

Response to **Anonymous Referee #1** concerning the paper "Direct radiative effects of dust aerosols emitted from the Tibetan Plateau on the East Asian summer monsoon – a regional climate model simulation" (<http://www.atmos-chem-phys-discuss.net/acp-2017-55/>)

We are very thankful to the reviewer who gave insightful and constructive comments. We believe that the reviewer's comments helped us highlight some critical aspects of the paper and improve the quality of our work. We have addressed all the reviewer's comments in a point-by-point manner. In the following, the underlined *italic* texts are reviewer's comments and normal (font) texts are our responses. The bold texts have been inserted to new version of our manuscript.

Referee #1 (Comments to Author):

This is an interesting study which investigates the direct radiative effects of dust aerosols emitted from the Tibetan Plateau on the East Asian summer monsoon with a regional aerosol-climate model. In general, it is well written and structured and there are original model results presented and discussed. However there are a number of major comments that have to be taken into consideration before acceptance of the manuscript for publication.

We now add more analyses and discussions which are summarized below:

- (1) compared simulated dust AOD with pure dust observation from CALIPSO in Figure 6.
- (2) added anomaly of geopotential height in Figure 11 and updated the figure of precipitation.
- (3) carried out two new sensitive experiments to isolate the effects of changed land cover alone on the results, and discussed uncertainty brought by the method used in the manuscript.
- (4) compared the aerosol-induced signal on the meteorological fields with that from the model's internal variability.
- (5) added more discussions throughout the manuscript to clarify uncertainty of our simulations, and updated the references.

Comments:

1. Please discuss briefly what is the added value of using a regional climate model instead of global climate model to study the impact of aerosols on climate.

In the revised version, we added the following statements to characterize advantages of using RCM instead of GCM to study the impact of aerosols on climate (Page 11, Line 3–10).

It is very beneficial to study the impact of aerosols on climate using a RCM instead of a coarse-resolution global climate model (GCM). The GCMs tend to systematically underestimate dust aerosol concentration, presumably due to their lower spatial resolution (Tegen et al., 2002; Zhang et al., 2009). The RCM simulated dust concentration, on the other hand, was closer to the observed magnitude compared with the results of global models (Sun et al., 2012). For example, previous studies showed that high-resolution RCMs had better capabilities than GCMs in simulating the effect of aerosols on Asian monsoon (Zhou and Yu, 2006; Gao et al., 2008; Ji et al., 2011). A high-resolution regional model is especially needed to capture subtle characteristics in the areas of complex terrain (Ji et al., 2011).

2. In the discussion section the authors should also comment on the limitations of using a regional climate model to study the impact of aerosols on climate. For example, could the authors comment if an RCM which is actually forced by lateral boundary conditions of a GCM or reanalysis can be able to provide the adequate spatial coverage for the development of atmospheric circulation feedbacks over a limited area.

Yes, RCM's high horizontal resolution comes at the expense of being covering a limited area. Although RCM's domain is relatively small in a global sense, the atmospheric circulation away for the domain still enter the domain via lateral boundary condition (BC). Given a properly designed BC and reasonably sized domain, RCM simulations should be able to provide adequate spatial coverage for atmospheric circulation to develop and exert feedback in the domain. The reasonably simulated in wind and temperature pattern compared with the observations did suggest the external forcing passed through the lateral boundary well and developed properly within the RCM domain. At your suggestions, the following elaboration and caution are added to Discussion Section (Page 11, Line 10–16).

However, limited area RCM naturally cannot fully account for external forcing remote from the domain of interest although the lateral boundary conditions allow large-scale features to propagate into the domain. Our domain size (9600 km × 640 km) is reasonably large enough so that the weather and climate systems can have adequate spatial extent to develop within the domain, as attested by reasonably validation of wind pattern, temperature field, and precipitation (Section 3.1). Cautions should be exercised, however, that results from regional simulations could be somewhat domain-size dependent quantitatively although main results should not be affected.

3. An issue that it is not discussed at all is if the aerosol induced signal on the meteorological fields is higher than the model's internal variability. Did the authors carried out some sensitivity experiments to investigate this important issue? I think at least a few comments on this issue are necessary. This is also a part of the limitations in these simulations.

