **Figure 2.** Global distributions of simulated annual mean aerosol column burdens
719 (units: mg m^{-2}).

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

723 **Figure 4.** Global distributions of difference in simulated annual mean CCN
724 concentration at surface (units: cm^{-3}). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c)
725 SIM4 – SIM1, (d) SIM5 – SIM1, and (e) SIM6 – SIM1.

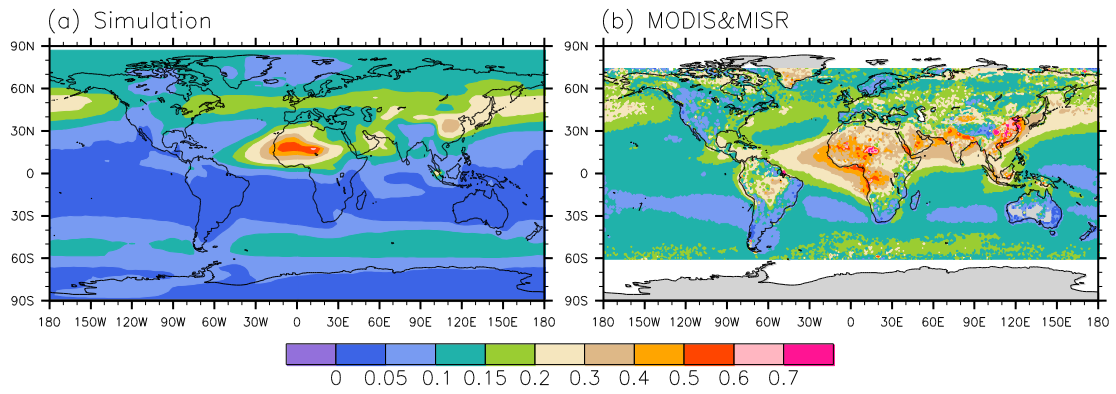
726 **Figure 5.** Global distributions of difference in simulated annual mean column CDNC
727 (units: 10^{10} m^{-2}). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c) SIM4 – SIM1, (d) SIM5
728 – SIM1, and (e) SIM6 – SIM1.

729 **Figure 6.** Global distributions of difference in simulated annual mean SWCF and
730 LWCF (units: W m^{-2}). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c) SIM4 – SIM1, (d)
731 SIM5 – SIM1, and (e) SIM6 – SIM1.

732 **Figure 7.** Global distributions of difference in simulated annual mean aerosol net
733 effect (units: W m^{-2}). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c) SIM4 – SIM1, (d)
734 SIM5 – SIM1, and (e) SIM6 – SIM1.

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738 **Figure 1.** Global distributions of simulated and observed annual mean AOD at 550

739 nm. (a) Simulation and (b) MODIS&MISR (van Donkelaar et al., 2010).

