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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Dust aerosol impact on North Africa climate: a GCM investigation of aerosol-cloud-radiation interactions using A-Train satellite data" *by* Y. Gu et al.

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We appreciate the detailed comments from Reviewer 2. Below are our responses to these comments.

This manuscript attempts to quantify the climatic effect of the aerosol indirect effect using a GCM with the empirical relationship between ice cloud properties and AOD obtained from the A-train satellite data. It is a very interesting paper and I recommend a publication after a revision.

My major concerns are: (1) About the 5 years of integration of climate model: This seems too short for me. The feedback of water vapor and clouds is the major factor

that leads to uncertainties in climate models. A quick check can be done if you run climate simulations longer, for example, for 20 years, and then compare model results from the final 10 years. You may see that the pattern and magnitude of the simulated climatic effect of aerosols can be different. Also, because of uncertainties with model results, a commonly used approach is to perform significance test on model results to distinguish model noise and climatic effect of aerosols.

It is a common practice to carry out climate simulations for 5-10 years (e.g., Lau et al., 2009; Kim et al. 2010; Kiehl et al., 2000). Nevertheless, following the reviewer's comments, we have extended climate simulation to 20 years. Differences between the last 5-year mean simulation results and the control run have similar patterns as those presented in the current manuscript. For this reason, results are presented in terms of the 5-year means. A brief discussion on this issue has been added in the revision (page 19, lines 455-458).

Significance tests have been performed following the reviewer's comment. Differences between the sensitivity experiment IND and CTRL are statistically significant at the confidence level typically exceeds 95% corresponding to the major changes in the OLR, precipitation, and cloud cover fields in North Africa. Anomalies are shown to be significant in all areas at above 70% level. We have added this information in the revision (page 19-20, lines 473-477)

(2) About the De-AOD-IWC relationship from A-train data, is this the same throughout the year? Or this has seasonal variations? In Africa the observed AOD includes the contributions of BC and OC aerosols from biomass burning, which needs to be clarified in the manuscript.

The De-IWC-AOD relationships reported in Jiang et al. (2011) are derived using climatological satellite data and are currently the same throughout the year but have different values for different regions. The seasonal variations of the relationships will be a subject for future work. The reviewer is correct that the AOD in North Africa also includes the contributions from BC and OC aerosols. However, in this study, our intent is to investigate the impact of dust aerosols on regional climate through their direct, semi-direct, and indirect effects. For this reason, we have specifically selected the North Africa region because a significant contribution of AOD comes from dust aerosols in this region (page 1, lines 52-57).

More specific comments:

(1) The abstract can be shortened.

We have shortened the abstract following the Reviewer's comment.

(2) Introduction: Most of the previous studies mentioned were published before 2007; more updated studies on climatic effects of dust should be cited, especially the GCM modeling studies that examined direct and indirect of dust.

The reviewer's comment is well-taken. We have added additional references on dust climatic effects (page 1, lines 48-49; page 2, lines 74-76; page 2-3, lines 85-87).

(3) Line 3 on Page 4 and Figure 1: Longwave readiative forcing of dust is missing, although you mention about it later. Actually I think Figure 1 can be removed because it is a general definition of aerosol forcing and not something special in this paper.

Following the reviewer's comment, we have added the IR radiative forcing in Figure 1. After careful consideration, we decide to keep Figure 1 in view of the fact that ACP readers who are not directly involved in the aerosol climate science field could be confused about the definitions and meanings of aerosol direct, semi-direct, and indirect effects.

(4) Line 3 on Page 8: Usually we would choose to use higher resolution model to have better characterization of clouds. Why chose 4x5 resolution for this study?

We agree with the reviewer that a higher resolution may be better to capture the regional characteristic of clouds. However, since the focus of this study is on the dust

climatic effect in the North Africa region, it appears that the current model resolution should be sufficient for this purpose. In fact, this type of resolution has been used in numerous climate simulations (e.g., Hansen et al. 2004; Köhler, 1999). Following the reviewer's comment, however, we have added some justification for the use of the current model resolution in the revision (page 7, lines 193-197).

(5) Page 8: About the UCLA GCM, do you have any references that evaluated the simulated water and ice clouds in the model?

The UCLA AGCM with the Fu-Liou-Gu radiation scheme has been successfully applied to climate studies related to water and ice clouds. For details, please see Gu et al. (2003) and Li et al. (2005). We have added a brief discussion and references for comparison of the model simulated water and ice clouds and available measurements using the UCLA AGCM (page 7, lines 183-189. Also see response to item 8).

(6) Figure 2 and related discussions: What are the relative humidity and size distributions assumed in calculation of optical properties of different aerosol species? The single scattering albedo of dust is about 0.8, which is in the low end of estimates in previous modeling and observation studies. May need to discuss how this would influence your results?

