Dear Editor,

First of all, we would like to thank you and the two anonymous reviewers for valuable comments on our manuscript!

Below please find our point-to-point replies to the questions and suggestions from the two reviewers. Our replies are in the **bold blue**.

Reviewer #1

This paper, "Consistent response of Indian summer monsoon to Middle East dust in observations and simulations", investigates the magnitude and spatial structure of changes in precipitation over the Indian sub-continent in response to dust aerosol using observations and the WRF-Chem model. The authors attempt to clarify the conflicting dust-rainfall responses from previous studies (e.g. Vinoj et al. 2014, Solmon et al., 2015, Jin et al., 2014) and determine the mechanism via a suite of simulations within the WRF-Chem model.

This is a well-written paper with well constructed experiments leading to a convincing argument for the mechanism through which dust from the Middle East influences the precipitation. I have a couple of comments on the uncertainty and other minor issues, but other than that I recommend the paper for publication.

1. The uncertainty in dust refractive index is not explored within the research. As atmospheric heating is the key driver of the response in this study, it would be interesting to know how much the uncertainty in imaginary refractive index modulates the precipitation response. Has any effort been made to explore this?

- **We agree with the reviewer that the imaginary refractive index of dust aerosols plays a significant role in modulating the precipitation response in our study. We have designed additional experiments using various imaginary refractive indices of dust obtained from previous studies. The details of the impacts of imaginary refractive index are not the focus of this paper, and will be studied in a separate paper. Based on the preliminary results of additional experiments, we find that the precipitation response increases with increasing imaginary refractive index. The following table lists the average and standard deviation of precipitation responses to various imaginary refractive indices. We add the following text to the last paragraph of our manuscript to address the potential impacts of dust imaginary refractive index on the results:**

  "Three issues warrant further discussion. First, the hypothesis of the Middle East dust–ISM rainfall connection largely relies on the dust-induced atmospheric heating, which is primarily determined by the imaginary refractive index of dust aerosols in the climate model. However, the observed imaginary refractive index of dust aerosols is found to span a wide range from 0.001 to 0.008 at 600 nm (e.g. Colarco et al., 2014), while only one constant value is used in the WRF-Chem model. The uncertainties associated with dust imaginary refractive index may add uncertainties to the rainfall responses in the model simulations. This issue will be examined in

more details in our future studies." (The second and third issues are listed in the manuscript not included here).

Imaginary refractive index		**0.0**	**0.001**	**0.0022**	**0.003**	**0.0063**	**0.008**
Precipitation response (mm day^{-1})	**μ**	**−0.41**	**0.06**	**0.40**	**0.42**	**0.87**	**1.05**
	σ	**0.69**	**0.51**	**0.43**	**0.46**	**0.34**	**0.53**

2. The change in rainfall over India is quoted to be 0.44 mm/day for the ensemble mean. I think it is important to include the standard deviation for this, based on the ensemble members, to provide some context for the uncertainty relative to the quoted fractional change in precipitation (~10%).

- **The standard deviation of the ensemble mean of the rainfall responses based on the ensemble members is 0.39 mm day^{-1}. We added the standard deviation in our manuscript to indicate the uncertainty.**

3. pg 15577 ln 23 - are there any estimates for the uncertainty on these refractive indices values?

- **The imaginary refractive index of dust aerosols span a large range from 0.001 to 0.008 at 600 nm based on the previous studies (e.g. Colarco et al., 2014). We added text in the Dicussion and clusions part to address this concern.**

4. pg 15580 ln 29 - it might be more clear to say something like "each with and without dust aerosol" rather than "two dust options", when listing the ensembles.

- **We changed "2 dust options" to "2 options with and without dust emissions".**

5. pg 15581 ln 3 - should this be "RRTMG SW" rather than "RRTMG LW"?

- **No, it should be "RRTMG LW". Here, we want to clarify that only one longwave radiations scheme—RRTMG LW is coupled with chemistry.**

6. pg 15584 ln 9 - How do the 7% and 17% fractions of coarse dust relate to the improved and widely-used dust size distribution parameterization discussed in Kok et al. (2011)? This puts more dust mass at coarse sizes than traditional GCMs.

- **First, the 7% and 17% fractions of emitted dust mass are assigned to accumulation mode instead of coarse mode.**

- **We acknowledge that there are large discrepancies in particle size distribution of dust aerosols in both models and observations. Less than 5% of total dust emission is assigned into accumulation mode by Kok (2011) (Their Fig. 3). This could be another key contributor to the uncertainties in our modeling study, because smaller particles interact more efficiently with shortwave radiation and have longer lifetime.**

7. pg 15585 ln 1 - "To compare... with model simulations", this is a little confusing when the data shown in the figure is observational. Consider revising the wording.

- **We revised this sentence and changed it to:**
  "To evaluate the modeled rainfall responses, the regressed rainfall on the area-averaged AOD in the DST region is calculated based on satellite retrievals, as shown in Figure 5."

8. pg 15586 ln 9 - "Goddard and YSU, respectively"

- **We changed the corresponding text in the manuscript to "Goddard and YSU, respectively".**

9. pg 15589 ln22 - "previous studies", but only one reference is listed.

- **We changed "previous studies" to "a previous study".**

10. Figure 3 - Do you know how much of the difference between MISR and MODIS is explained through sampling differences with MISR generally having more than 5 times fewer retrievals?

- **Kahn et al. (2009) studied the correlation between MISR versus MODIS coincident AOD at about 550 nm for January, 2006. They found that the correlation coefficient could reach up to 0.9 over ocean and 0.7 over land. These correlations can give us a general idea about how sampling differences contribute to the difference between MISR and MODIS.**

11. Figure 7 - replace "donations" at the end of the caption with "descriptions"? I'm curious, do you get an even higher ensemble mean correlation coefficient if you average all members except the YSU PBL scheme that seems to perform poorly?

- **We replaced "donations" with "denotations" to keep it consistent with the caption of Figure 8.**

- **Yes, we get higher ensemble mean correlation coefficient when we exclude the YSU PBL scheme. We thank the reviewer's suggestion to calculate the correlation with the YSU PBL scheme excluded, which leads us to take a further look at SW scheme and aerosol chemical mixing rules. The following figure shows the pattern correlation coefficients between the regressed rainfall and modeled rainfall responses in the Indian subcontinent in each ensemble member as well as the ensemble means of several subgroups of ensemble members. Accordingly, we replaced the second paragraph on page 15586 with the following description of Figure 7b:**

  "Figure 7b illustrates the centered spatial correlations between the regressed rainfall pattern in Figure 5c and the ensemble means of rainfall responses in several subgroups of the ensemble members. Figure 7b shows the higher correlation coefficient of the regressed rainfall with the ensemble means of the ensemble

members using the BouLac PBL scheme (PB8) than those using the YSU scheme (PB1). The higher correlation coefficient is also found when using the RRTMG SW radiation scheme (SW4) than using the Goddard scheme (SW2). However, those correlation coefficients using the different aerosol chemical mixing rules show very little differences."