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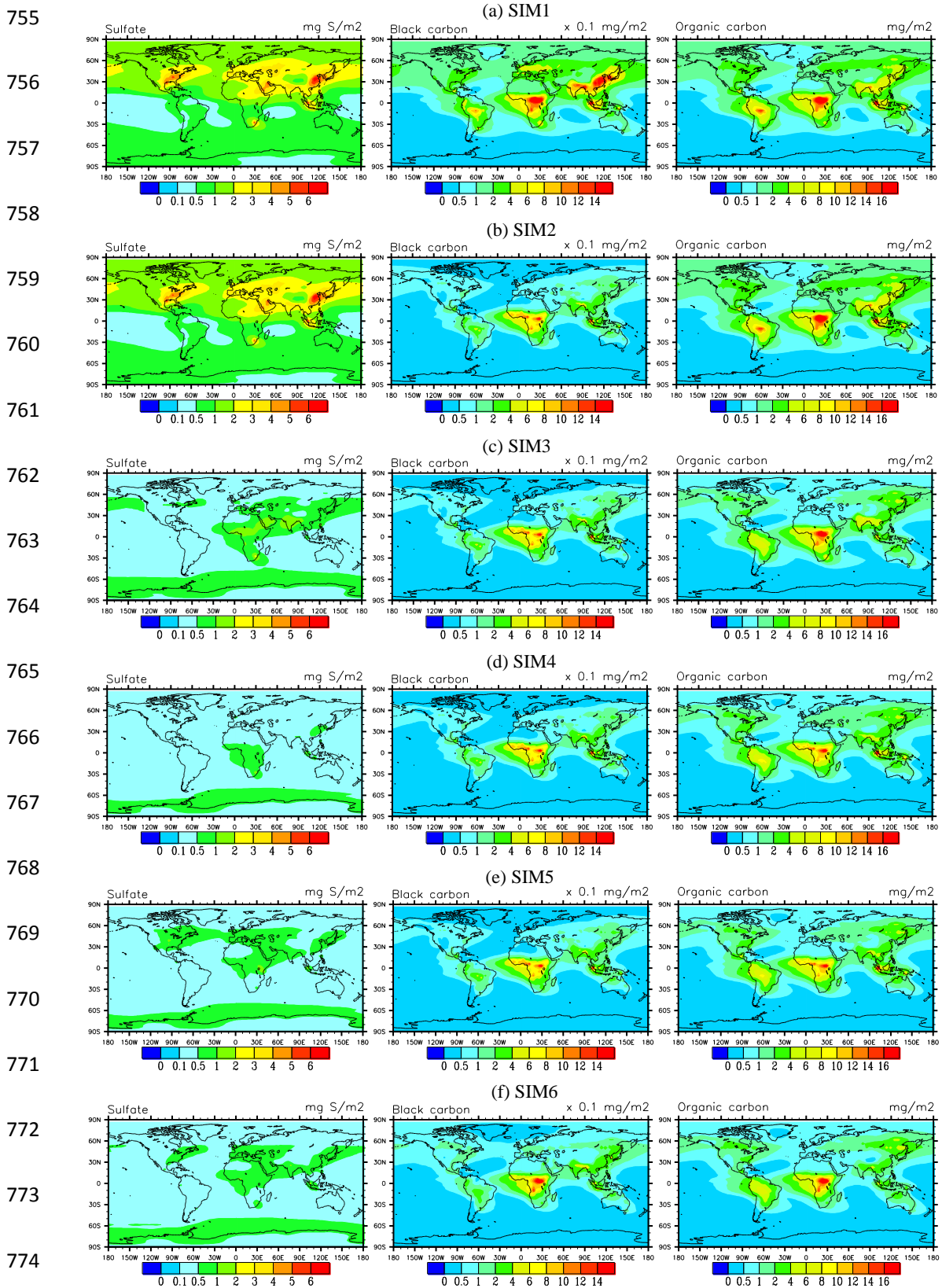