In the Fu-Liou-Gu radiation scheme for the UCLA AGCM, the single-scattering properties for a total of eighteen aerosol types are parameterized by using the recent addition of the Optical Properties of Aerosols and Clouds (OPAC) database (d'Almeida et al., 1991; Tegen and Lacis, 1996; Hess et al., 1998). The database provides the single-scattering properties for spherical aerosols computed from the Lorenz-Mie theory, in which the humidity effects are accounted for. For aerosols that are able to take up water, the single-scattering properties for eight sets of humidity are provided in OPAC database: 0%, 50%, 70%, 80%, 90%, 95%, 98%, and 99%. For each model grid point, the single-scattering properties of dust particles are interpolated based on model simulated humidity using the eight sets of data. The lognormal distribution function has been used which have been found to be suitable to characterize the size distribution of atmospheric aerosols (d'Almeida et al., 1991; Hess et al., 1998). Following the reviewer's comment, we have added a brief description on the relative humidity and size distributions assumed in parameterization of the single-scattering properties of different aerosol types. (page 10, lines 261-267)

In order to examine the aerosol semi-direct effect associated with the aerosol absorption of sunlight, which leads to the heating of the atmosphere and reduces large-scale cloud covers (Hansen et al. 1997), we have used larger absorptive dust particles in this study. For smaller dust particles which scatter solar radiation, smaller absorption would be produced in the atmosphere, leading to a negative radiative forcing at TOA. Following the reviewer's comments, we have added a brief discussion on this subject in the revision (page 14, lines 356-361).

(7) Bottom of Page 11: It is stated that "When there is no aerosol, De must be prescribed or calculated from other cloud microphysical parameterizations." Describe exactly whether it is prescribed or calculated in this study. If prescribed, give the values.

The comment is well-taken. In this study, a prescribed De with a value of 85 ïĄ■m based on available ice crystal sizes from six observational campaigns reported by Fu (1996) was used in clean conditions of offline studies. This information has been added in the revision (page 12, lines 306-308)

(8) Line 11 on Page 13: Simulated IWCs are used. How accurate are they? Any evaluation with measurements?

The UCLA AGCM with the Fu-Liou-Gu radiation scheme has been successfully applied to climate simulations and studies related to ice clouds (e.g., Gu et al. 2003). To assess the performance of global climate models (GCMs) in simulating upper-tropospheric ice water content (IWC), a new set of IWC measurements from the Earth Observing System's Microwave Limb Sounder (MLS) are used to compare with simulations from several GCMs, including the updated UCLA AGCM with the Fu-Liou-Gu radiation scheme.

Results show that the UCLA AGCM is capable of capturing the global distributions of IWC as compared to MLS data and is among the best in terms of simulated IWC values (Li et al. 2005, Figures 2 & 3). We have added some discussion regarding comparison of the model simulated IWC and available measurements from previous studies using the UCLA AGCM (page 7, lines 183-189).

(9) Section 3 is a little confusing to me. Is it a one-column study using the radiative transfer model? Or a calculation within the GCM for the desert area?

Section 3 presents an off-line one-column study using the Fu-Liou-Gu radiative transfer model. We have modified the text to make it clearer (page 14, lines 354-356)

(10) Bottom of Page 12: Why is surface albedo assumed to be 0.1? I would expect it is higher for deserts?

The reviewer is correct that the surface albedo in the North Africa region would be higher. However, the off-line study is just a general study. While the surface albedo does affect the magnitude of the aerosol forcing, the sign of the forcing, and hence the conclusion, wouldn't be affected. In the GCM simulation, the surface albedo for North Africa was taken from the UCLA AGCM in which surface albedo and roughness length are specified following Dorman and Sellers (1989). (page 6, lines 175-176).

(11) I would suggest comparing forcing values obtained here with those in previous studies.

Following the reviewer's comment, comparison with previous studies have been added for the off-line calculations (page 16, lines 382-393; page 17, lines 415-417)

(12) Line 7 on page 14: "while semi-direct effect can be inferred from the results for cloudy conditions". Explain in more details how you estimate semi-direct effect here.

It is very difficult to quantify the semi-direct in a GCM setting due to the intricate interactions among different physical processes. That is why we perform off-line simulations to show the semi-direct effect. The semi-direct has been discussed in detail in Section 3. When ice clouds are present simultaneously with the dust aerosols, positive IR radiative forcing is enhanced since ice clouds trap substantial IR radiation, while the positive solar forcing with dust aerosols alone has been changed to negative values due to the strong reflection of solar radiation by clouds, indicating that cloud forcing could exceed aerosol forcing. With the presence of ice clouds, the solar, IR, and net forcings still increase with increasing AOD but with a much smaller slope. As a result, when AOD is approaching 1.0, the net forcing with the combined aerosol and cloud effects is approximately equivalent to that with dust aerosols alone. This means that under heavily dusty cases, the cloud radiative forcing can be masked by the dust direct radiative forcing. In a GCM setting, aerosol absorption of sunlight can heat the lower troposphere and reduce cloud cover and/or cloud ice water content. When aerosol loading is small (AOD < 0.2), the net combined aerosol-cloud forcing is particularly significant for IWP = 80 g m-2. However, the net aerosol-cloud forcing for a smaller IWP becomes substantial and increases with AOD for AOD > 0.2, indicating that the aerosol effect modulates cloud forcing. The aerosol semi-direct effect could exert an extra net forcing of about 10 W m-2 for heavily polluted case with AOD = 1.0 along with the reduction in cloud IWP from 80 g m-2 to 20 g m-2. With the aerosol indirect effect, the net cloud forcing is reduced in the case for IWP > 20 g m-2. The magnitude of reduction increases with IWP, with a decrease of about 25 W m-2 in the net TOA forcing for IWP = 100 g m-2 and AOD = 0.8 (page 16, lines 393-397; pages 16-17, lines 399-411; page 17, lines 419-421).