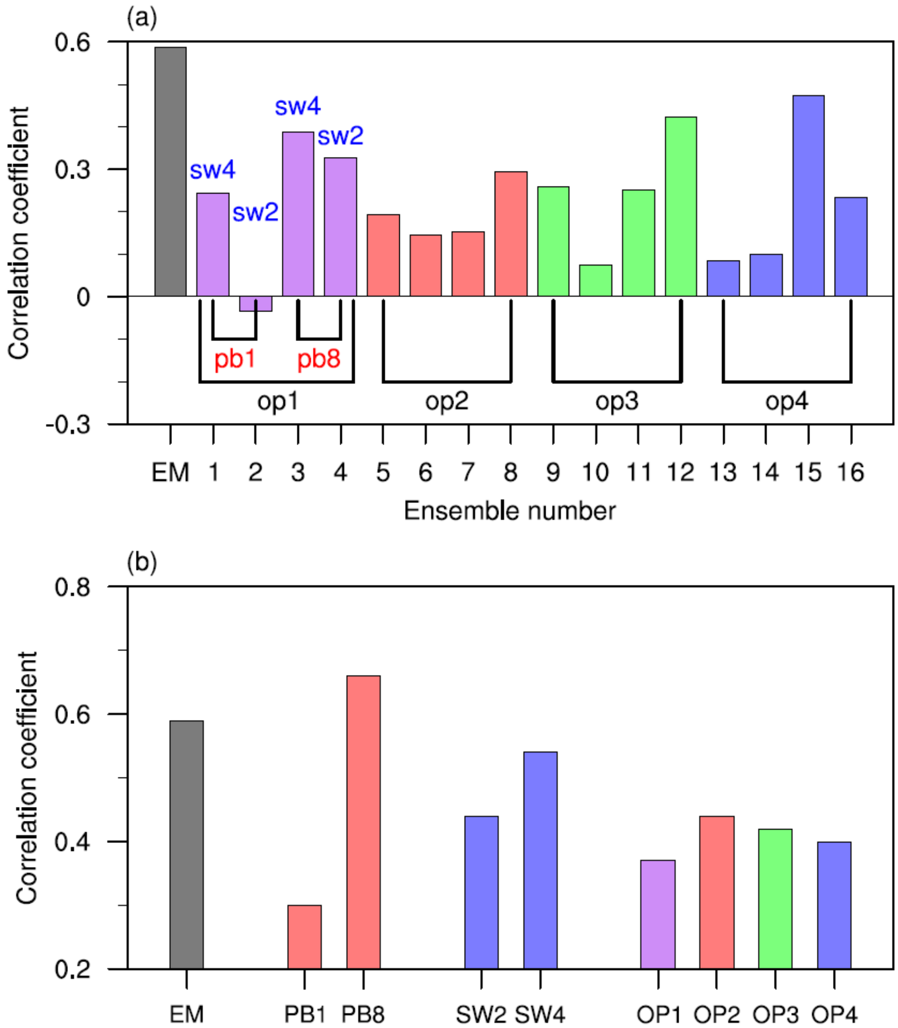

Figure S1. The spatial correlation coefficients between the regressed rainfall change pattern (Fig. 5c) and the modeled rainfall response (Fig. 6) from (a) the ensemble members (marked by numbers from 1 to 16) and their ensemble mean (marked by "EM") and (b) their ensemble means using various physical and chemical schemes. "EM" stands for the ensemble mean. The region for calculating the spatial correlation is WHI. Using other combinations in Fig. 5 for the evaluations gets similar results.

12. Figure 9 - this figure is not very clear. I recommend altering the green and red line colors as they will probably be indistinguishable in grayscale (and also to people with common color blindness). Also, the ensemble mean for ALLF and NDST are pretty similar to each other, such

that including dust doesn't appear to significantly improve agreement with observations much beyond correction of the low bias. True? However, there is quite a lot of spread between the ensemble members - do any of the ensembles lead to better temporal correlation with the observed rainfall?

- **We changed the green colors in Figures 9a and 9b to blue colors and used the partially transparent shadings to represent the spread of the ensemble members to make this figure clearer.**

- **We also scaled the y-axis in Figures 9a and 9b into smaller magnitude so that the difference between the ensemble means for ALLF and NDST can be clearly seen as much as possible. We agree that including dust can improve the rainfall agreement with observations in limited extent. However, here we want to address dust can significantly increase the ISM rainfall.**