We deeply appreciate this great comment and agree that the model's internal variability could be large, so we compared the standard deviation of summer surface temperature and precipitation in CON with signals induced by the dust effects (CON minus SEN) during heavy dust years (Figure A1). It seems that the signal induced by the dust is much greater than the standard deviations. Therefore, the dust effects in our simulation is significant. We mentioned this in the revised version as below (Page 10, Line 17–22).

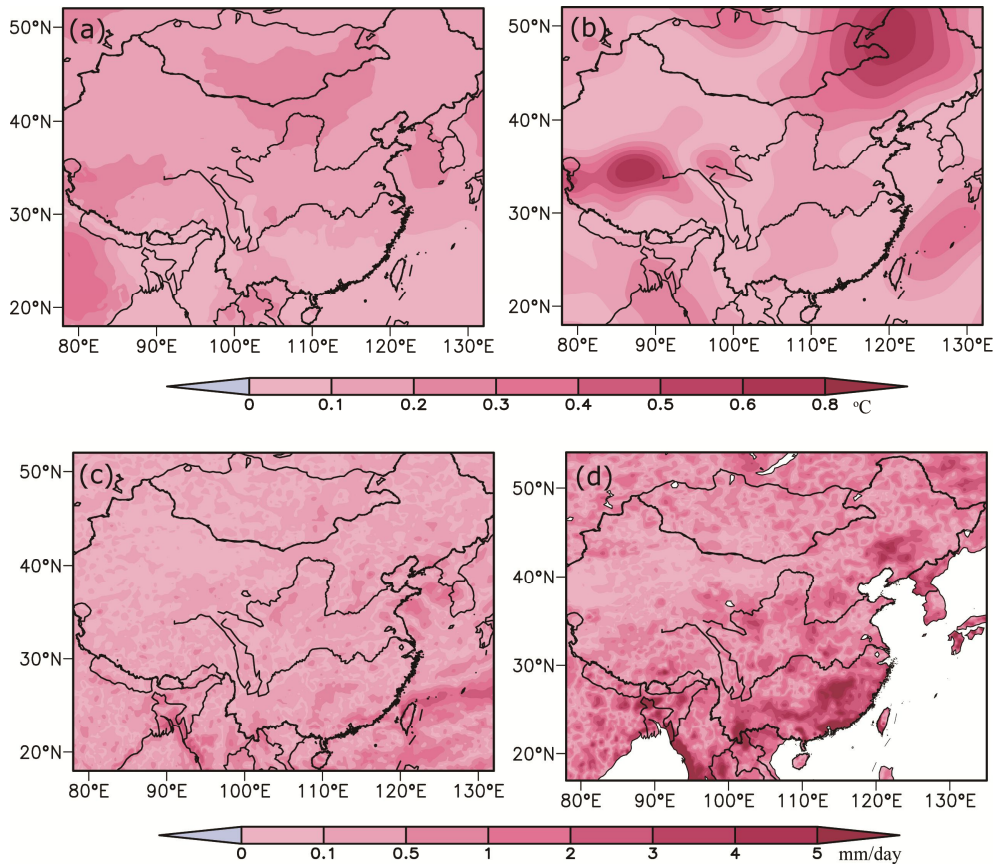


Figure A1: Standard deviation of summer surface temperature (a) and precipitation (c) in CON, and differences (absolute value) of summer surface temperature (b) and precipitation (d) between CON and SEN during the heavy dust years.

It is worth mentioning that the model's internal variability could influence the results; so we compared the standard deviation of summer surface temperature and precipitation in

CON with the signal induced by the dust effects (CON minus SEN) during the heavy dust years. The signal induced by the dust is much greater than the standard deviations (figures not shown). Therefore, the dust effects reported in our simulation is significant in the heavy dust years, but the cooling over central India in the light dust years may be caused by the model's internal variability.

4. Page 3, lines 4-7: There are a number of other recent published studies that have looked the effect of aerosols on climate using RegCM e.g. Das et al., Clim. Dyn., 2015 and Das et al., TAC, 2016 for Asia, Zanis et al., Clim.Res. 2012 for Europe, Ji et al., Clim. Dyn., 2015 and Komkoua et al., Int. J. Clim., 2017 for Africa.

Thanks. We have cited these articles in the revised version (Page 3, Line 8–9).

5. There is a recent study by Tsikerdekis et al., ACP (2017) testing a newly implemented 12-bin approach for RegCM which is also compared with the default RegCM4 4-bin approach used in the RegCM simulations of this work.