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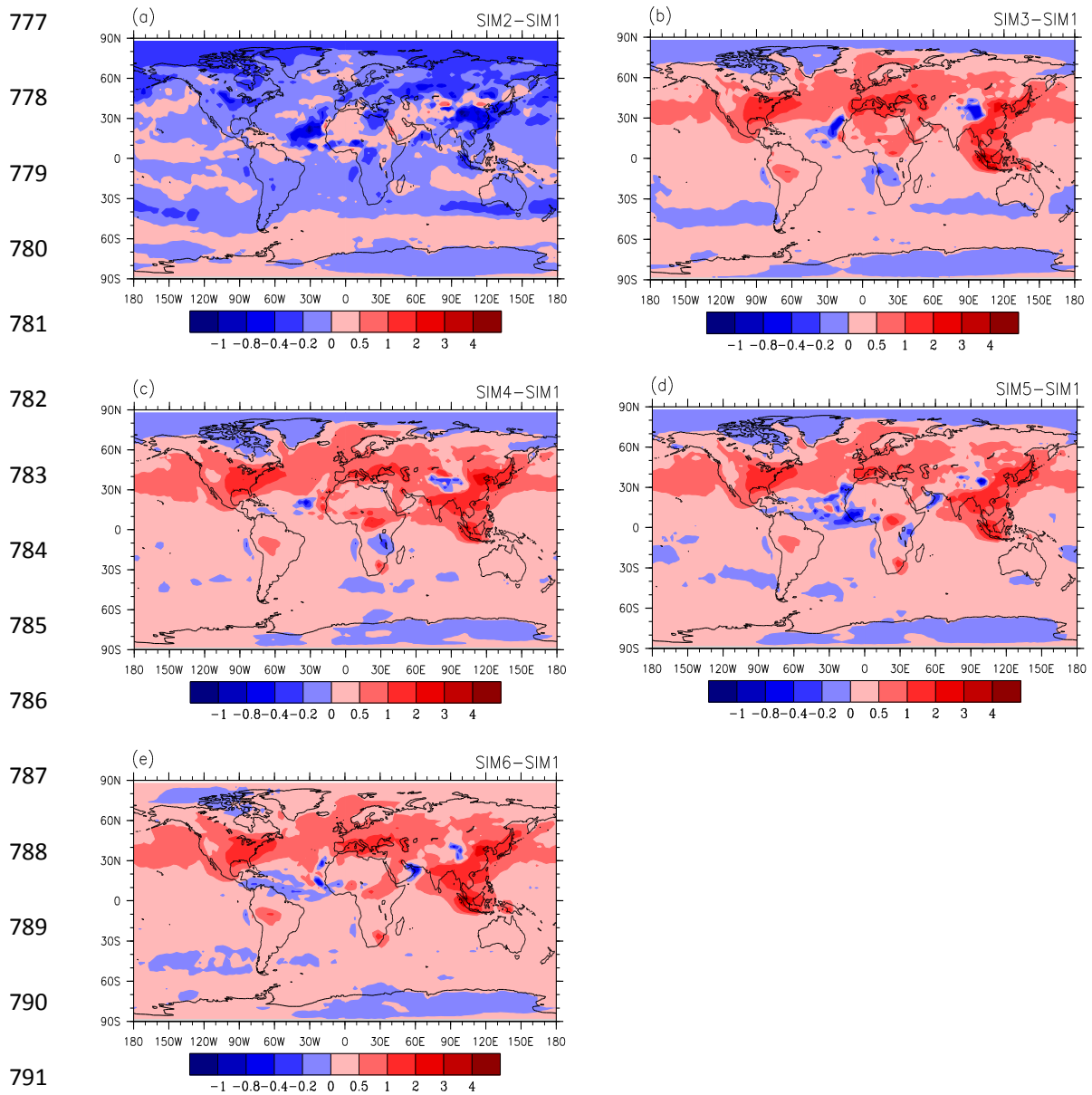
