Review of "Snow-darkening versus direct radiative effects of mineral dust aerosol on the Indian summer monsoon: role of the Tibetan Plateau" by Shi et al.

This paper examines the dust snow-darkening (SDE) and direct radiative effects (DRE) on Indian summer monsoon (ISM) with global climate model simulations. The authors found that dust SDE (DRE) tends to induce a warming (cooling) over Tibetan Plateau, and weakens (intensifies) the ISM. The main findings of this manuscript are contradictory to previous studies, but the authors did not provide convincing explanations. Thus, this manuscript needs careful revisions to meet the standard of Atmospheric Chemistry and Physics and resubmitted.

RE: Thanks for the comments. The reviewer said that the main findings of our paper are contradictory to previous studies. But we do not agree with the reviewer's viewpoint although we admit that some inaccurate arguments in the original manuscript may mislead the readers. We overemphasized the role of Tibetan Plateau in the original manuscript and it is actually not accurate based on new experiments and results.

We agree with the reviewer that we did not provide convincing explanations previously, thus, we conducted three additional experiments, with a special focus on black carbon. The aim is to examine whether the SDE and DRE of black carbon is similar with mineral dust or not. In most previous studies, black carbon is mainly considered to understand the effect of absorbing aerosols but mineral dust is indeed different from black carbon both for spatial distribution and radiative effect. Fortunately, the black carbon experiments tell that the SDE and DRE both intensify the Indian summer monsoon during the onset, which are in good agreements with previous studies (e.g., Lau et al., 2006; Qian et al., 2011).

The SDE of black carbon warms the surface over Tibetan Plateau (TP) and intensifies the monsoon during the onset, consistent with what were found in Qian et al (2011). Interestingly, the same model with the SDE of dust gives a quite different response of monsoon, which indicates different mechanisms behind SDE of dust and black carbon. As we proposed, the spatial distributions of dust and black carbon are not similar. The main difference is that black carbon from the industrial countries is generally transport eastwards and scarcely into upwind Central Asia. Central Asia is also covered by snow although far less than TP. As a result, the forcing of black carbon is restricted to TP but the forcing of dust is over Central Asia and TP. Westwards/northwestwards expansion of warming also shifts the pattern of low level circulation change, which weakens the summer monsoon.

The DRE of black carbon also warms the surface over the TP and intensifies the monsoon during the onset, consistent with Lau et al. (2006). Although the 3D distribution of black carbon are not the same, our experiments also support the DRE of black carbon can strengthen the monsoon. Comparing the responses to dust and black carbon under the same model and experiment design, we found that the summer monsoon during the onset is both intensified no matter whether it is warming or cooling over the TP. As the reviewer said, the TP cooling is unlikely to intensify the monsoon (at least few evidence support it). We agree it and ascribe the monsoon strengthening to the warming over Arabian Peninsula/Middle East, which also gains strong support from previous researches (Vinoj et al., 2014; Jin et al., 2014; Solomon et al., 2015). Although the TP cooling tends to weaken the monsoon, the Middle East warming overacts and induces a stronger monsoon instead. In addition, the simulated TP cooling might be model dependent because DRE of dust is largely uncertain and depends closely on the size distributions, optical properties and etc (Kok et al., 2017). Anyway, our results support the important role of Middle East warming.

To summarize, we found different mechanisms for Indian monsoon to dust and black carbon forcing. The significant contributions from temperature changes over source areas (Central Asia for SDE and Middle East for DRE, respectively) are highlighted. The role of TP we proposed previously is not accurate. In the revision, we removed it and changed to "role of dust source temperature changes". Detailed results and responses are shown in the following. We wish the current version of manuscript could give more convincing results and arguments.

Major comments:

The Indian summer monsoon is primarily driven by the thermal contrast between land and ocean (Wang et al., 2000). The up troposphere meridional temperature gradient south of Tibetan Plateau is one of the key controls of the Indian summer monsoon (Li and Yanai, 1996). An up troposphere warming over TP tends to increase the meridional temperature gradient, and intensifies the Indian summer monsoon (Wu et al., 2005; Liu et al., 2001). Previous studies show that both DRE and SDE of absorbing aerosols could induce a warming around TP and intensify the Indian summer monsoon (EHP effect), which is in general consistent with the observed relationship. In this study, however, the authors found the Indian summer monsoon is intensified (weakened) associated with cooling (warming) over TP, which is just opposite to previous studies. The authors should carefully check the model settings and give some explanations.

