Response to **Anonymous Referee #2** 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 offered 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 #2 (Comments to Author)

General comments: The authors use an RCM in order to investigate the effect of Tibetan Plateau dust sources on the East Asian Summer Monsoon (EASM). They find that removing the desert cells in Tibet reduces precipitation and generally weakens the EASM. The subject of the study is interesting and original, the presentation is clear (but a little lacking in depth) and the flow is smooth. There are a few major points that need to be clarified or otherwise addressed before the paper is accepted.

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 the 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.

Specific comments in order of appearance :

p.1, l.24: "dust ... accounts for about half of all the aerosols". By mass? This is not supported from Table 1 of the Chin et al. 2002 reference.

Yes. Dust aerosol has the largest emissions (1500 Tg/yr) and abundance of mass (32.2 mg/m^2) compared to other aerosols (IPCC, 1994). We overstated a little in the first draft. The wording was likely to lead to ambiguity; so we delete these words in our revised version (Page 1, Line 26).

p.5, l.10: The alleged supremacy of MISR over MODIS is justified based on only one paper which itself is based on only one AERONET station. The better agreement of MISR AOD with the specific station cannot be considered representative, see for example Bibi et al., 2015 (http://dx.doi.org/10.1016/j.atmosenv.2015.04.013) who show that MISR compares better with AERONET at two stations, and MODIS at the other two stations of the Indo-Gangetic plains. I wouldn't exclude MODIS from the analysis.

MODIS AOD has a large portion of missing data in Northwest China; so we only used the data from MISR. Our statement was inaccurate and thus we rephrased these sentences as below (Page 5, Line 14–22). We also used dust AOD from CALIPSO to evaluate our simulations (Page 7, Line 1–11).

level-3 monthly mean AOD data during 2000 to 2009 obtained from the Multiangle Imaging Spectroradiometer (MISR) onboard NASA's Earth Observation System Terra satellite (http://www-misr.jpl.nasa.gov/). Since MODIS AOD has a large portion of missing data in Northwest China, MISR was used to evaluate the simulated dust AOD in CON. The effectiveness of the MISR data was investigated by Martonchik et al. (1998, 2004) and Bibi et al. (2015).

p.6, l.20: It would be nice to include some statistics (correlation coefficient, bias, etc) in Figs. 4 and 5

Thanks. We added correlation coefficient in Figure 4 (Page 22) and Figure 5 in the revised version (Page 23).

p.7, l.13 and Fig.8: The widespread aerosol-induced cooling is quite impressive, but also raises questions. In much of the literature the direct radiative effect of dust is predominantly positive (warming) over land areas and becomes negative in specific situations like a large zenith angle (e.g. Quijano et al., 2000, J. Geophys. Res, 105(D10), 12207-12219). Specifically over Tibet, Chen et al. (2006) (reference in manuscript) show net aerosol warming. I would suggest that the authors explore more their derived aerosol cooling and provide information on the reasons *behind this behaviour. For example, is the LW cooling from dust particles so much larger than the SW warming? How much less absorbing in SW is Tibetan dust compared to dust from other locations? What are the optical properties of the dust emitted by Tibet?*