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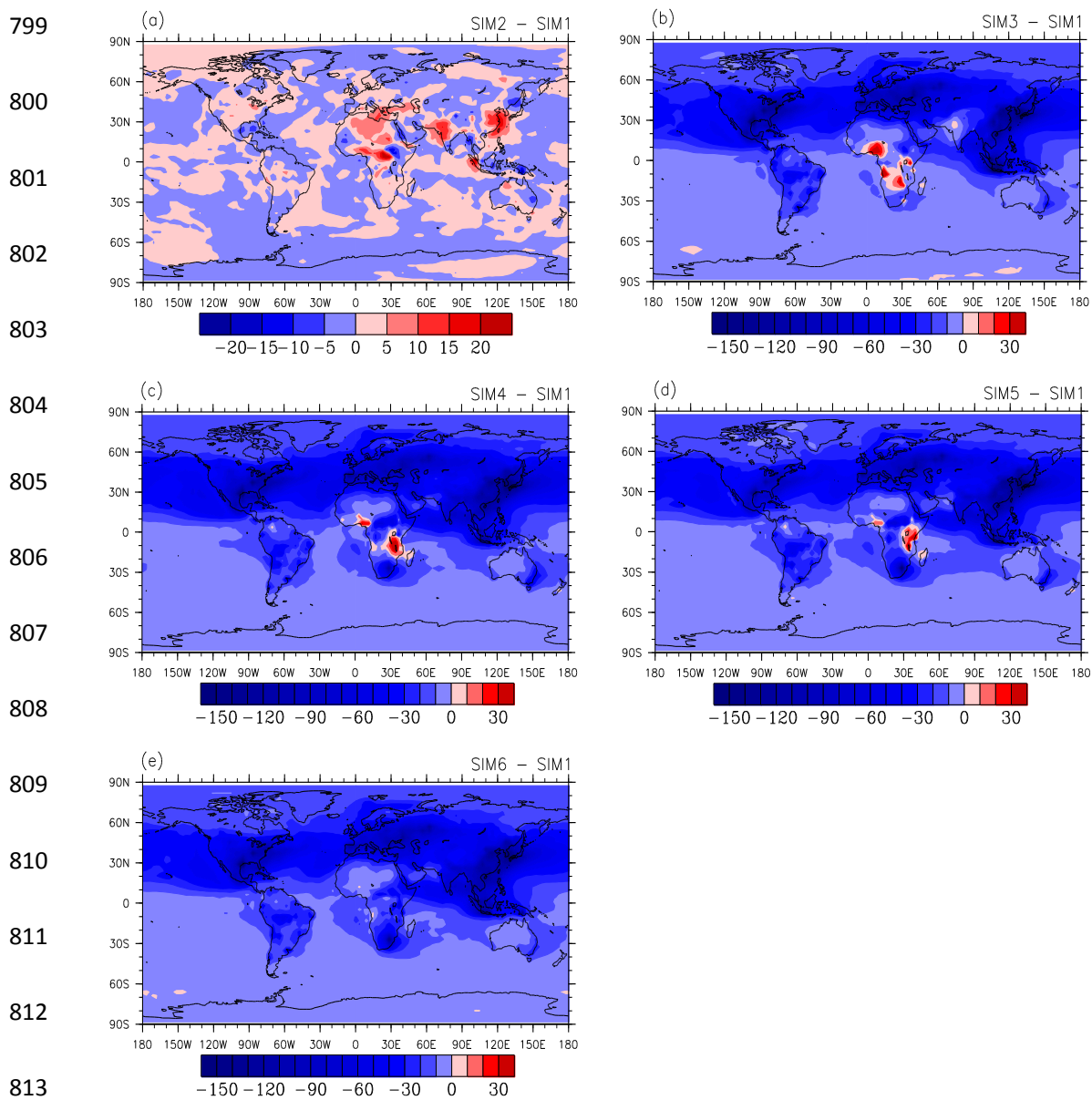


