Responses to reviewer comments

Anonymous Referee #2

This study carries out extensive climate model simulations to understand the global and regional precipitation changes due to aerosol variations. Three models with different sophistications of aerosol effects are employed to provide an ensemble assessment. The model analysis is done in a quite comprehensive manner and the paper is well written overall. Therefore, I recommend accepting this manuscript by ACP after some necessary revisions as suggested below.

We thank the reviewer for the comments.

1) The limitations of current GCM in assessing aerosol effect on precipitation have to be clearly stated. For example, three GCM in this study do not account for the aerosol microphysical effects on convective clouds and precipitation which are still parameterized as the sub-grid scale processes (Wang et al., 2014, Fan et al., 2016).

We have added the following sentence to the concluding paragraph of the manuscript:

"One caveat of our study is that in each of the models, aerosols do not exert a microphysical effect on deep convective clouds; however they can alter precipitation associated with deep convection through the aerosol direct effect."

Further model description relevant to precipitation and clouds is referenced in Westervelt et al. (2017).

Westervelt, D.M., A.J. Conley, A.M. Fiore, J.-F. Lamarque, D. Shindell, M. Previdi, G. Faluvegi, G. Correa, and L.W. Horowitz, 2017: Multimodel precipitation responses to removal of U.S. sulfur dioxide emissions. *J. Geophys. Res. Atmos.*, **122**, no. 9, 5024-5038, doi:10.1002/2017JD026756.

2) Table 1, the sign of ERF from the removal of BC can be either positive or negative for different regions among three different models. Why is that? BC direct radiative forcing has been widely reported to be positive by previous modeling and observational studies (Ghan et al., 2012; Peng et al., 2016). Does your results imply the large spread of BC microphysical effects on cloud and precipitation among the models?

GFDL-CM3 and GISS-E2 only includes direct effects for BC, thus removing BC in results in small negative ERF values in these cases. In the case of positive numbers for NCAR-CESM1, this could be caused by the differences in aerosol treatment between the models. For instance, CESM1 uses an internal mixing approach with modal aerosol microphysics. Internally mixed BC-sulfate particles can activate clouds in this model setup, which could lead to a slight positive radiative forcing when BC is removed. Another possible explanation is that since these regional BC perturbations can be quite small in magnitude, the role of internal climate variability may be outweighing the BC forcing, especially for a global mean ERF value.

Finally, many of the ERFs reported in Table 1 are close to zero and are not statistically significantly different from zero, so the signs of these small numbers should not be overanalyzed. For example, the standard error for the IN_BC in GISS-E2 simulation is 0.028 W m^{-2}, so the ERF mean of 0.011 W m^{-2} is not even significant at the 1-sigma level. Similarly, none of the BC ERF values in GFDL-CM3 are significant at the 2-sigma level. We have edited Table 1 in the revised manuscript, putting the ERFs that are significant at the 2-sigma level in **boldface** type.

We have also added the following sentence to the manuscript in light of the reviewer comments:
"The black carbon aerosol global mean ERF (Table 1) varies in sign and magnitude, indicating a strong sensitivity to different model configurations for black carbon and, perhaps, a role for internal climate variability. In many of the black carbon simulations, the global mean aerosol ERF values reported are not statistically significant."

3) P3L18, are those model coupled with full chemistry? Like for CESM1, is the MOZART on?

Yes, all models include full chemistry, as stated in the manuscript on Page 3, Line 17-20.

4) P4L15-25 and Fig. S2, I'm not fully convinced that precipitation changes should be well correlated with ERF in physics. As you hinted in the paper, precipitation is related with atmospheric heating, while ERF is about the radiative flux variations at the top of atmosphere. The response of surface energy fluxes is an unknown factor. Moreover, I'm not sure if the global mean precipitation change is a good indicator here, as you have showed that the major spatial pattern of the simulated precipitation change is the "ENSO like" seesaw. The regional changes may be largely offset in the global mean.

We agree with the reviewer that the correlation between ERF and global precipitation is imperfect, and do not intend to imply a strong causal relationship. Therefore, based on the reviewer comment we have removed the following sentence from the manuscript (and a similar one in the conclusions section) in order to not overemphasize a causal relationship between ERF and global precipitation:

"This suggests that TOA aerosol ERF may explain some of the variation in global precipitation response, but not all of it."

We have also added the following sentence regarding a caveat to using global precipitation:

"Global precipitation may also be an imperfect metric for correlation, if opposite-signed regional changes are largely offset in the global mean."