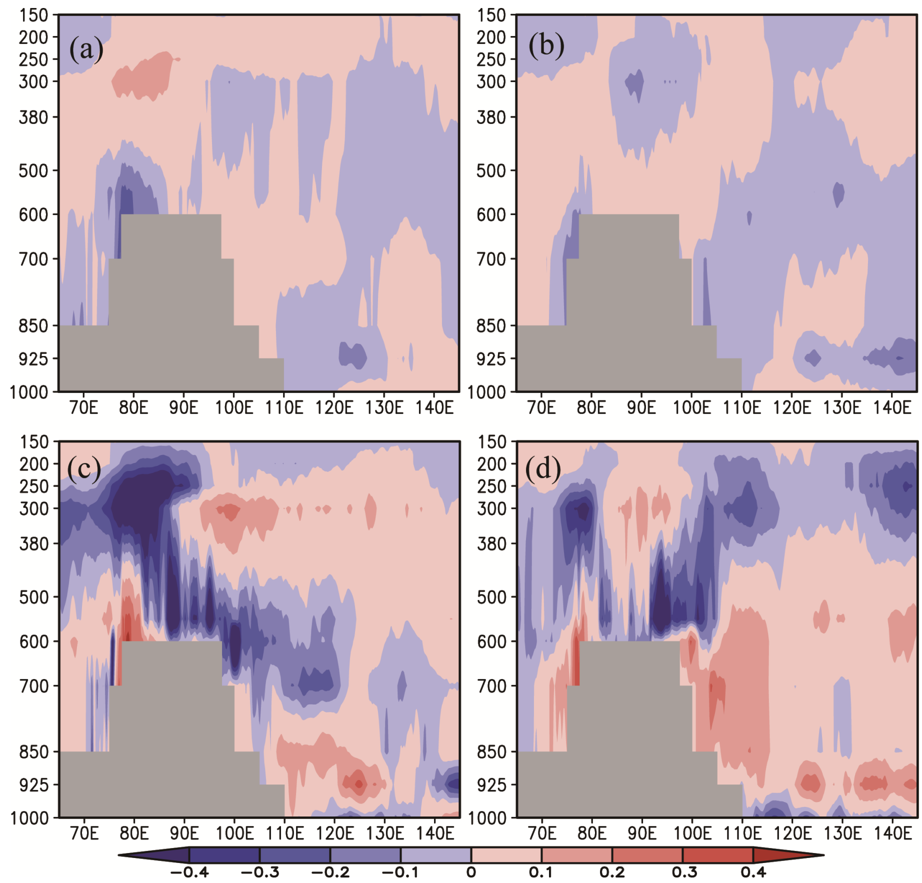

Figure B1 Longitudinal cross-section of the differences between CON and SEN averaged over 32–36°N in summer. (a) and (b): net short-wave heating rate (K day^{-1}). (c) and (d): long-wave cooling rate (K day^{-1}) in heavy (a, c) and light dust years (b, d) respectively.

We deeply appreciate this great suggestion. We agree that direct radiative effect of dust is predominantly positive over land areas in most of previous reports (Zhang et al., 2013; Chen et al., 2013). We further examined differences in the dust AOD between day and night over the TP using the pure dust observation from CALIPSO and found that the observed dust AOD at night is higher than that during daytime over the TP (Figure 6b and 6c), which means that the dust over the TP is more active at night than daytime. Therefore, SW warming is much weaker than LW cooling (Figure B1). We noted the positive (warming) effects reported by Chen et al., (2013), but their results included the effects of other strong absorbing aerosols such as black carbon. Besides, they did not exclude contribution of other dust sources including that from the Taklimakan and the Gurbantunggut Desert to the north of the TP and that from the Great Indian Desert to the south of the TP. The warming effects in their study may be caused by black carbon or the dust aerosols from Taklimakan during daytime, but the cooling effects in our study is mainly caused by the dust aerosols emitted from the TP at night. We added comparison between the simulated and CALIPSO observed dust AOD in the revised version (Page 7, Line 1–11), and discussed the differences (Page 10, Line 7–16) between our simulations and those of simulated by Chen et al., (2013). The following texts and Figures 6 are added in the new version.