775 **Figure 2.** Global distributions of simulated annual mean aerosol column burdens
 776 (units: mg m^{-2}).



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

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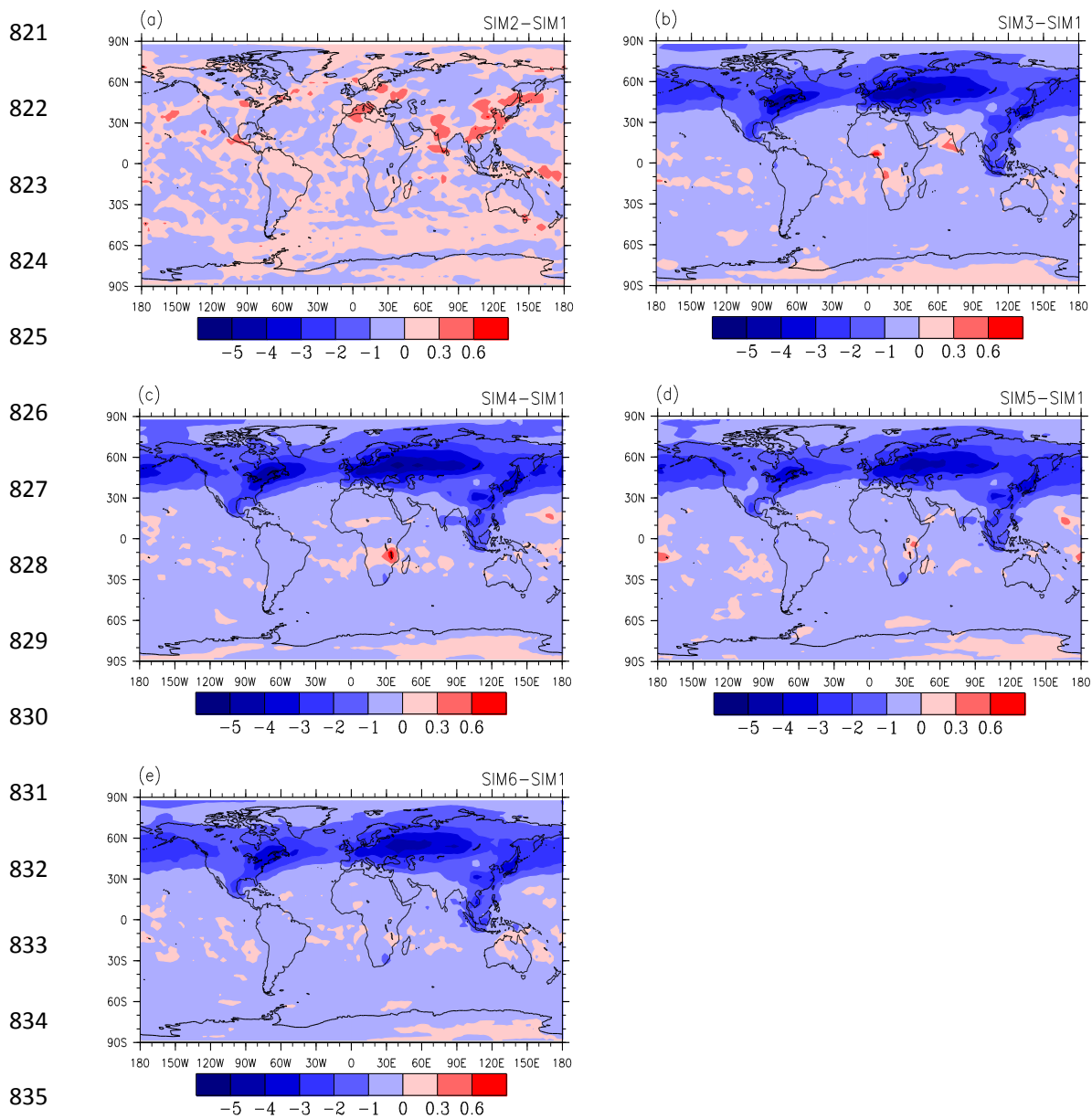
814 **Figure 4.** Global distributions of difference in simulated annual mean CCN
 815 concentration at surface (units: cm^{-3}). (a) SIM2 - SIM1, (b) SIM3 - SIM1, (c) SIM4
 816 - SIM1, (d) SIM5 - SIM1, and (e) SIM6 - SIM1.

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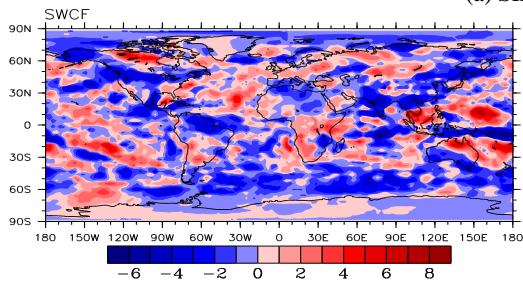


836 **Figure 5.** Global distributions of difference in simulated annual mean column CDNC
 837 (units: 10^{10} m^{-2}). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c) SIM4 – SIM1, (d) SIM5 –
 838 SIM1, and (e) SIM6 – SIM1.

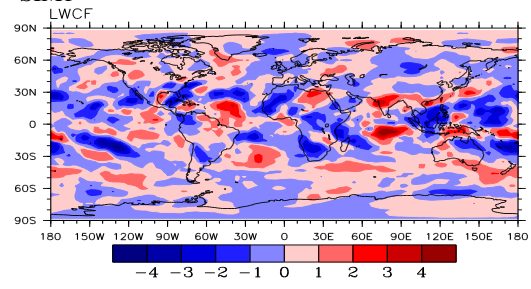
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(a) SIM2 – SIM1



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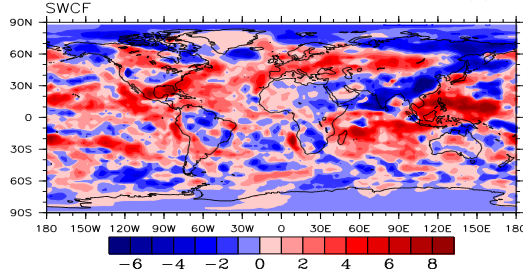