Thanks. We read and cited the reference in the revised version as below (Page 11, Line 21–23).

A recent study by Tsikerdekis et al. (2017) demonstrated that simulated dust load and induced radiation change are sensitive to the dust particle size division in the model; so further sensitivity experiments using more dust size bins would be worthwhile.

6. Please clarify if the RegCM simulations in this work use only dust aerosols or other aerosols as well (such as anthropogenic or marine aerosols). To my understanding the simulations include only dust particles. Hence the comparison of modelled dust AOD with AOD from satellite (MISR) and ground based (AERONET) measurements is not one to one comparison since these observations include all types of aerosols. Mind though that there are available pure dust satellite products from CALIPSO (see e.g. Amiridis et al., ACP, 2013 and Marinou et al., ACP, 2017).

Only dust aerosols included in our simulation, and we have clarified this point in the revised version as below (Page 4, Line 26–27).

In order to isolate the effect of dust aerosols, only dust aerosols are included in our simulations, without considering other aerosols (such as anthropogenic or marine

aerosols).

We agree that these comparisons are imperfect, and are grateful for reminding us availability of the pure dust observation from CALIPSO. We added a section to compare the simulated dust AOD with those of observed by CALIPSO, and the comparison is good (Figure 6). Accordingly, we updated the data description in Section 2 (Page 5, Line 18–22), and added following figure and texts in the revised version (Page 7, Line 1–11).

3.1.4 Simulated and CALIPSO-observed dust AOD comparison

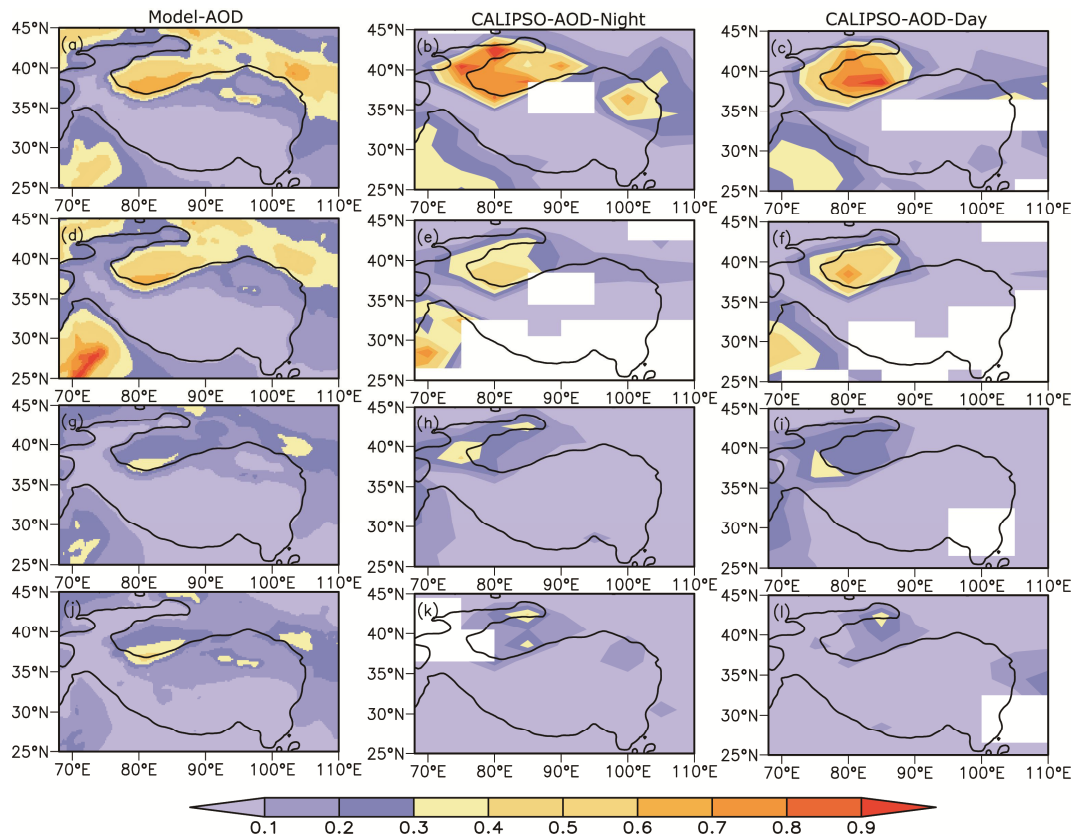


Figure 6: Spatial distribution of the dust AOD simulated by the control experiment (left panels) and observed by CALIPSO at night (middle) and during daytime (right panels) averaged in (a, b, c) spring, (d, e, f) summer, (g, h, i) autumn and (j, k, l) winter during the time period 2007–2009.