3.1.4 Simulated and CALIPSO-observed dust AOD comparison

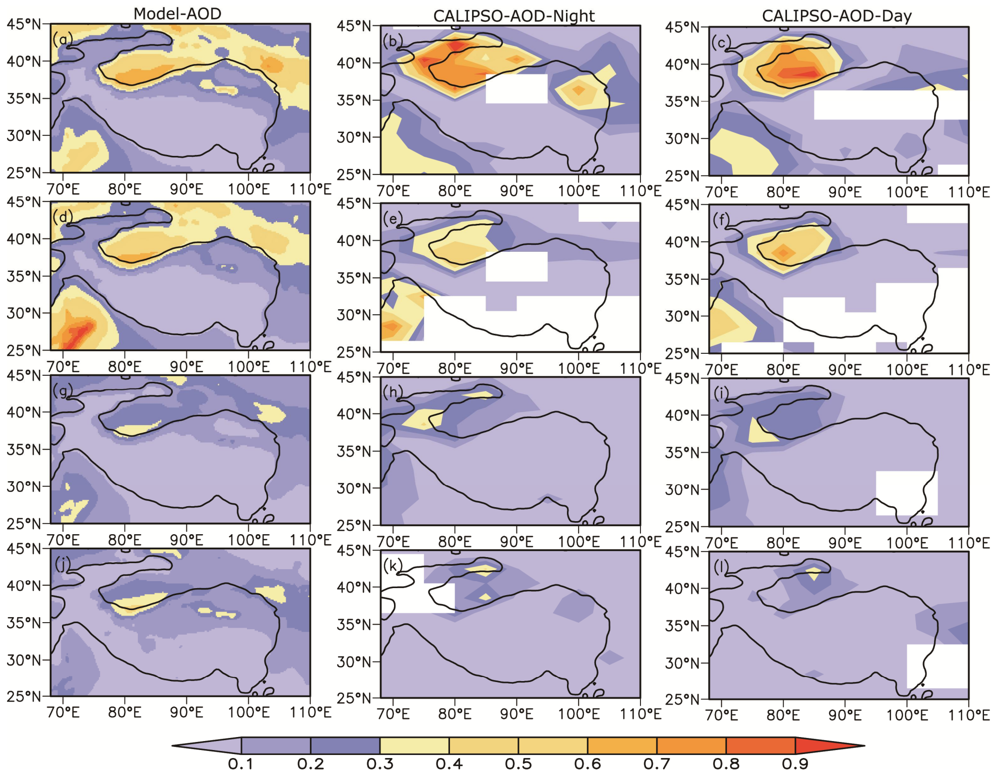

Figure 6: Spatial distribution of the dust AOD simulated by the control experiment (left panels) and observed by CALIPSO at night (middle) and during daytime (right panels) averaged in (a, b, c) spring, (d, e, f) summer, (g, h, i) autumn and (j, k, l) winter during the time period 2007–2009.

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 implies 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 the subsequent section of 3.4.1

Dust direct radiative effect is reported predominantly positive (warming) over land areas in most of previous researches (Zhang et al., 2013; Chen et al., 2013), but it can become negative under specific situations like a large zenith angle (Quijano et al., 2000). It is interesting to note that it can also become negative when dust activities are mainly vigorous at night over the TP. The observed dust AOD at night is much higher than those of during daytime over the TP (Figure 6b and 6c); so the SW warming effects is quite weaker than the LW cooling effects (figures not shown). The simulations of Chen et al., (2013) included strong absorbing aerosols such as black carbon and included contribution from other dust sources such as the Taklimakan and the Gurbantunggut Desert to the north of the TP and that from the Great Indian Desert to the south of the TP; thus the warming effects of dust aerosols reported in their study is broader. In contrast, the cooling effects in our study is mainly caused by the dust aerosols emitted from the TP at night.

p.7, l.18: It would be interesting to see why the dust generates this downward motion.

Geopotential heights (at 600 hPa) increased in most of land in East Asia (Figure 11a), and the downward motion induced by the LW cooling of dust over the TP is enhanced (Figure B1 C). The following texts (Page 8, Line 10–11) were added in the discussion of revised version.

The enhanced descending motion was induced by the LW cooling effects of dust over the TP (figures not shown).

Fig.9: How does the Tibetan dust cause cooling over central India only during the light dust years? I'm afraid that using heavy and light dust years introduces aerosol unrelated interannual variability that complicates the picture. It would be much better if it were possible to tweak the dust productivity directly (please see below).