RE: Please see the next two comments for detailed explanations.

The authors found that the dust SDE induced TP warming tends to weakens Indian summer monsoon, which is opposite to what found in Qian et al. 2011. The authors stated that the opposite response is due to the difference in TP warming center distribution. Lau et al. 2010 found that aerosol SDE could produce an "elevated-heat-pump (EHP)" effect and increase the precipitation over Indian in May. Their results is in generally consistent with Qian et al. 2011, although the warming center is over western TP. The authors should provide convincing explanations why the response to dust SDE in this study is contradictory to previous studies.

RE: Yes. From previous studies (e.g., Lau et al., 2010; Qian et al., 2011), it can be obtained that the SDE of black carbon or all absorbing aerosols intensifies the Indian monsoon, which is different from what we simulated for dust. We pointed out that our study is not contradictory to previous studies because our study merely focused on dust and the spatial distribution of dust is different. In our opinion, the key point is that we can not directly compare our results and previous studies. Thus, we conducted three additional experiments, with a special focus on black carbon, to support our study. The aim is to examine whether the SDE and DRE of black carbon is similar with mineral dust or not.

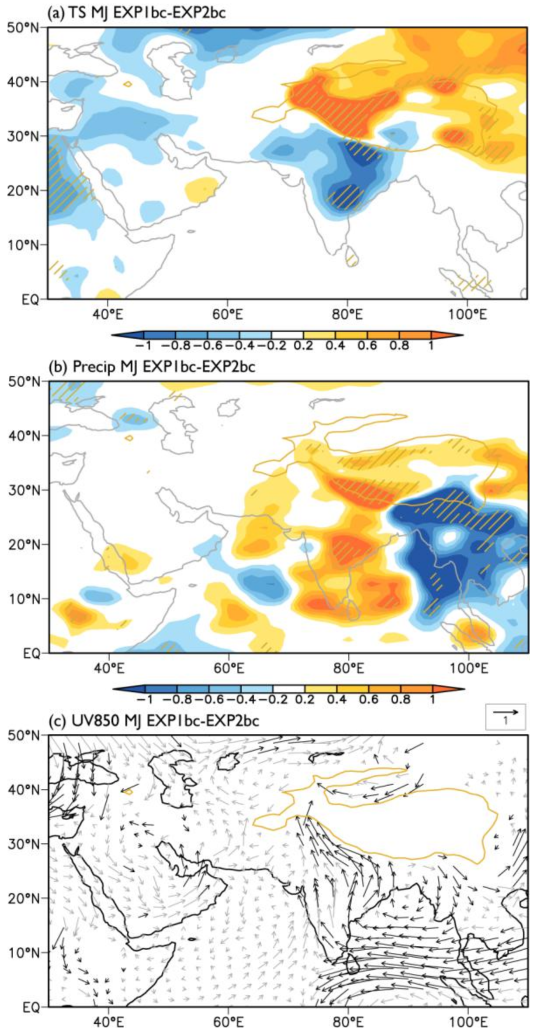

Figure R2: Spatial distribution of changes in precipitation rates (a, mm day^{-1}), surface temperature (b) and 850hPa wind vectors (c, m/s) in May and June induced by snow-darkening effect of black carbon.

The SDE of black carbon warms the surface over western TP only, with a cooling over northern India (Figure R2a). The southerly winds and precipitation over India are significantly larger (Figure R2b, R2c), which indicates that the summer monsoon is intensified during the onset. This is consistent with what were found in Qian et al (2011), which proves that our experiments are not contradictory to previous studies on black carbon.

However, the same model with the SDE of dust (not specifically focused) gives a quite different response of monsoon, which indicates different mechanisms behind

SDE of dust and black carbon. As we proposed, the spatial distributions of dust and black carbon are not similar. The main difference is that black carbon from the industrial countries is generally transport eastwards and scarcely into upwind Central Asia. Central Asia is also covered by snow although far less than TP. As a result, the forcing of black carbon is restricted to western TP but the forcing of dust is over Central Asia and western TP. These differences in surface warming by dust and black carbon are also simulated in the experiments by NASA Goddard Earth Observing System Model (Yasunari et al., 2014).