While MISR and AERONET data contain all types aerosols including those anthropogenic ones, the CALIPSO observation sole devotes to dust aerosols. Figure 6 shows that the simulated seasonal variation, center positions and magnitude of dust AOD are very consistent with those observed by CALIPSO during day and night. Both simulations and observations not only showed that dust AOD increased in spring and summer and

decreased in autumn and winter, but also captured three maximum centers of dust AOD in Taklimakan, the Great Indian Desert and Qaidam Basin located in the northern TP in spring. The simulated center values were still high in summer. Besides, it is very interesting to note that the observed dust AOD in the Qaidam Basin is higher at night than that during daytime (Figure 6b and 6c), which implied that dust activities in the TP may be more prominent at night. This unusual feature could cause dust radiative effects in the TP is very different from those of in other locations, which is further discussed in subsequent section of 3.4.1.

7. The authors mention that in order to eliminate the dust emission in the Tibetan Plateau they replaced the land cover types of these areas with the nearby vegetated types. This change could stop the dust emission but will also change the surface albedo which itself could have an impact on radiation budget, temperature and circulation. In other words if it is like this the results do not show simply the effect of eliminating the emission of dust particles but also the effect of land cover type and albedo change. Please comment on this important issue.

We deeply appreciate this great comment. We agree that our method is imperfect and uncertainty exists in the results. To address your concerns, we carried out two additional sensitive experiments to evaluate effects of the changed land cover. Dust cycle in the two experiments was turned off, but the land cover was changed to become similar to the modification in SEN. The differences between the two experiments only included effects of the changed land cover. The results showed that change (from desert to vegetated land) brought about 0.4 °C warming (Figure A2 and Figure A3), and this warming effect is weaker than the combined cooling effects (−0.6°C) induced by the dust aerosols and the changed land cover. Besides, we have noted that Li and Xue (2010) demonstrated that land cover change from vegetated land to bare ground (mainly desert) in the TP decreased the radiation absorbed by the surface and resulted in weaker surface thermal effects, which means that effect of land cover change from desert to vegetated land may also cause warming effects. This is opposite to the cooling effects induced by the dust aerosols over the TP in our simulation, and it may partly offset the dust aerosols induced cooling effects. However, our results showed that the cooling signal was not changed, and it may even be underestimated in the heavy and light dust years. Therefore, actual cooling should be stronger than the simulated. We will try a new better method in our future work. We mentioned the uncertainty brought by the method and discussed the influences on the results in the revised version as below (Page 10, Line 22–34, and Page 11, Line 1–2).

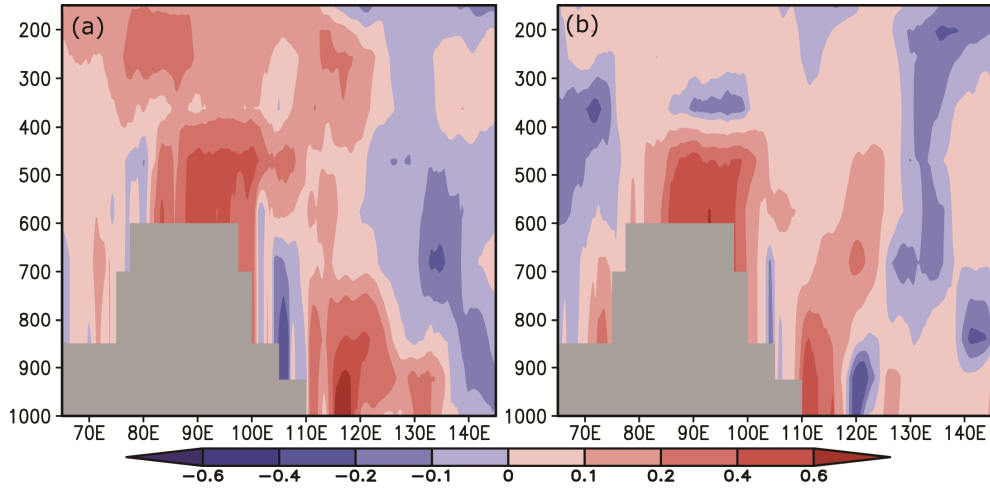


Figure A2: Longitudinal-height cross-section of air temperature anomaly induced by the land cover changed averaged over 32–36°N in summer in heavy (a) and light (b) dust years.