Thanks for pointing this out. Interaction of aerosols with EASM is very complicated, and many factors can influence the monsoon. Contribution of dust aerosol to the monsoon variability may be only a small part. Perhaps the dust effects is significant only in the heavy dust years or monsoon anomaly years. Therefore, we focus on the heavy and light dust years. Because of less dust aerosol in the light dust years, the cooling over central India may be caused by the model's internal variability (Figure B2 a). We explained this in the revised version as below (Page 10, Line 17–22).

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 (figure not shown). Therefore, the dust effect 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.

p.7, l.27 and Fig 10: As mentioned also by referee #1, the anticyclonic activity might be better visualized through geopotential heights.

Thanks for the suggestion. We updated the figure and rephrased this part, Please see Section 3.4.2 (Page 8, Line 19–25)

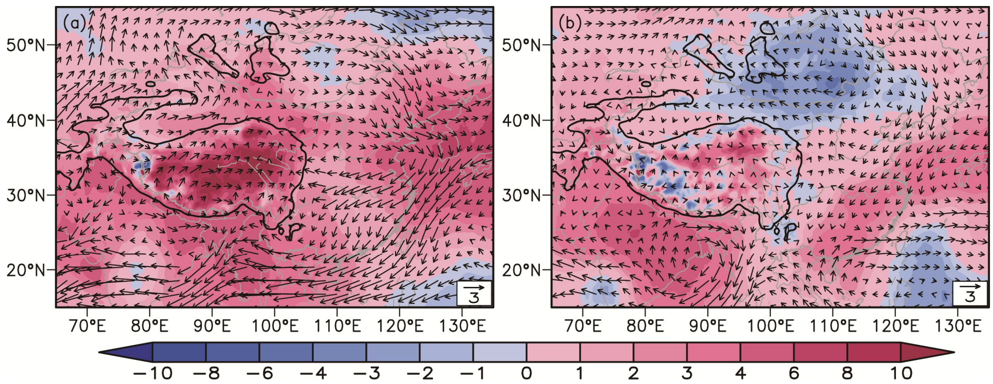

Figure 11: Simulated difference in atmospheric circulation at 850 hPa (vector, m s^{-1}) and geopotential height at 600 hPa (shaded, m) in summer between CON and SEN in (a) heavy and (b) light dust years.

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).

p.8, l.15 and Fig.12: If I understand correctly, this difference in the EASM onset is rather marginal and probably circumstantial. For example if the value 5.5 were selected instead of 6, then the CON experiment shows earlier onset. The aerosol-induced delay of the EASM does not seem like a robust result.

Yes. Result 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 future.

Section 3.4.3: I think it would be interesting to show the change in precipitation with a Figure similar to Figs. 9 and 10. Also, there is no mention of precipitation changes in the north monsoon region.

Thanks for the suggestion. We updated this part with a new figure for precipitation change similar to temperature and rephrased this part. Precipitation in the northern monsoon regions was also suppressed by the dust. Please see Section 3.4.2 (Page 8, Line 26–31, and Page 9, Line 1–3).

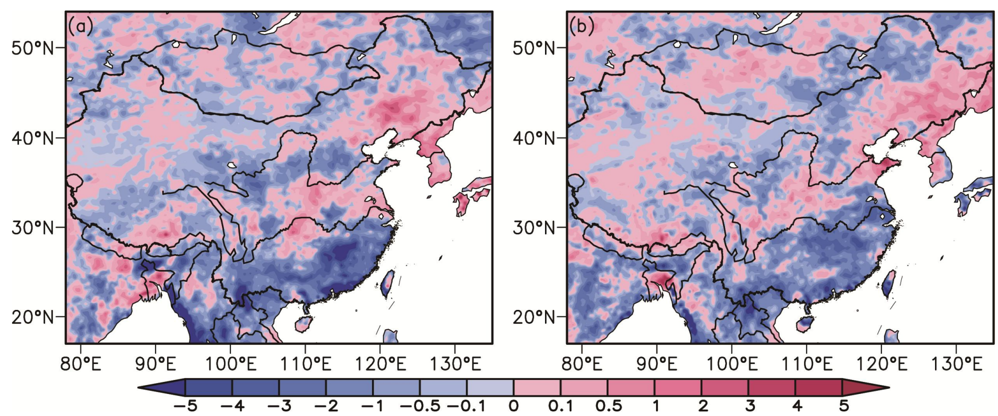

Figure 12: Simulated difference in summer precipitation between CON and SEN in (a) heavy and (b) light dust years.