(13) Page 15: How do you treat the oceans in climate simulations? Prescribed SSTs or using a mixed-layer or dynamic ocean? Yue et al. ACP 2011 found that simulated climatic effect of dust can be quite different with different assumptions about SSTs.

In the UCLA AGCM, the geographical distribution of SST is prescribed based on a 31-yr (1960–90) climatology corresponding to the Global Sea Ice and Sea Surface Temperature dataset (GISST) version 2.2 (Rayner et al. 1995). Following the reviewer's comment, additional descriptions on the UCLA AGCM, including the SST, has been

incorporated in the revision (pages 6, lines 171-176). We agree with the reviewer that the SST response may play an important role in the simulation of the climatic effect of mineral dust aerosols. Based on the study of Yue et al. (2011), the SST responses could influence the simulated dust-induced climate change, especially when climate simulations consider the two-way dust-climate coupling to account for the feedbacks. We have added a note in the revision and referred to the aforementioned paper (page 6-7, lines 176-180).

(14) Page 15: The manuscript is focused on ice clouds, but how about your assumptions of water clouds under clean and dusty conditions?

This paper focuses on the indirect effect of dust on ice clouds. Therefore, for water clouds, we have used a prescribed value for the effective radius in which the aerosol indirect effect was not included (page 14, line 348).

(15) Line 20 on Page 16: Why present model results for JJA only? Results for other seasons might be different and interesting.

During the boreal summer, June-July-August, the rainfall system in West Africa could be significantly affected by dust particles. Also since differences between the sensitivity experiments and the control run are mainly located in the summer hemisphere associated with the position of the sun, results are presented in terms of the JJA means. A brief justification has been added in the revision (page 19, lines 458-462).

(16) Figures 5-7: it might be helpful to have significance test on model results, so that you just need to discuss results that are statistically significant.

Significance tests for the confidence levels for differences have been performed. The confidence level typically exceeds 95% corresponding to the major changes in the OLR, precipitation, and cloud cover fields. Anomalies are shown to be significant in all areas at above 70% level. (page 19, lines 473-477; Also see the response to major concerns Item 2)

(17) About cloud cover in Figures 5 and 7, can you show water cloud and ice cloud separately? Feedback in water clouds can contribute to the changes in parameters shown in Figures 5-7, which should be discussed in the text.

In the UCLA AGCM, the total cloud cover is parameterized using liquid and ice water mixing ratio. Therefore, besides IWC, we have examined differences in the simulated liquid water content (LWC) following the reviewer's comment. The differences in LWC show the same patterns as in IWC but with a much smaller magnitude, which is expected and appears to be reasonable. In this case, the feedback in water clouds could only slightly contribute to the magnitude of the changes but wouldn't affect the results and conclusions presented in this study. Following the reviewer's comment, we have added a brief discussion about the changes in water clouds due to the aerosol effect in the revision (pages 20, lines 492-495).

(18) Conclusion: I would suggest having a final paragraph to discuss sources of uncertainties with model results from this study. For example, De-AOD-IWC relationship from A-train data may include the impacts of BC/OC from biomass burning; assumptions about SST can influence simulated climatic effect; second aerosol indirect effect should be considered in future studies; etc.

The reviewer's comment is well-taken. In this study, the De-IWC-AOD relationships reported in Jiang et al. (2011) have been derived using the climatological satellite data and are currently the same throughout the year. Further analyses are needed to capture the seasonal variations of the relationships. Also they are derived using IWC at 215 hPa because $\sim$200 hPa is approximately the level of convective detrainment and the ice water content is proportional to the convective intensity. Future studies will be needed in order to parameterize De in a vertically inhomogeneous atmosphere. Following the reviewer's comment, we have added some discussion regarding uncertainties in the application of De-IWC-AOD relationships to climate model studies (page 12, lines 308-314). The De-IWC-AOD relationships reported in Jiang et al. (2011) actually applies to AOD from different aerosol types. In this study, our objective is to investi-

gate the impact of dust aerosols on regional climate through their direct, semi-direct, and indirect effects. We specifically select North Africa region because a significant contribution of AOD comes from dust aerosols in this region.

The possible influence of SST has been added (page 6-7, lines 176-180. Also see response to item 13).

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