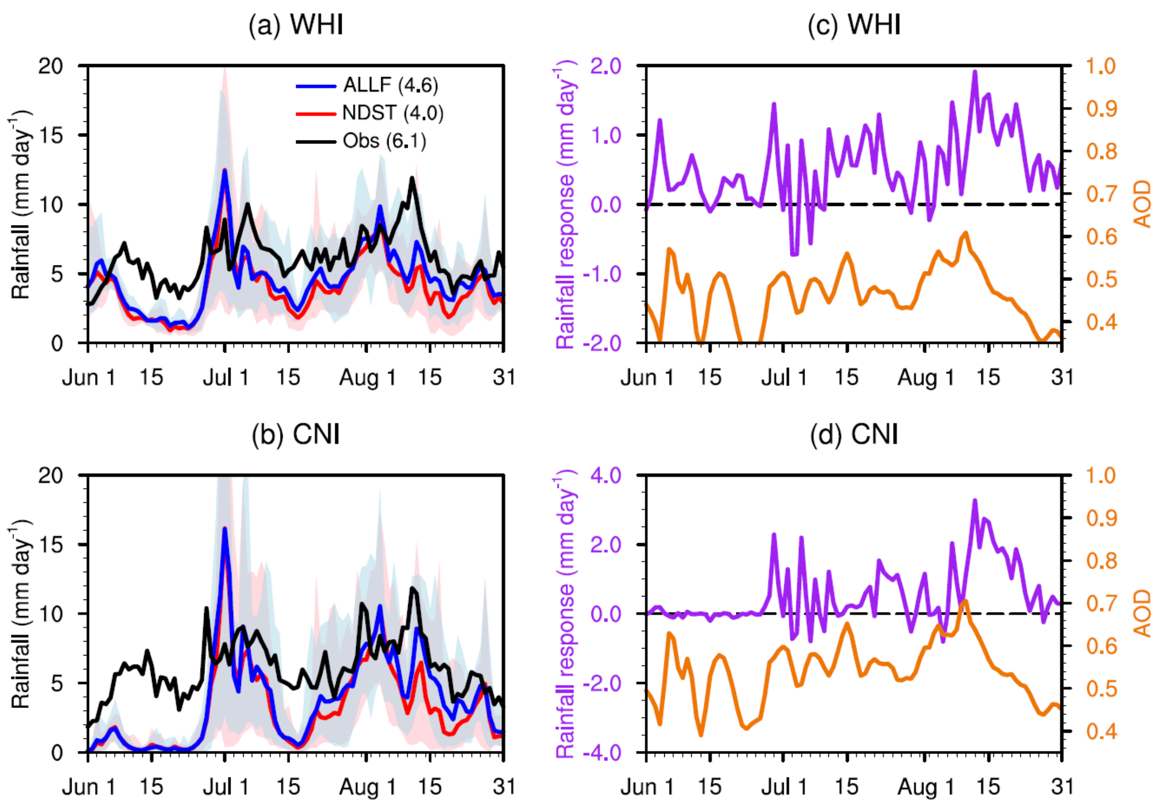

Figure S2. (Left) Time series of rainfall (mm day^{-1}) in 32 ensemble members and ensemble means of ALLF and NDST experiments and (Right) ensemble mean rainfall responses (mm day^{-1}) in WHI and CNI and AOD in DST (from ALLF). The numbers in parentheses are time-averaged rainfall.

- **The following figure shows the temporal correlation coefficients between modeled and observational daily precipitation in the WHI region. Yes, there are a couple of members, whose correlations with observations are larger than their corresponding ensemble means, such as member 7, 16 in NDST group and member 12 in ALLF group. Note that the ensemble mean of ALLF members has larger correlation coefficients than that of NDST members.**

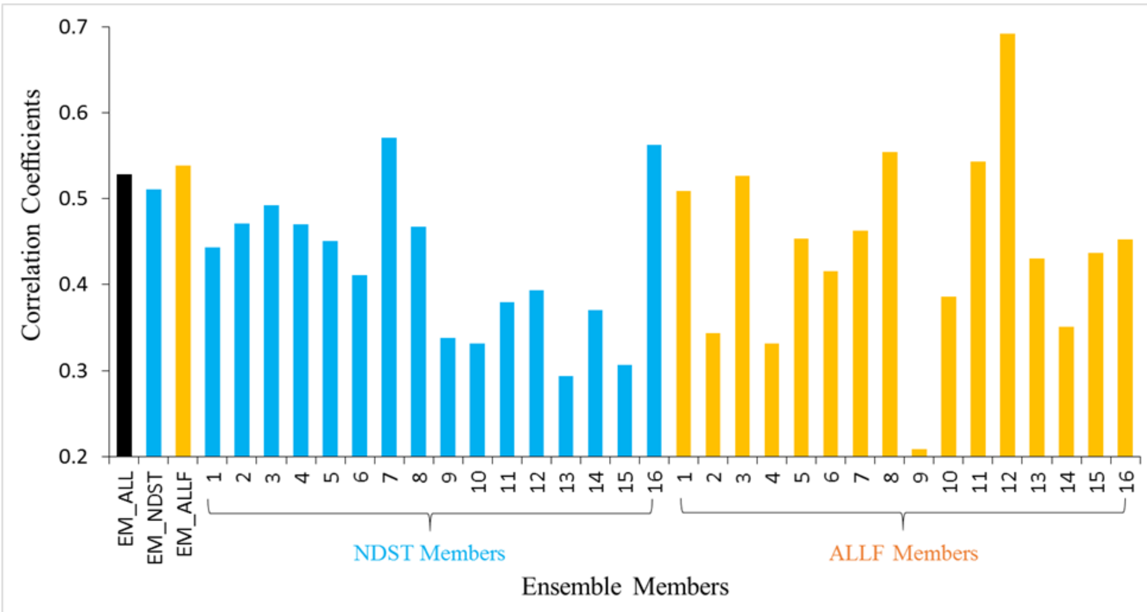

Figure S3. Correlation coefficients between the observed and modeled daily rainfall of all the ensemble members and their ensemble means.

Reviewer #2

This paper addresses the impact of Middle East dust on Indian summer monsoon precipitation. By combining results of ensemble simulations using WRF-Chem model with analyses based on observational data, the authors have presented certain correlations between variations of Middle East dust and Indian summer monsoon precipitation. They have derived a leading time of the former ahead of the latter by about 11 days, which is very close to the number from their previous analysis solely based on observations, and explained why this delay is dynamically reasonable. In addition, the authors also identified the sensitivities of modeled results to several selected parameters or model numerical schemes. I found the result intriguing because it reveals certain detailed features of dust emission, forcing, and the intraseasonal evolution of monsoonal precipitation, all derived from high-resolution modeling along with observations. It makes a good contribution to the current effort in examining the role of dust in influencing monsoonal precipitation variability.

Comments.

1. The physics background of the sensitivity simulation outcomes, i.e., why some parameters have substantial whereas others have little influence on precipitation response, could be further discussed. For instance, is the modeled precipitation supposed to be sensitive to aerosol mixing state, through optical or microphysical (i.e., nucleation) processes?