We prefer to keep Fig. S2 in the supplemental section, however, as this figure allows for comparison between similar studies, such as the work from PDRMIP, which is cited in our manuscript.

5) P5L13-19, to better unravel the role of BC on convection, it would be useful to separately analyze the convective and stratiform precipitation in each model. I assume those two quantities are available for those models.

We have looked at convective and large-scale precipitation responses to black carbon in the models. The figures below shows the total precipitation response, the large-scale response, the convective response, and the shallow convective response to zero-out India BC emissions in GFDL-CM3 and NCAR-CESM1. As can be seen in the figures, both the large-scale and convective responses exhibit large amounts of noise and variability. Convective precipitation seems to dominate the total response, especially in convective regions such as the tropics. Large-scale precipitation responds more strongly in the mid-latitudes.

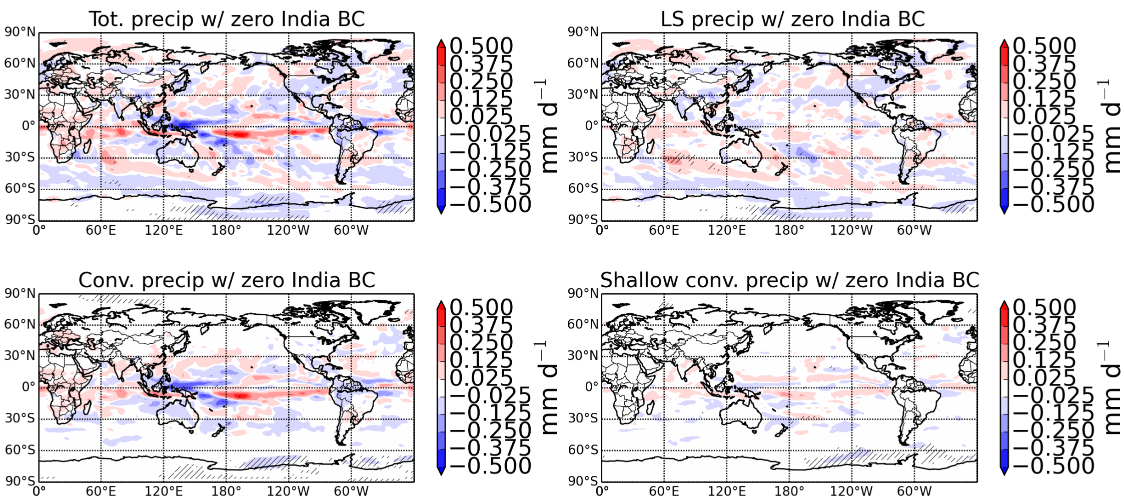

Figure 2: Total, large-scale, convective, and shallow convective precipitation response to zero India BC emissions in GFDL-CM3

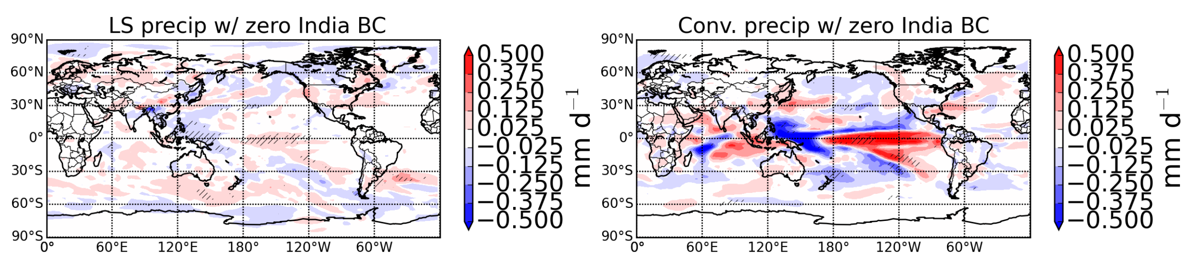

Figure 3: Large-scale and convective precipitation response to zero India BC emissions in NCAR-CESM1

Because of large amounts of variability and lack of statistical significance, it is difficult to discern anything further from the breakdown of precipitation types that cannot already be discerned from the total precipitation. Thus, we elect to keep the discussion in the paper as is and leave these figures in the response to reviews document.

6) As the fully coupled models are used in this study, the simulated large-scale circulation changes should be closely linked with the polar climate change and the “Arctic amplification” is evident in Fig. 3. Therefore, the influence of emission changes on the Arctic sea ice and temperature should be relevant here, as discussed by Wang et al. (2018).

In the revised manuscript, we have cited the Wang et al. (2018) paper in our discussion of Figure 3.