The SDE of dust induces significant warming over western TP and Caspian Sea in Central Asia (Figure 5c), which leads to two cyclonic anomalies over these two regions (Figure 6a). These two cyclonic anomalies intensify the northern branch of Indian monsoon westerly, allowing more dry air from Central Asia penetrating into the monsoon region. But the southern branch of the monsoon westerly is decreased with the associated anticyclonic anomaly over Arabian Sea and India, which weakens the moisture transport from oceans in the south.

There is no doubt that the important role of TP temperature change in Indian monsoon development (Li and Yanai, 1996; Wu et al., 2005; Liu et al., 2001), as the reviewer said. We did not argue against it, however, the role of dust source temperature (not mentioned before) is highlighted from our results. We put Figure R2 in the supplement and largely revised the manuscript (Page 6 Lines 14-17, 21-26; Page 7 Lines 3-8, 13-16, 24-28; Page 8 Lines 4-6, 9-11, 29-35; Page 9 Lines 6-9, 18-29; Page 10 Lines 23-28). Some paragraphs in the original text are deleted. We do not show these intensive revisions here and please see the text.

The dust DRE impacts on Indian summer monsoon is also inconsistent with previous studies, and the results are difficult to understand. The authors found dust DRE could induce a significant cooling over TP, and the cooling is attributed to snow-albedo feedback. The dust AOD is very small over TP (less than 0.05), which implies very weak DRE. How such small DRE produce strong snow-albedo feedback over TP? The feedback processes should be detailed explained. More confusing thing is that the Indian summer monsoon (ISM) is intensified associated with the TP cooling, which is similar to the response induced by TP warming (Lau et al., 2006). The authors simply explained it as a response to downward motion right over TP, which is not convincing. Please provide detailed explanations and supportive reference.

RE: Our black carbon experiments show that the DRE of black carbon can strengthen the monsoon, consistent with Lau et al. (2006). A surface warming over western TP is simulated (Figure R3a). The warming is also over northern India although it is not significant. This effect strengthens the southwesterly winds over the Arabian Sea and moisture transport from ocean (Figure S2b) and the precipitation is intensified over the Arabian Sea and southern India (Figure S2c). These results support that the warmer TP intensifies the monsoon, agreeing with traditional viewpoints (Li and Yanai, 1996; Wu et al., 2005; Liu et al., 2001).

However, comparing the responses to dust and black carbon under the same model and experiment design, we found that the summer monsoon during the onset is both intensified no matter whether it is warming or cooling over the TP. Since the TP cooling is unlikely to intensify the monsoon (at least few evidence support it). We agree it and ascribe the monsoon strengthening to the warming over Arabian Peninsula/Middle East, which also gains strong support from previous researches (Vinoj et al., 2014; Jin et al., 2014; Solomon et al., 2015).

The Arabian Peninsular warming (Figure 5d) induces a local cyclonic anomaly (Figure 6b). The northern branch of monsoon westerly is remarkably reduced in its intensity across the southern slope of the TP, the Persian Gulf and northern Arabian Peninsula (Figure 6b). The southern branch of Indian monsoon westerly over Arabian Sea is simulated to be stronger, which intensifies the water vapor transport from oceans. Although the TP cooling tends to weaken the monsoon, the Middle East warming overacts and induces a stronger monsoon instead. From an observation study, the heating and intensified high pressure cell over Arabian Peninsula is proved to be an important factor affecting the onset of Indian monsoon (Zhang et al., 2014). Thus, based on the new results, we do not emphasize the role of TP and propose the role of dust source temperature in the revision (Page 6 Lines 18-19, 29-33; Page 7 Lines 8-11, 17-18, 28-30; Page 8 Lines 19-21, 29-35; Page 9 Lines 10-14; Page 10 Lines 9-16, 23-28). Figure R3 is also put in the supplement. Some paragraphs in the original text are deleted. We do not show these intensive revisions here and please see the text.