- **We selected two groups of ensemble members based on Figure 8 in our manuscript. The first group includes members of 1, 5, 12, and 14, in which rainfall responses have larger positive anomalies than other members (hereafter "good"), whereas members of 2, 4, 6, and 8 have smaller positive or even negative anomalies (hereafter "poor"). The spatial distribution of the mean difference between "good" and "poor" for various variables are analyzed. Figure S4 shows the rainfall responses in "good", "poor", and "poor" minus "good". The "good" members demonstrate positive rainfall responses to dust in Pakistan and India except several small regions in southeast and east India, but the "poor" members show dry anomalies in central and northwest India.**

- **The spatial patterns of the differences in rainfall response between "good" and "poor" members are consistent with the cloud fraction response, as shown in Figure S5, with increases in cloud fraction in almost entire India in the lower and middle troposphere in the "good" members and decreases in cloud fraction in central and southeast India in the "poor" members. For cloud fraction in the higher troposphere, the "good" members tend to have positive and negative anomalies in northwest and southeast India, respectively, but the "poor" members shows the opposite spatial patterns.**

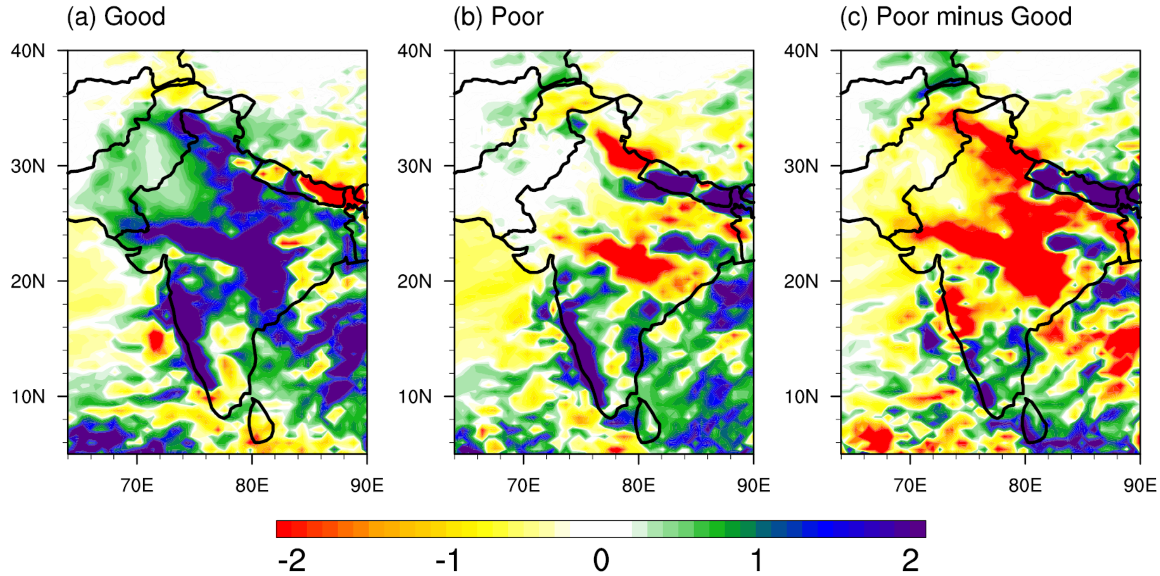

Figure S4. The mean responses of the rainfall (mm day^{-1}) to dust aerosols in the "good" and "poor" ensemble members.

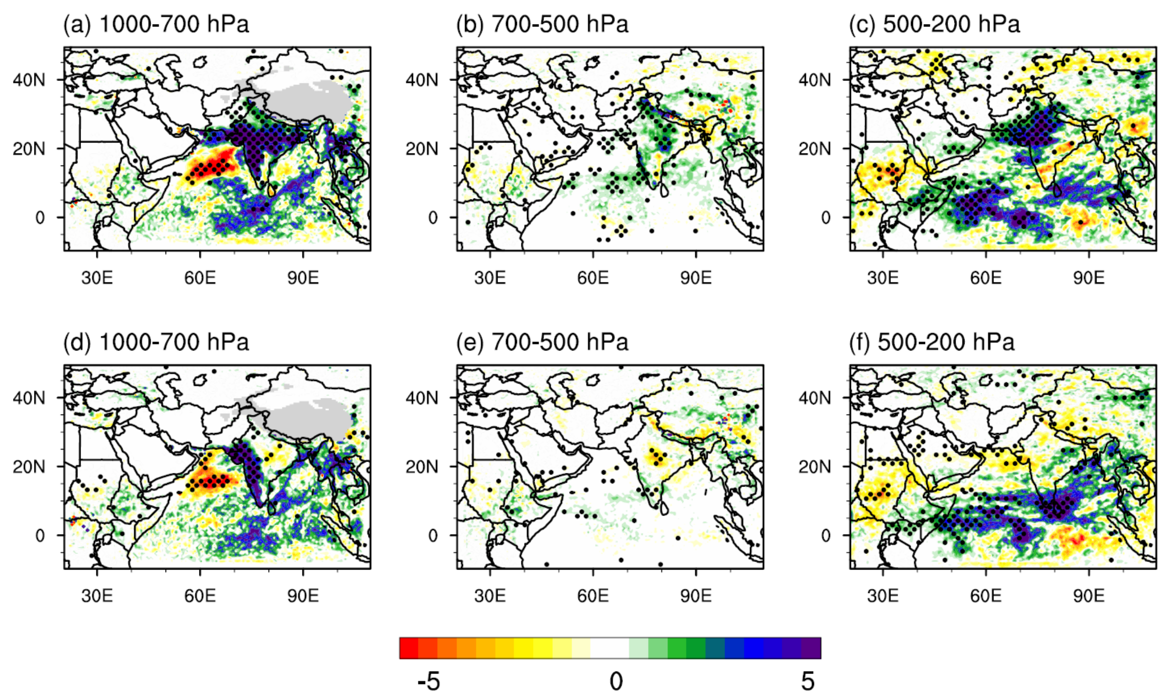

Figure S5. The mean responses of the cloud fraction (scale factor: 10^{-2}) to dust aerosols between various atmospheric layers in the "good" (top row) and "poor" (bottom row) ensemble members.

- Figure S6 illustrates the responses of geopotential height (shadings) and winds (vectors) both at 850 hPa in the "good" and "poor" members. Dust-induced low-pressure system over the Arabian Peninsula, the Arabian Sea, and central India is much stronger in the "good" members than that in the "poor" members. Correspondingly, the convergence over the Arabian Sea and north India is also stronger in the "good" members. The differences in the spatial patterns of the pressure and winds between the "good" and "poor" members are responsible for the differences in the rainfall responses.