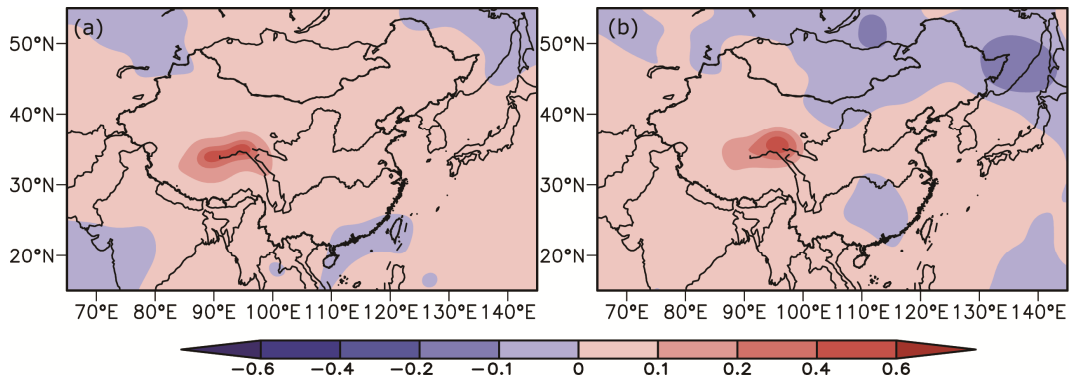


Figure A3: Summer surface temperature change induced by the land cover change in (a) heavy and (b) light dust years.

Besides, the results could also include the role of changed land cover in addition to the role of dust aerosols because turning off dust emission in the TP was through modifying underlying surface types. Hence, we carried out two additional sensitive experiments to isolate effects of the changed land cover alone. The dust cycle in the two experiments was turned off, but the land cover was changed to one similar to the modification in SEN. The differences between them only included effects of the change in land cover. The results showed that the change (from desert to vegetated land) brought about 0.4 °C warming (figures not shown), and this warming effects is weaker than the combined cooling (-0.6°C) induced by the dust aerosols and the changed land cover together. Besides, it is interesting to note that Li and Xue (2010) had demonstrated that the land cover change from vegetated land to bare ground (mainly desert) in the TP decreased the radiation absorbed by the surface and resulted in weaker surface thermal effects, which means that the effect of land cover change from desert to vegetated land may also cause warming effects. This is

opposite to the cooling effect induced by the dust aerosols over the TP in our simulation, and the warming may partly offset the dust aerosols-induced cooling effect. However, our results showed that the signal of cooling effects was not changed, although it may even be underestimated. Therefore, actual cooling should be stronger than the simulated value. Hence, the reported dust effects also need be evaluated by using a refined way in the future.

8. The authors mention in Section 3.2 that "the dust aerosol increases and decreases over the TP as the EASM index weakens and enhances, respectively". Please could provide some discussion on the physical explanation for this anti-correlation. Also provide some short description for the EASM index used.

We added some short description for the EASM index in Section 3.2 in the revised version as below (Page 7, Line 14–15).

This index measures the intensity of the southerly wind to the east of TP in lower troposphere above East Asia.

We added following schematic diagram and texts for physical explanation of the anti-correlation in the revised version (Page 9, Line 16–25).