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 in the heavy dust years as a result of weakening of the 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 aerosol 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.**

A general remark: The authors focus on heavy and light dust years in order to evaluate the EASM sensitivity to aerosol emissions. Relying only on the heavy/light year classification, the problem retains the interannual variability from irrelevant factors such as the meteorological fields. Instead of (or maybe complementary to) the heavy/light year experiment, I would try reducing or increasing by specific percentages (e.g. 10%- 100% in steps) the dust emission from the surface of Tibet, through modifications in the dust module. Then I would try to present the "climatological" 20-yr average change. I am not experienced with RegCM and do not know if these modifications are easy, so this is more suggestion than a requirement. This suggestion touches also on the valid problem (already pointed out by referee #1) of removing dust by substituting desert cells by vegetated ones. Except the aforementioned albedo changes, there could be other unwanted interferences to the aerodynamic resistances and land-air interactions. I would think that the tweaking of dust emission through modifications of e.g. Eqs. 2, 3 in the dust module would be a much better technique.

We deeply appreciate this remark and thanks for the great suggestions. On one hand, the interaction of aerosols and EASM is very complicated, and there are many factors that can influence the monsoon. Contribution of dust aerosol to the monsoon variability may be only a small part. Perhaps the dust effect is significant only in the heavy dust years or strong monsoon years. Therefore, we focused on the heavy and light dust years. We agree that the meteorological fields could influence the results, especially in the light dust years with less dust aerosol. Thus, 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 (Figure B2). 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 (Page 10, Line 17–22).