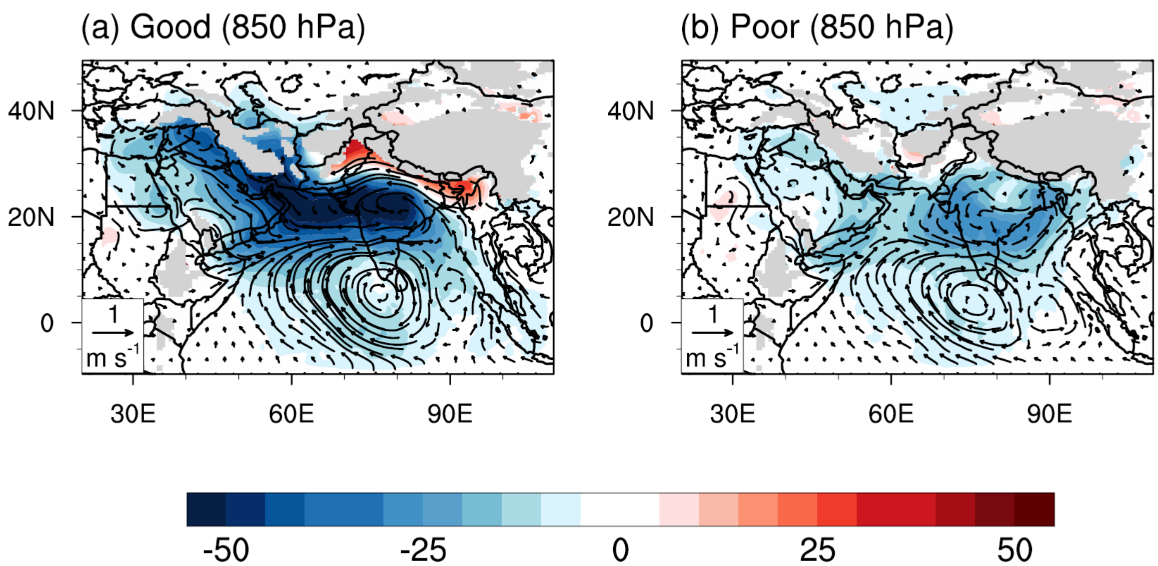

Figure S6. The mean responses of the geopotential height (m) and winds both at 850 hPa to dust aerosols in the "good" and "poor" ensemble members.

- The differences in the atmospheric heating spatial patterns and magnitude in the "good" and "poor" members in the lower troposphere are associated with the differences in the geopotential height and winds, as shown in Figure S7.

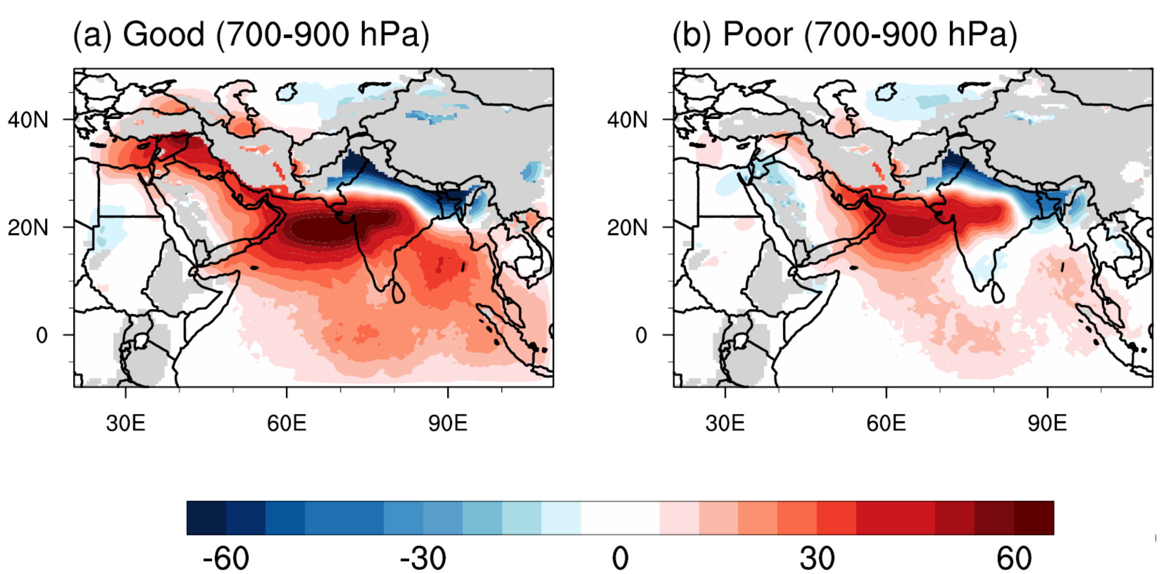

Figure S7. The mean responses of the atmospheric thickness (m) to dust aerosols between 700 and 900 hPa in the "good" and "poor" ensemble members.

- **Based on the above analyses, we conclude whether a specific member can simulate a substantial rainfall increase in India and the surrounding regions depends on how strong the atmospheric heating over the Arabian Sea and west India is in this member. The atmospheric heating is calculated by SW radiative scheme based on aerosol chemical mixing rules and aerosol mass. One of the model parameters that influences aerosol mass is the diffusion coefficient in the PBL scheme. Therefore, in our simulations, the atmospheric heating is determined by the three schemes together.**

- **Moreover, as we mentioned in our reply to the first question of the first reviewer, the magnitude or even the sign of rainfall responses depend on the imaginary refractive index of dust aerosols, indicating the dominant role of optical process in modulating the monsoon rainfall responses, instead of microphysical process.**

2. Section 7 provided some good discussions of the potential mechanisms behind the dust effects on precipitation. In 7.2, perhaps the authors should also look at lower level entropy to see if dust aerosols had caused any interesting change, if so, this might provide an additional explanation for dust induced circulation change. 7.3 appears to be too brief, the moist flux should be analyzed both in the lower atmosphere (e.g., below the cloud base) and upper troposphere (divergence layer). Moisture flux derived from integration through the entire atmospheric column might not be a good indicator for detecting the dust induced moisture flows.

- **We calculated the moist static energy (i.e. entropy; hereafter MSE) differences due to dust aerosols, as shown in the following figure (b).**

- **We added another sub-section to include the analysis of MSE in our manuscript. "6.5. Dust impact on moist static energy**
  The moist static energy (MSE) in sub-cloud layer has been demonstrated closely related to the boundary of the monsoon circulation (Prive and Plumb, 2007b, a). Following the method of Wang et al. (2009), the mean MSE is calculated in the three lowest model layers to represent the sub-cloud MSE. Figure 14b shows the spatial distribution of the ensemble mean of MSE differences between ALLF and NDST experiments for JJA 2008. We found increased MSE in Pakistan and India, with a magnitude between 1 and 2 kJ kg^{-1}. The maximum increase of MSE is co-located with changes in precipitation and precipitable water in the IGP region. The spatial distribution and magnitude of the MSE response to Middle East dust in this study is very similar to the MSE changes induced by anthropogenic aerosols in the study of Wang et al. (2009), suggesting the robustness and usefulness of adopting sub-cloud MSE to characterize changes in the ISM system due to desert dust as well as

anthropogenic aerosols.”