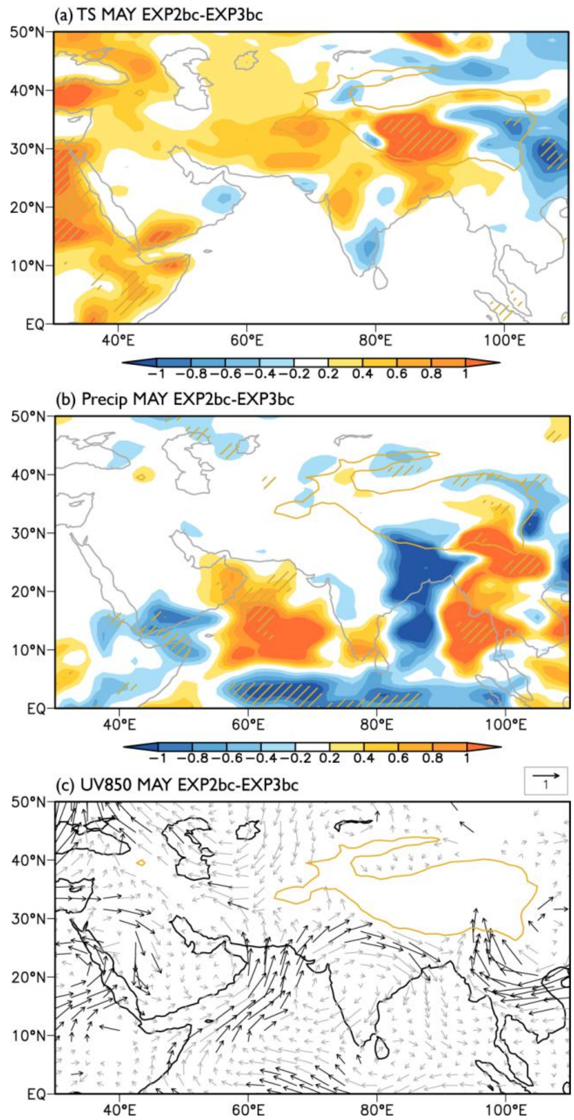

Figure R3: Spatial distribution of changes in precipitation rates (a, mm day-1), surface temperature (b) and 850hPa wind vectors (c, m/s) in May induced by direct radiative effect of black carbon.

For the simulated large cooling over TP, we only found in our analysis that the snow albedo feedback amplifies the response of temperature to small dust forcing. Certainly, we can not deny the possible role of other feedbacks. In addition, compare to that of black carbon, the DRE of dust on temperature is largely uncertain (Kok et al., 2017).

In this study, the CAM4 was run with prescribed climatological SST and sea ice. The SST response to aerosol forcing (slow response) is not taken into account. Many previous works showed that the slow response can play a dominant role in the total response of Indian summer monsoon to aerosol forcing (Ganguly et al., 2012). Many previous studies investigated dust impacts on ISM with coupled simulations (e.g. Qian et al, 2011). It could be a possible reason why the monsoon response is opposite to previous studies. Thus, the authors should run coupled simulations and make a comparison with current results.

RE: Thanks for the comments. We agree with the reviewer that the slow response of ocean may make the response more complicated. However, due to the limited time of final response phase, it is difficult for us to conduct addtional coupled model simulations, which are always integrated for hundreds of years for quasi-equilibrium. More importantly, three atmospheric GCM experiments focused on black carbon were conducted to support our arguments. The results strongly support the distinct forcing of black carbon and dust on the Indian monsoon via different mechanims, as we said in responses above.

In the revision, we cited the references and emphasized the possible role of slow ocean processes (Page 4 Lines 27-29): "Due to the limit of calculation resource, we only conducted atmospheric model experiments in this study and coupled ocean-atmosphere model experiments are not included. Actually, slow ocean response can play a dominant role in the response of Indian summer monsoon to aerosol forcing (Ganguly et al., 2012)."

This study investigates the dust impacts on Indian summer monsoon. However, only the dust effect during the monsoon onset periods (May and June) is investigated. The Indian summer monsoon is from June to August (or September). Please show the monsoon response in July and August, for the dust concentration is still high in Indian at that time (Gu et al., 2016). The response of ISM could be quite different in July and August, for dust DRE impacts could be more important at that time. Only with an examination of the response in entire monsoon period, the title of this manuscript could be appropriate.

RE: Thanks. The response of monsoon during its mature period (July-September) to DRE and SDE of dust is also important. However, these changes in the precipitation and low-high level circulation are similar but complicated, and also not as significant as those during the onset, possibly because the monsoon onset is more sensitive to radiative and temperature changes. Lots of previous studies indicated the sensitive responses of monsoon onset to external forcing, e.g., the sensible heat changes over TP or to its southwest (e.g., Li and Yanai, 1996; Wu and Zhang, 1998; Wu et al., 2012), in agreement with our study. To be accurate, as the reviewer commented, we revised our title to "Indian summer monsoon onset" in the revision.