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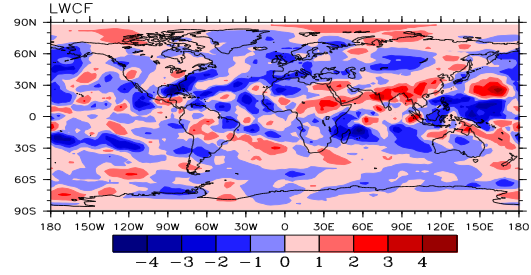
(b) SIM3 – SIM1



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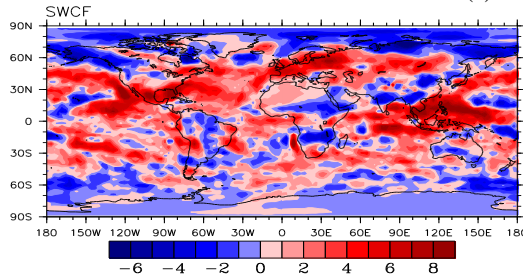
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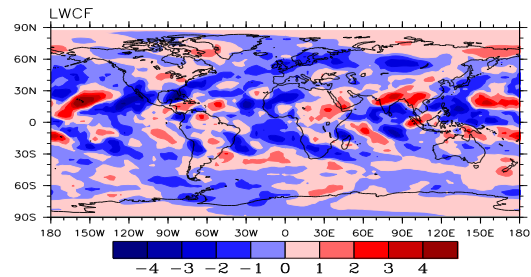
(c) SIM4 – SIM1



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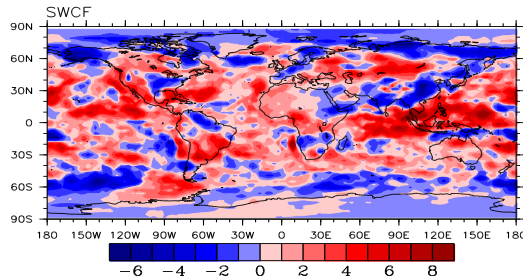
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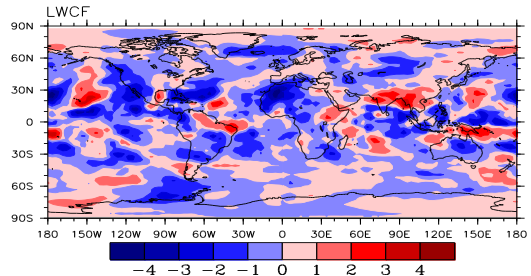
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(d) SIM5 – SIM1



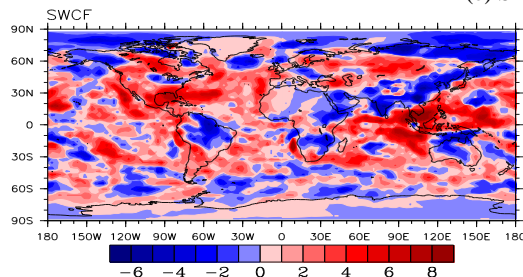
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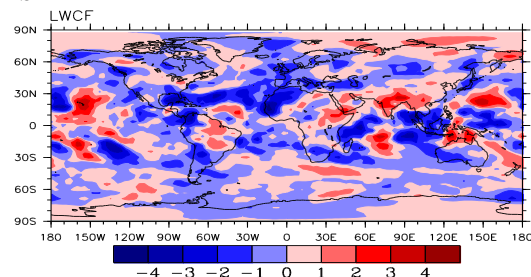
(e) SIM6 – SIM1