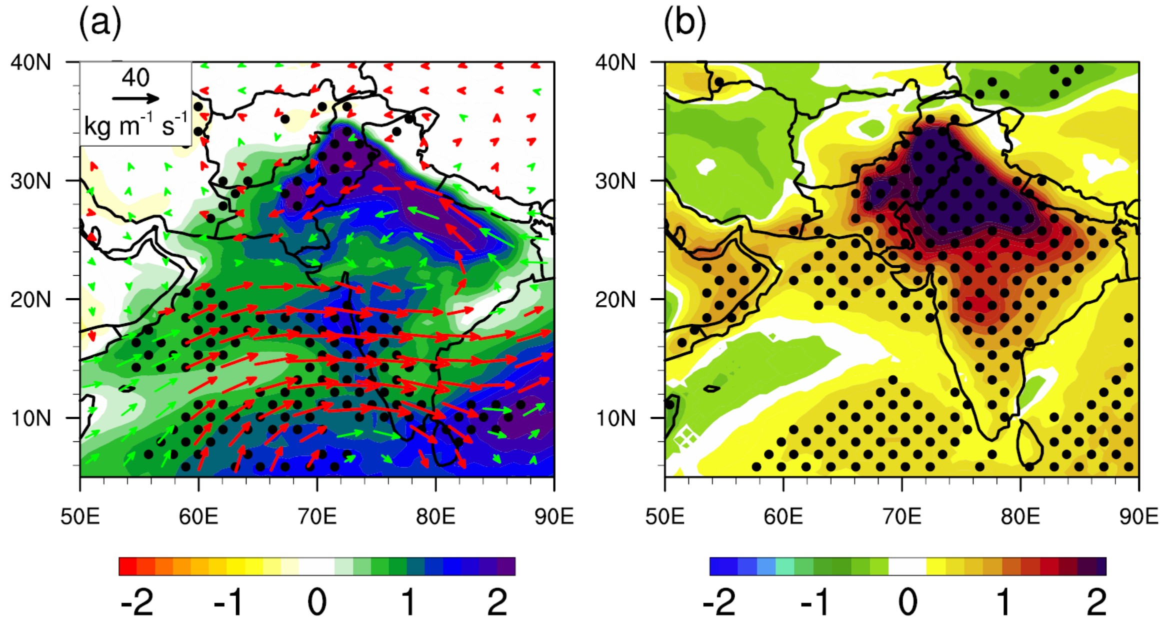

Figure S8. Same as Figure 6 in the manuscript, but for (a) precipitable water (shading; unit: mm) and water vapor flux (arrows; units: kg m^{-1} s^{-1}) both integrated within the entire atmospheric column and (b) moist static energy (units: kJ kg^{-1}) in the three lowest model layers. Black dots represent the differences in precipitable water and moist static energy that are 95% confident based on a one-sided Student's *t*-test. The red arrows represent wind differences that are 95% confident, and the green arrows represent other wind differences (not confident).

- **The following figure shows the responses of the integrated moisture flux in various atmospheric layers to the dust aerosols. These is no significant difference between integrated moisture flux in the lower troposphere (i.e. 1000–700 hPa) and that in the entire atmospheric column. We add the following text in section 6.3 to discuss this concern in our manuscript.**

- **“The moisture flux integrated in the lower troposphere (i.e. 1000–700 hPa) shows little difference compared with that integrated in the entire atmospheric column. Furthermore, the moisture flux integrated in the upper troposphere (i.e. 500–200 hPa) has a much smaller magnitude than that in the lower troposphere (about 5%). Therefore, they are not shown in this study.”**

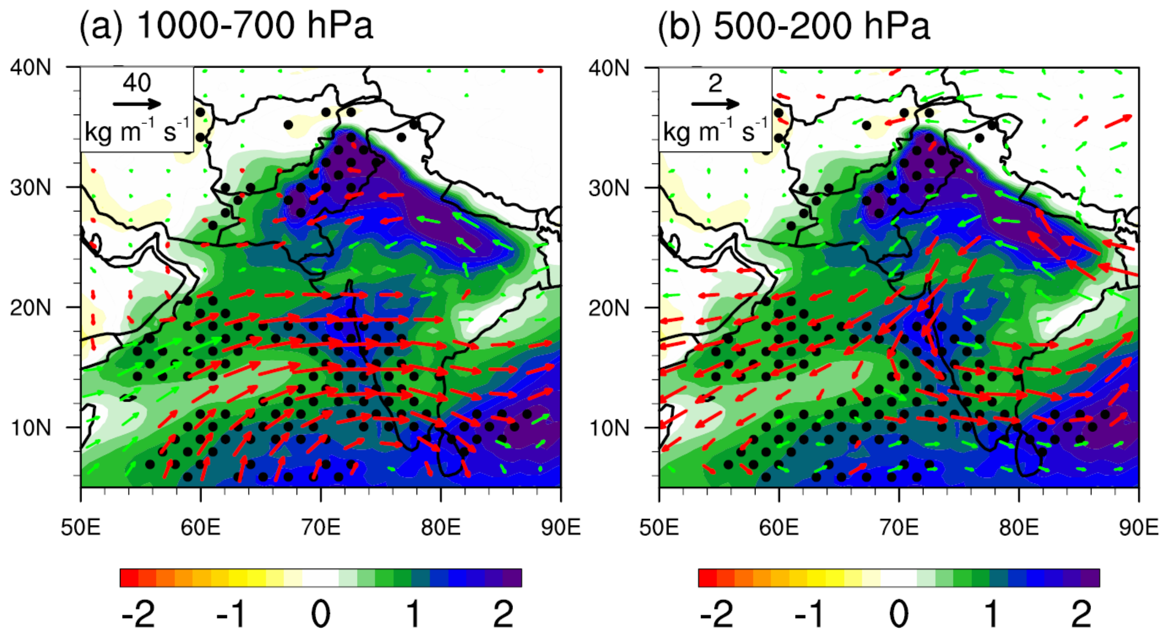

Figure S9. Responses of vertically integrated moisture flux (arrows; units: kg m^{-1} s^{-1}) in (a) 1000 to 700 hPa and (b) 500 to 200 hPa and precipitable water (shadings; unit: mm) to dust aerosols for JJA 2008. The shadings are the same in (a) and (b).

3. Page 15573, Line 5: "cloud condensation nuclei", note that this also applies to ice nuclei, especially for dust aerosols.

- **We changed the sentence from:**
  "by serving as cloud condensation nuclei"

  to

  "by serving as cloud condensation nuclei and ice nuclei".