Other comments:
Page 1, Line 2："have" should be "has".

RE: Corrected.

Page 4, Line 6-7： Please give more explanations on "snow-darkening and direct radiative feedbacks". Does it mean the permit of dust snow-darkening and direct radiative effects in simulations? What is the meaning of feedback?

RE: Yes. We meant the snow-darkening and direct radiative effects are considered in the experiments. We revised the sentence (Page 4 Lines 10-11).

Page 5, Line 13: Please provide references for the two branches of Indian summer monsoon.

RE: A reference is added here (Wu et al., 2012).

Page 5, Line 25: If EXP1-EXP2 equals to the impacts of dust SDE, please use the dust SDE in the rest of manuscript for consistency. So do the cases for EXP2-EXP3.

RE: We used SDE and DRE instead.

Page 5, Line 26: Please clarify the definition of "Indian monsoon area".

RE: We specified the region (10-25°N, 65-100°E) in the text (Page 6 Line 1).

Page 5, Line 28: Indian summer monsoon lasts from June to August. Please show the precipitation change in July and August, as well.

RE: As we responded previously, we changed the title to "... Indian summer monsoon onset". Thus, in the revision, we still showed the monsoon response in May and June.

Page 6, Line 9： Why dust SDE induces significant cooling over Tibetan Plateau? The dust AOD is very small over Tibetan Plateau.

RE: We think here the reviewer means DRE (not SDE). In this paper, the DRE-induced cooling over Tibetan Plateau is explained by the snow-albedo feedback. We do not find the important contributions from other processes in our analyses. More importantly, based on the new results, we do not emphasize the role of TP in the revision. Thus, we turn our eyes on the new-proposed role of dust source temperature and give detailed explanations on this point.

Page 6, Line 15： Why is the southern branch of the monsoon westerly significantly decreased？

RE: We found that surface temperature becomes warmer over most Asia, which responds to the SDE. The most obvious warming is found over western TP where the surface snow cover is larger. Another significant warming center is around Caspian Sea in Central Asia also with certain snow covers at this time.Following the temperature changes, a significant cyclonic anomaly is simulated over western TP and there is also a cyclonic anomaly around the Caspian Sea. These two cyclonic anomalies tends to intensify the northern branch of Indian monsoon westerly, allowing more dry air from Central Asia penetrating into the monsoon region. However, the southern branch of the monsoon westerly is significantly decreased due to the associted anticyclonic anomaly over Arabian Sea and India.

We emphasized it in the revision (Page 6 Lines 21-26): "In the SDE-induced difference, a significant cyclonic anomaly is simulated over western TP and to its west there is also a cyclonic anomaly around the Caspian Sea (Figure 6a), following the surface temperature changes (Figure 5c). These two cyclonic anomalies tends to intensify the northern branch of Indian monsoon westerly, allowing more dry air from Central Asia penetrating into the monsoon region. However, the southern branch of the monsoon westerly is significantly decreased with the associated anticyclonic anomaly over Arabian Sea and India, which weakens the moisture transport from oceans in the south."

Page 8, Line 10: Please show the dust snow forcing (outputted by SNICAR), dust deposition (dry and wet), and dust concentration in snow over TP and their seasonal variation. A comparison with previous studies (e.g., Qian et al., 2011) is also needed.

RE: We analysed the suggested variables and the results are shown in Figure R4. It is clearly seen that the dust deposition flux and concentration in top snow layer reach its peak in boreal spring. The forcing (as shown by changes in surface radiation, snow cover fraction and albedo) due to SDE of dust is maximal during April-June, the vital period for snow melting. The peak of dust forcing lags the deposition by about one month, which indicates the memory effect of snow processes. The seasonality of dust deposition and dust snow forcing is similar with previous studies, supporting that our experiments are reasonable. Due to the change of our emphasis, these changes over TP are not added to the revision.