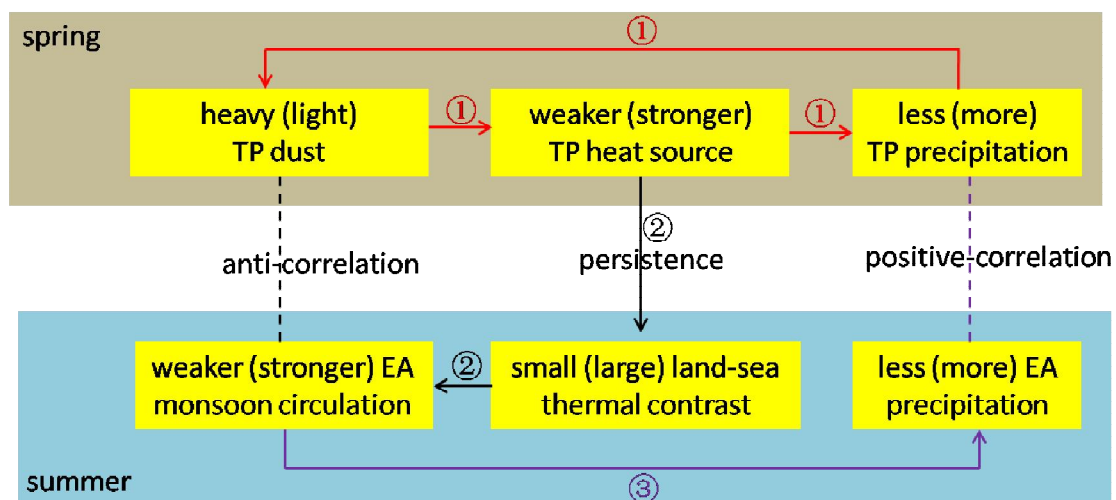


Figure 13 Schematic diagram showing the relation of dust aerosols emitted from the TP in spring with EASM precipitation

The spring dust aerosols from the TP have a close relation with EASM. Although the cause-effect relationship is not immediately clear, the following processes are proposed as a

possible mechanism of this relation based on the results in our simulation (Fig. 13). Firstly, increasing (decreasing) in dust aerosols over the TP in the heavy (light) dust years in spring can weaken (enhance) the TP heat source and thus reduce (increase) precipitation over the TP. Reduction (increase) in precipitation over the TP can also further enhance (diminish) dust emission over the TP. Secondly, the weakened (enhanced) TP heat source can persist from spring to summer and shrink (expand) the land-sea thermal contrast and thus weaken (enhance) the EASM. Therefore, the change of dust over the TP has an anti-correlation with the variation of EASM circulation intensity. Thirdly, weakened (enhanced) monsoon circulation can reduce (increase) precipitation in East Asia. As a result, the precipitation variation of the TP presents a positive-correlation with that of EASM.

9. The authors point is Section 3.4.1 that the effect of TP aerosols on surface temperature are not limited to the areas that the dust aerosols are locally emitted. So the effect on temperature is not solely due to local radiation imbalance from the presence of dust aerosols but also due to aerosol induced circulation changes. Similar results have been pointed for Asia by Das et al., 2015 as well as in earlier studies by Zanis, 2009 and Zanis et al., (2012) for Europe.

Thanks. We read and cited these references in the revised version as below (Page 8, Line 16–18).

Similar phenomena were reported earlier from Europe for anthropogenic aerosols (Zanis 2009; Zanis et al., 2012) and from South Asia for natural aerosols (Das et al., 2015a).

10. It would be helpful if the authors could also add in Figure 10 the Geopotential Height anomalies with colors to point spatially the anticyclonic circulation anomaly.

Thanks for the suggestion. We updated this figure and rephrased this part. Please see Section 3.4.2 in our revised version (Page 8, Line 20–25).

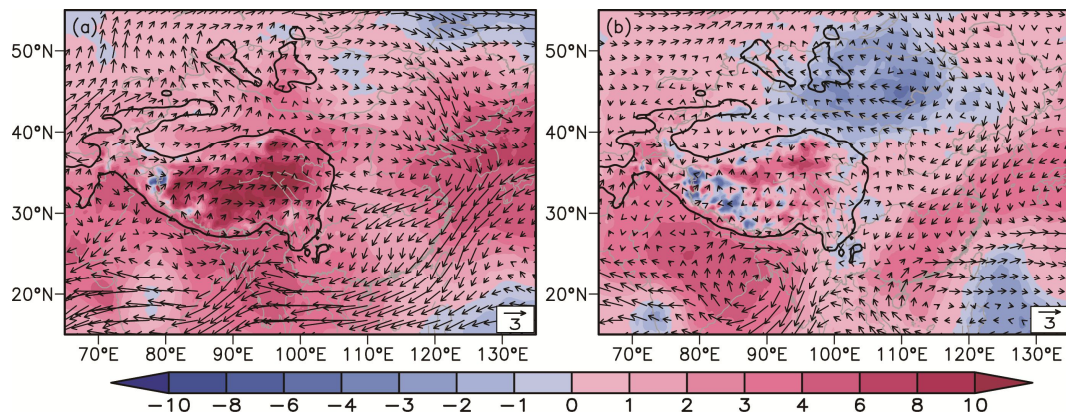


Figure 11: Simulated differences in atmospheric circulation at 850 hPa (vector, m s^{-1}) and geopotential height at 600 hPa (shaded, m) in summer between CON and SEN in (a) heavy and (b) light dust years.