4. Page 15573, Line 10: "half of the world population", perhaps this should be linked to the entire monsoonal climate zone rather than the Indian summer monsoon region?

- **We corrected it to "about one-third of the world's population".**

5. Page 15573, Line 14: Use only "solar dimming" and "elevated heat pump" to summary the referred studies might not well reflect various hypotheses proposed in these papers.

- **We added the following description of both the "solar dimming" and "elevated heat pump" effects in the Introduction part:**

- **"The "solar dimming effect" proposed that the anthropogenic aerosol-induced reduction of north-south land-sea thermal contrast through aerosols' surface cooling effect contributes to a weaker meridional monsoon circulation. In contrast, the "elevated heat pump effect" hypothesized that the anthropogenic and desert dust aerosols stacked up on the southern slope of the Tibetan Plateau can heat the air in the mid-to-upper troposphere due to their high elevation, which in turn**

results in the earlier onset of the Indian summer monsoon and more precipitation during monsoon season."

6. Page 15578, Line 13: "divided" could be replaced by, e.g., "aggregated accordingly" or alike.

- **We changed "divided" to "aggregated accordingly".**

7. Page 15588, the authors should indicate corresponding layer of the discussed quantity in the discussions of various radiative forcings, e.g., "atmospheric forcing", "TOA", or "surface forcing".

- **We changed the following sentence in section 6.1**

- **"The direct radiative forcing of dust at all-sky conditions is calculated at the top of the atmosphere (TOA), in the atmosphere, and at the surface."**

  to

  "The direct radiative forcing of dust at all-sky conditions is calculated at the top of the atmosphere (i.e. 50 hPa; hereafter TOA), in the atmosphere (i.e. the atmospheric layers between TOA and surface), and at the surface."

- **We also added "TOA" or "in the atmosphere" or "at the surface" whenever it might be misleading.**

8. Page 15589, discussion of longwave fluxes, is any dust longwave effect associated with cloud change? Line 14: "hotter" to "warmer".

- **Yes, we see that changes in cloud fraction can affect both LW and SW radiative effects, as shown in the following two figures and described in an additional section of 6.2 in the manuscript.**

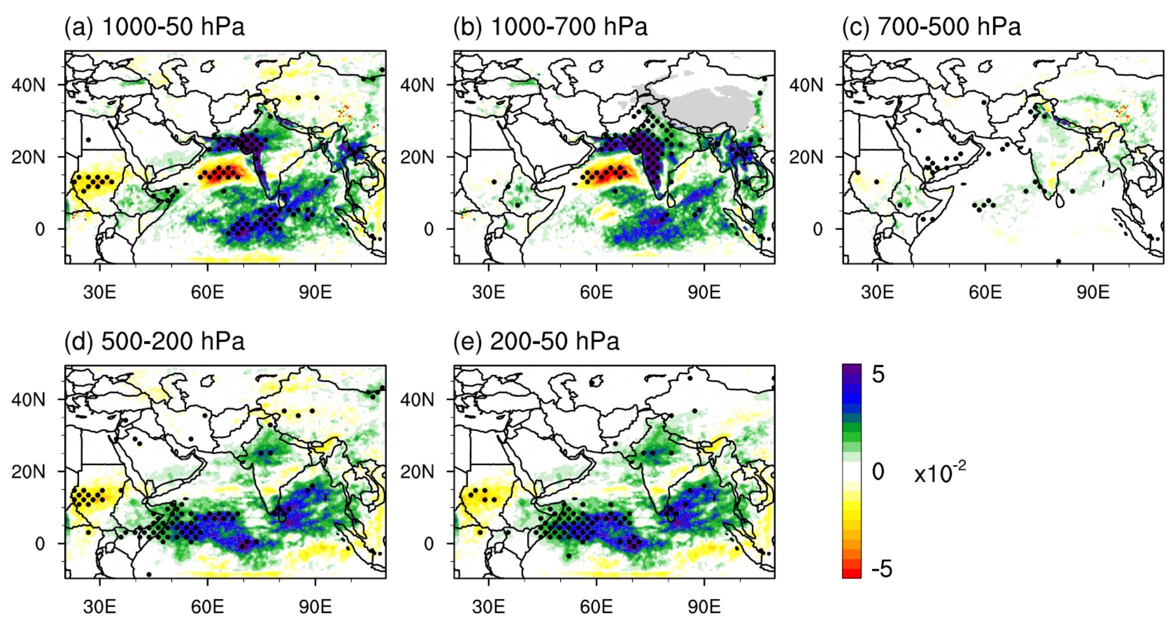

Figure S10. Spatial patterns of the ensemble means of cloud fraction responses (ALLF minus NDST; scale factor: 10^{-2}) for JJA 2008 between various atmospheric layers. The dotted areas mean that cloud fraction responses are 95% confident based on one-sided Student's *t*-test.