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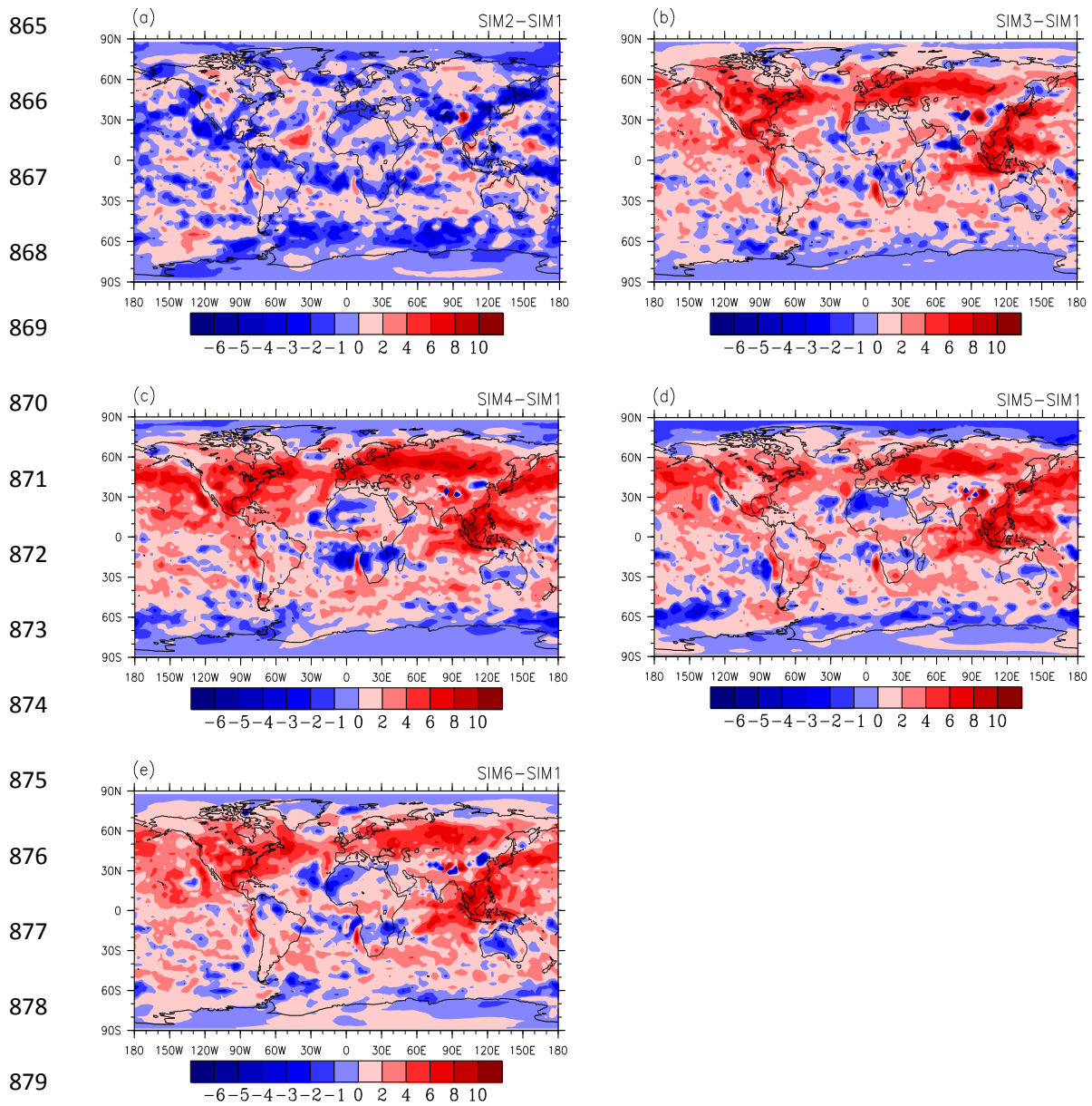
861



862 **Figure 6.** Global distributions of difference in simulated annual mean SWCF and

863 LWCF (units: $W m^{-2}$). (a) SIM2 – SIM1, (b) SIM3 – SIM1, (c) SIM4 – SIM1, (d)

864 SIM5 – SIM1, and (e) SIM6 – SIM1.



880 **Figure 7.** Global distributions of difference in simulated annual mean aerosol net
 881 effect (units: W m^{-2}). (a) SIM2 - SIM1, (b) SIM3 - SIM1, (c) SIM4 - SIM1, (d)
 882 SIM5 - SIM1, and (e) SIM6 - SIM1.