The overall effects of TP aerosols cool the troposphere surrounding the TP (Fig. 10a) and thus the land–sea thermal contrast was reduced by the dust aerosols over the TP. The atmospheric circulation anomaly induced by the dust aerosols emitted over the TP in heavy dust years shows an overall gigantic anticyclonic circulation centered over the TP **with a positive anomaly (>10m) in geopotential height** (Fig. 11a). The northeasterlies that run against the southwesterly monsoon is especially strong over the EASM region, which indicates that the EASM was weakened greatly. The anomaly still existed in the light dust years, but its intensity was much weaker than in the heavy dust years (Fig. 11b).

11. The discussion in Section 3.4.3 for the dust particle effect on precipitation in heavy and light dust years needs more elaboration. Maybe the authors could include a figure for precipitation similar to Figure 9 for temperature.

Thanks for the suggestion. We updated this part with a horizontal distribution figure for precipitation change similar to temperature and rephrased this part. Please see Section 3.4.3 in the revised version (Page 8, Line 26–31, and Page 9, Line 1–3).

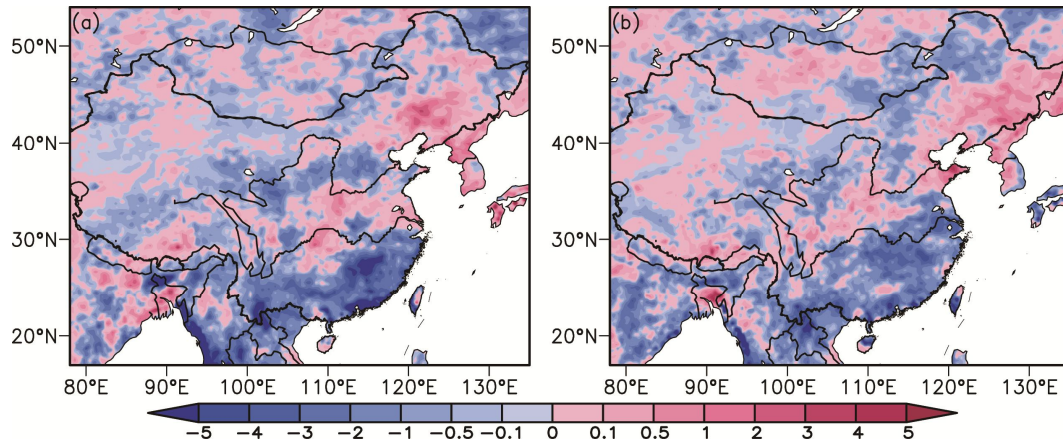


Figure 12: Simulated difference in summer precipitation between CON and SEN in (a) heavy and (b) light dust years.

Figure 12 shows the simulated change in summer precipitation in **East Asia** induced by dust emitted over the TP in heavy and light dust years. The precipitation decreased in **both the southern and the northern monsoon regions** in summer during heavy dust years as a result of weakening EASM (Fig. 11), **and the reduction in the southern monsoon region is greater than that in the northern monsoon region**. The dust aerosols also reduced precipitation in the two monsoon regions in the light dust years. The simulated suppressive effects of the dust aerosols were consistent with previously reported modeling results (Sun et al., 2012; Guo et al., 2015). **Besides, precipitation in the heavy dust years reduced more than that in the light dust years in the TP, which may be suppressed by the enhancement of descending motion induced by the strong cooling effects of dust aerosols over the TP.**

12. The conclusion that Figure 12 shows that the dust aerosols emitted over the TP delay the onset of the EASM is really weak since no uncertainty analysis is implemented and the differences between control and sensitivity experiments are small. I think this statement needs more elaboration and justification.

Yes. Results of this part is not very robust. Since it is off the major focus of this paper, we delete this part in our revised version. We will explore this in the future.

13. Since the work is focusing on summer monsoon season I think that Figure 2 (a, b, c and d) should also refer to the summer season for consistency reasons, similarly to Figures 2e and 2f.