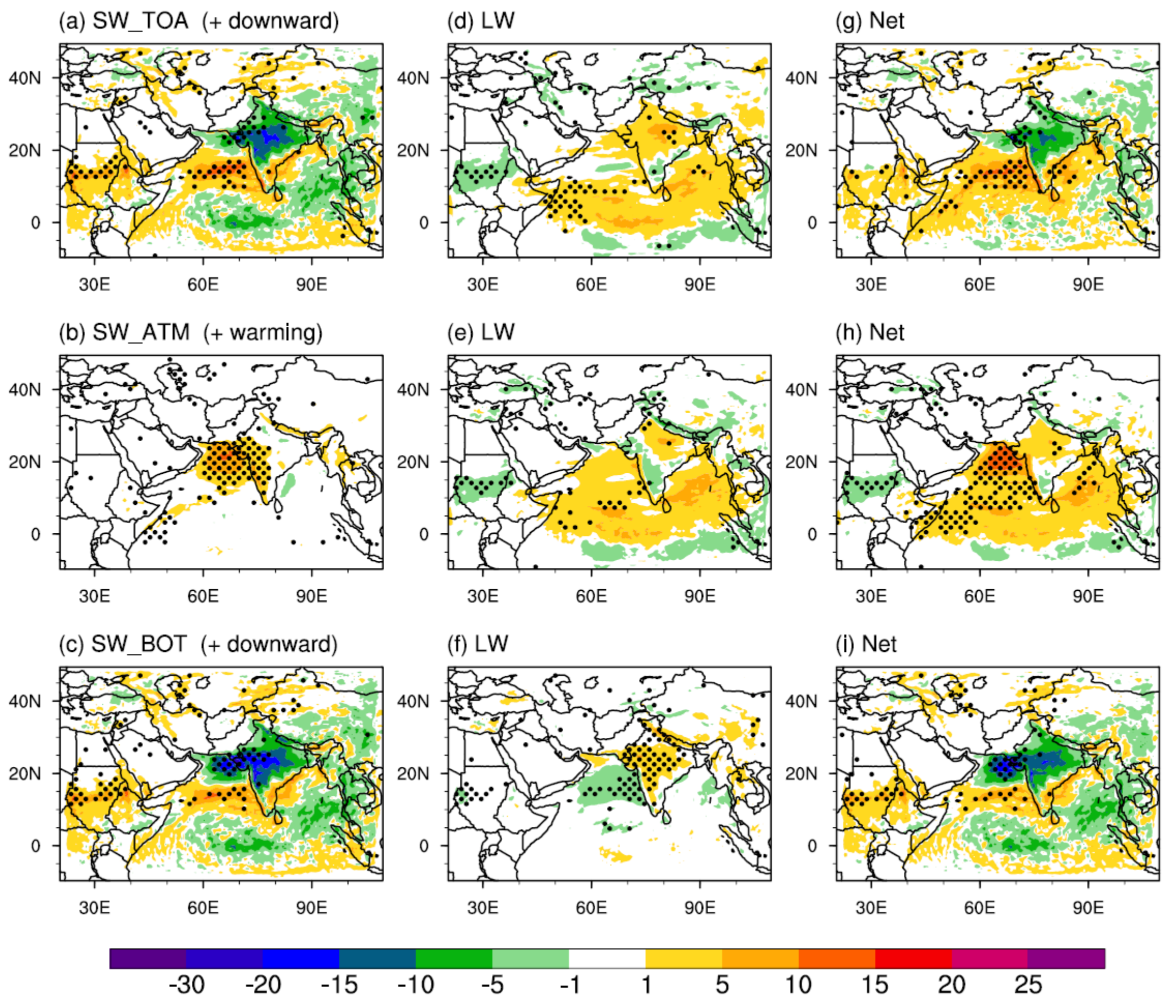

Figure S11. Same as Figure 11 in the manuscript, but for radiative effects (W m^{-2}) at cloudy conditions, calculated as radiative effects at all-sky conditions minus those at clear-sky conditions.

- **"6.2 Radiative effect of clouds**
  Figure 12 shows the ensemble means of cloud fraction responses (ALLF minus NDST) between various atmospheric layers to Middle East dust aerosols in JJA 2008. Cloud fraction in the entire atmospheric column (i.e. 1000–50 hPa) increases in the north Indian Ocean, Somalia, the north Arabian Sea, CSWI, northwest India, and the Bay of Bengal with a magnitude from 0.02 to 0.05 (Figure 12a). In contrast, it decreases in the central Arabian Sea and Sudan, with a magnitude from 0.01 to

0.04. Figure 12b illustrates the similar spatial patterns of the cloud fraction responses in the lower troposphere (i.e. 1000–700 hPa) to those in the entire atmospheric column, but with a larger magnitude and more significant areas in CSWI and northwest India. However, cloud fraction changes in the middle troposphere (i.e. 700–500 hPa; Figure 12c) is very small. Figure 12d demonstrates increased cloud fraction in the upper troposphere (i.e. 500–200 hPa) in the western part of the north Indian Ocean, Somalia, and the Bay of Bengal, with a magnitude from 0.02 to 0.04 (Figure 12d). Cloud fraction responses in the stratosphere (i.e. 200–50 hPa) are similar to that in the upper troposphere (Figure 12e).

Figure 13 illustrates the radiative effects at various atmospheric layers due to changes in cloud fraction calculated by subtracting the radiative effects at the clear-sky conditions from those at the all-sky conditions. The SW radiative effect at TOA decreases (Figure 13a) in areas where cloud fraction in the entire atmospheric column increases (Figure 12a), which is because more cloud can scatter more SW radiation to space. Decreased SW radiation at TOA is also seen in the central Arabian Sea and Sudan where cloud fraction decreases. At the surface, the spatial distribution of SW radiative effect displays a very similar pattern to that at TOA, but with a smaller magnitude (Figure 13c), which results in a positive radiative effect in the atmosphere (Figure 13b) over the north Arabian Sea and CSWI. The LW radiation increases at TOA (Figure 13d) in areas where cloud fraction in the upper troposphere or stratosphere increases, because clouds emit less LW radiation to space than the surface due to their lower temperature. At the surface, LW radiation effect is determined by changes in cloud fraction in the lower troposphere through cloud blocking effect of LW radiation from the surface, which decreases in the central Arabian Sea and increases in the Indian subcontinent (Figure 13f). Figure 13e shows increased LW radiation effect in the south Arabian Sea. Figures 13g–13i demonstrate the net (LW+SW) radiative effect. At TOA and the surface, the spatial pattern of the net radiative effects is dominated by SW radiative effects. However, in the atmosphere, the net radiative effect is determined by both SW and LW radiative effects. The area-averaged radiative effects due to cloud are summarized in Table 4, showing that cloud response contributes about 14% to the total radiative effect (warming) in the atmosphere, which amplifies the aerosol induced atmospheric heating effect."

- **Changed "hotter" to "warmer".**

9. Page 15590: "Dai et al. . . .Asian monsoon. . .", the cited paper might be discussing the East Asian monsoon rather than the Indian summer monsoon?

- **Dai et al (2013) studied both the South Asian Summer Monsoon (i.e. the Indian summer monsoon) and the East Asian Summer Monsoon.**

10. Figure 6, caption, "AFFL" should be "ALLF".

- **Done.**

References

Colarco, P. R., Nowottnick, E. P., Randles, C. A., Yi, B. Q., Yang, P., Kim, K. M., Smith, J. A., and Bardeen, C. G.: Impact of radiatively interactive dust aerosols in the NASA GEOS-5 climate model: Sensitivity to dust particle shape and refractive index, J Geophys Res-Atmos, 119, 753-786, 2014.

Kahn, R. A., Nelson, D. L., Garay, M. J., Levy, R. C., Bull, M. A., Diner, D. J., Martonchik, J. V., Paradise, S. R., Hansen, E. G., and Remer, L. A.: MISR Aerosol Product Attributes and Statistical Comparisons With MODIS, Ieee T Geosci Remote, 47, 4095-4114, 2009.

Kok, J. F.: A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle, P Natl Acad Sci USA, 108, 1016-1021, 2011.