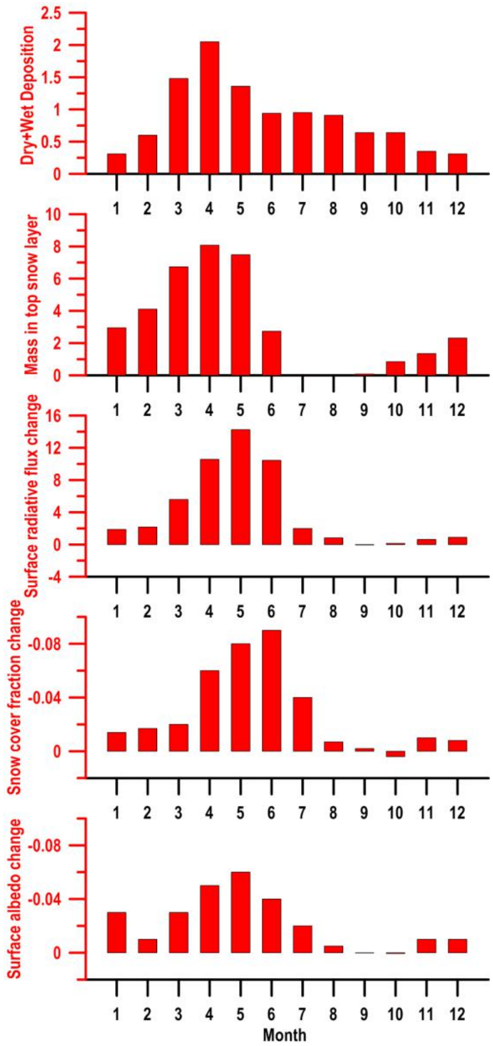

Figure R4: Total dust deposition fluxes and mass of dust in top snow layer in EXP1 experiments and the changes in surface radiative fluxes, snow cover fractions and surface albedo due to SDE of dust averaged for the TP region (70-90°E, 30-45°N)

Page 8, Line 23: Please explain the feedback.

RE: We meant the snow-albedo feedback here based on our analyses.

Page 8, Line 23: Dust aerosols could absorb both shortwave and longwave radiative fluxes. Why the longwave radiative flux change is negative?

RE: From our results, only the net longwave forcing for column atmosphere is negative. The reason is that the warmer atmosphere as a black body emits more longwave radiation, which exceeds over the absorbed amount. Previous studies also showed similar features for net longwave radiation change (Albani et al., 2014; Xie et al., 2018).

Page 8, Line 34: The dust AOD is very small over TP (less than 0.05), which implies very weak DRE. How such weak DRE produce significant snow cover increase and surface cooling over TP? It could not be simply attributed to snow-albedo feedback.

RE: In this paper, the DRE-induced cooling over Tibetan Plateau is explained by the snow-albedo feedback. We do not find important contributions from other processes in our analyses. More importantly, based on the new results, we do not emphasize the role of TP in the revision. Thus, we turn our eyes on the new-proposed role of dust source temperature and give detailed explanations on this point.

Page 9, Line 19-30: In Lau et al. 2010, they found that TP warming tends to increase the Indian precipitation in May, and the warming center is located at western TP. Their result is consistent with Qian et al. 2010, but different with the results of this manuscript. Explanations are needed here.

RE: Please see Figure R2 and the associated response.

Page 10, Line 12: How could downward motion right over TP induce an upward motion over Indian？ Is it noticed any previous studies? Please provide more explanations as well as the references.

RE: Thanks. We revised this assertion because we do not have enough evidence. As we discussed in other responses, the TP cooling and downward motion may be not closely associated with the intensified monsoon and upward motion over India. In the revision, we ascribed the intensified monsoon to the warming over Arabian Peninsula, which gains strong support from previous studies (Vinoj et al., 2014; Jin et al., 2014; Jin et al., 2015; Solomon et al., 2015).

Figures:
Figure 2 and Figure 3 could be put in the supplement, for they are too many figures for this manuscript.

RE: We kept Figure 2 and Figure 3 in the manuscript because we removed several figures in the revision. We will put them in the supplement if the reviewer still feels there are too many figures.

Figure 4：Please use the specific date in figure 4 (e.g. May 1st).
Figure 4：Please specify the regions of precipitation change.

RE: We changed the date and also specified the region (10-25°N, 65-100°E) in the caption.

Figure 5：Please display the precipitation and surface temperature with different color tables.

RE: We used different color bars.

Figure 5 and so on: Please show “SDE” and “DRE” in figure title.

RE: We used “SDE” and “DRE” instead of “EXP1-EXP2” and “EXP2-EXP3”, respectively.

Figure 5 to Figure 10: There are too many figures for this part. Decide what is important and put the rest in supplement.

RE: We removed original Figure 7, 10, 13 because we wish to avoid the repeating and also do not emphasize the TP temperature any more. Two new figures, showing black carbon’s related results, are added in the supplement.

References:

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