All the figures in Figure 2 are summer average. We rephrased the caption of Figure 2 as below (Page 20, Line 6).

Figure 2: Spatial distribution of (a, b) **summer** surface air temperature ($^{\circ}\text{C}$) and (c, d) **summer** precipitation (mm day^{-1}) simulated in the control experiment (left) and the CRU observations (right) for 1990–2009. The bottom two panels are wind vectors at 850 hPa simulated in (e) the control experiment and (f) the NCEP–DOE re-analysis during the summer monsoon season (June–August) averaged for 1990–2009.

References

- Amiridis, V., Wandinger, U., Marinou, E., Giannakaki, E., Tsekeri, A., Basart, S., Kazadzis, S., Gkikas, A., Taylor, M., Baldasano, J., Ansmann, A.: Optimizing CALIPSO Saharan dust retrievals, *Atmos. Chem. Phys.*, 13, 12089–12106, doi: 10.5194/acp-13-12089-2013, 2013.
- Gao, X. J., et al.: Reduction of future monsoon precipitation over China: comparison between a high resolution RCM simulation and the driving GCM. *Meteor Atmos Phys*, 100, 73–86, 2008.
- Guo, J. and Yin, Y.: Mineral dust impacts on regional precipitation and summer circulation in East Asia using a regional coupled climate system model, *J. Geophys. Res.*, 120, 10378–10398, doi: 10.1002/2015JD023096, 2015.
- Ji, Z. M., Kang, S. C., Zhang, D. F., Zhu, C. Z., Wu, J., and Xu, Y.: Simulation of the anthropogenic aerosols over South Asia and their effects on Indian summer monsoon, *Clim Dyn*, 36: 1633–1647, 2011
- Li, Q., and Xue Y. K.: Simulated impacts of land cover change on summer climate in the Tibetan Plateau, *Environ. Res. Lett.*, 5, 015102, doi: 10.1088/1748-9326/5/1/015102, 2010.
- Marinou, E., Amiridis, V., Biniotoglou, I., Solomos, S., Proestakis, E., Konsta, D., Tsikerdekis, A., Papagiannopoulos, N., Vlastou, G., Zanis, P., Balis, D., Wandinger, U., Ansmann, A.: 3D evolution of Saharan dust transport towards Europe based on a 9-year EARLINET-optimized CALIPSO dataset, *Atmos. Chem. Phys. Discuss.* doi: 10.5194/acp-2016-902, 2016.
- Sun, H., Pan, Z. T., and Liu, X. D.: Numerical simulation of spatial-temporal distribution of dust aerosol and its direct radiative effects on East Asian climate, *J. Geophys. Res.*, 117(D13), 110–117, doi: 10.1029/2011JD017219, 2012.
- Tegen, I., Harrison, S. P., Kohfeld, K., Prentice, I. C., Coe, M., and Heimann, M.: Impact of vegetation and preferential source areas on global dust aerosol: Results from a model study, *J. Geophys. Res.*, 107(D21), 4576, doi:10.1029/2001JD000963, 2002.
- Tsikerdekis, A., Zanis, P., Steiner, A. L., Solmon, F., Amiridis, V., Marinou, E., Katragkou, E., Karacostas, T., Foret, G.: Impact of dust size parameterizations on aerosol burden and radiative forcing in RegCM4, *Atmos. Chem. Phys.*, 17, 769–791, doi:

10.5194/acp-17-769-2017, 2017.

Zanis, P.: A study on the direct effect of anthropogenic aerosols on near surface air temperature over Southeastern Europe during summer 2000 based on regional climate modeling, *Ann. Geo.*, 27, 3977–3988, 2009.

Zanis, P., Ntogras, C., Zakey, A., Pytharoulis, I., and Karacostas, T.: Regional climate feedback of anthropogenic aerosols over Europe using RegCM3, *Clim. Res.*, 52, 267–278, doi: 10.3354/cr01070, 2012.

Zhang, D. F., Zakey, A. S, Gao, X. J., Giorgi, F., and Solmon, F.: Simulation of dust aerosol and its regional feedbacks over East Asia using a regional climate model, *Atmos. Chem. Phys.*, 9, 1095–1110, doi:10.5194/acp-9-1095-2009, 2009.

Zhou, T. J, Yu, R. C.: Twentieth century surface air temperature over China and the globe simulation by coupled climate models, *J. Clim.*, 19(22): 5843-5858, 2006.