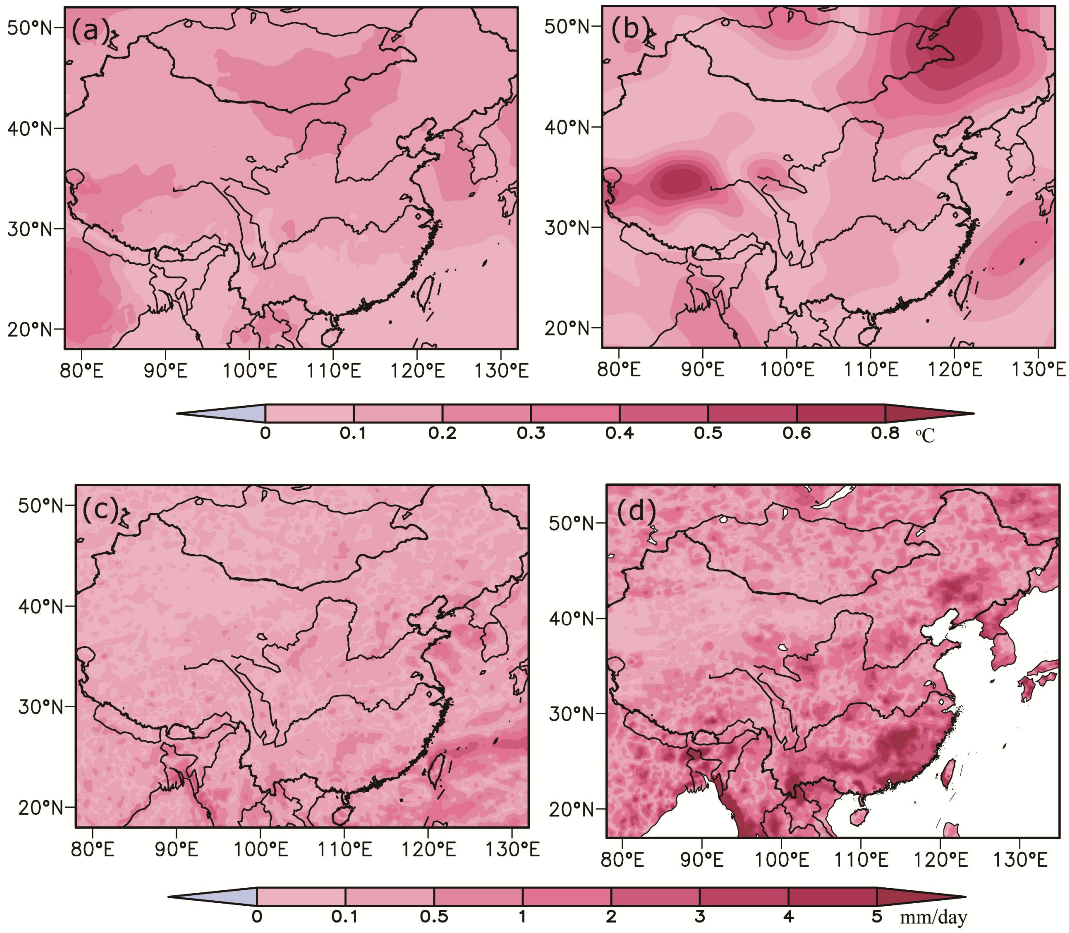

Figure B2 Standard deviation of summer surface temperature (a) and precipitation (c) in CON, and differences (absolute value) of summer surface temperature (b) and precipitation (d) between CON and SEN during the heavy dust years.

On the other hand, we agree that our method to turn off the dust emission in the TP is imperfect, and it will bring uncertainty to the results. Therefore, we carried out two new sensitive experiments to isolate effects of the changed land cover alone. Dust cycle in the two experiments is turned off, but the land cover is changed into one similar to the modification in SEN. The differences between them only include effects of the changed land cover. The results showed that the change (from desert to vegetated land) brought about 0.4 °C warming (Figure B3 and Figure B4), and this warming effect is weaker than the combined cooling effects (–0.6°C) induced by the dust aerosols and the changed land cover together. Besides, we have noted that Li and Xue (2010) 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 a warming effects. This is opposite to the cooling induced by the dust aerosols over the TP in our simulation, and it may partly offset the dust aerosol induced cooling effects. However, our results show that the signal of cooling effect is not changed and it may be even underestimated in the heavy and light dust years. Therefore, actual cooling should be stronger than the simulated value. We admit that turning off the dust emission through modifications of Eqs. 2, 3 in the dust module would be a much better choice but it would be difficult to carry out given the short time frame. It is definitely worth trying in the future. We added discussion (Page 10, Line 22–34, and Page 11, Line 1–2) about uncertainty brought by the method used in this paper. The following texts were added in the discussion of the revised version.

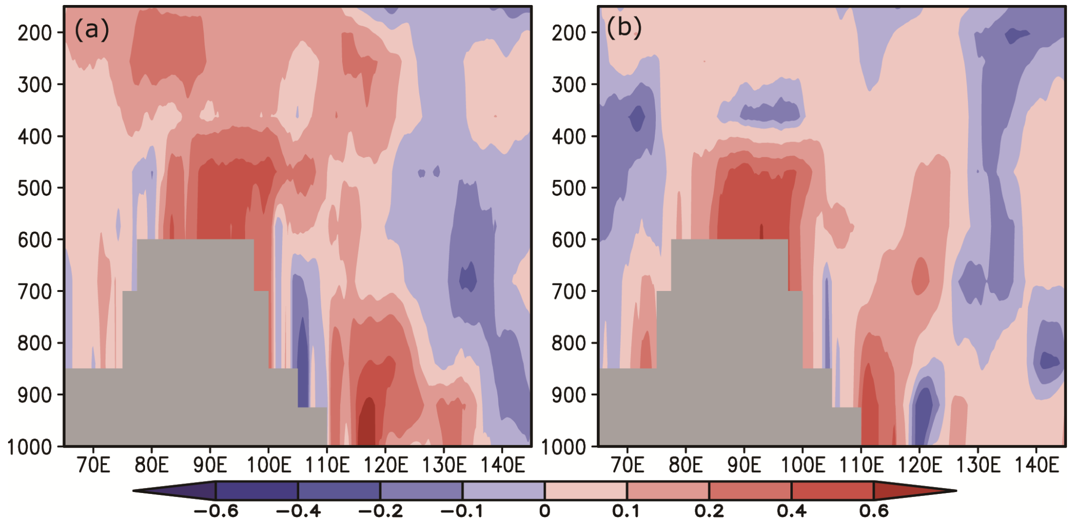

Figure B3 Longitudional-height cross-section of atmospheric temperature anomaly induced by the land cover changed averaged over 32–36°N in summer in heavy (a) and light (b) dust years.

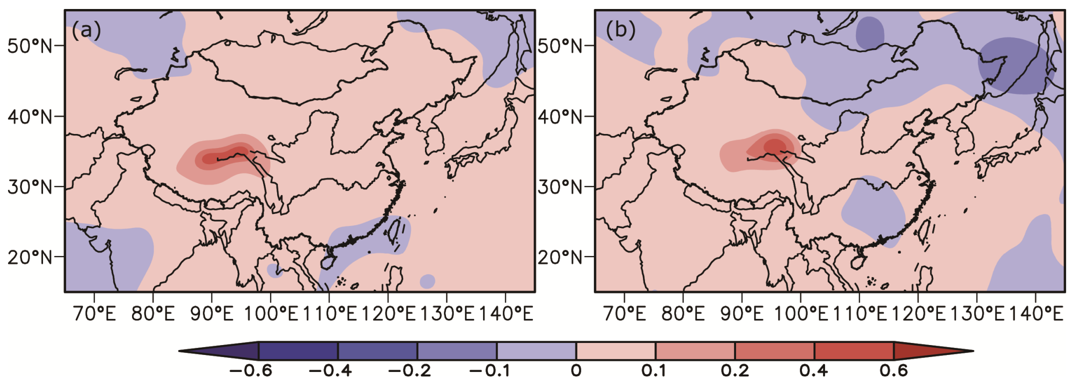

Figure B4 Summer temperature change induced by the land cover change in (a) heavy and (b) light dust years.

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 effect 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. 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 addition sensitive experiments to isolate effects of the changed land cover alone. Dust cycle in the two experiments was turned off, but the land cover was changed into the one similar to the modification in SEN. The differences between them only included effects of the changed 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 effects (–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) 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 mean 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 aerosol-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.

Technical corrections:
My rather trivial corrections are listed below
p.1, l.20: Please use "stationary" instead of "stationery"

Taken care of. Thanks for the catch. (Page 1, Line 22)

p.1, l.26: Here "dust emission" is slightly better than "dust load".

Taken care of. Thanks for the catch. (Page 1, Line 27)

p.1, l.29: Please use "drivers of" instead of "drivers on".

Taken. Thanks for the catch. (Page 2, Line 1)

p.2, l.24: Please use "Gurbantunggut" instead of "Gubantunggut".

Taken care of. Thanks for the catch. (Page 2, Line 24)

p.2, l.27: Please use "elevated" instead of "elevate"

Taken care of. Thanks for the catch. (Page 2, Line 28)

p.4, Eq.4: χ and v are never defined

They are defined in the revised version as below (Page 4, Line 14).

χ is the dust mixing ratio, $\overline{V}$ is vector wind.

p.6, l.27: Please correct "respevtively" to "respectively"

Corrected. Thanks for the catch. (Page 6, Line 17)

p.9, l.22: Please use "spatiotemporal" instead of "spatiotemporal spatial"

Corrected. Thanks for the catch

Reference

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