The authors appreciate the reviewers' comments. In response to the comments, we have made relevant revisions in the manuscript. Each comment of the reviewers (black) is listed and followed by our response (blue).

Interactive comment on "Aerosol effects on the cloud-field properties of tropical convective clouds" by S.-S. Lee and G. Feingold

Anonymous Referee #1

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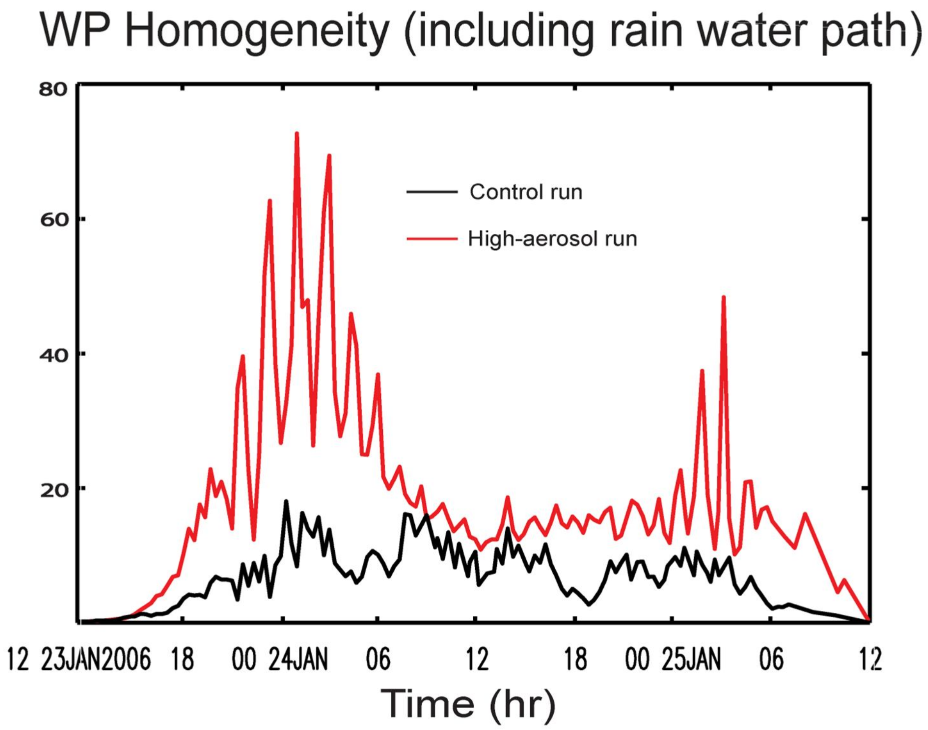
The authors analyze the effect of aerosols on cloud microphysical and dynamical properties and precipitation from tropical convective clouds using 2-d model with bulk-parameterization scheme.

Traditionally tropical convective clouds are considered as the most sensitive to aerosols. The authors found a comparatively low effect of aerosols on accumulated precipitation: even ten-fold increase in aerosol concentration results in a similar temporal evolution of mean precipitation and a small (9%) difference in cumulative precipitation between the high-and low-aerosol cases. At the same time the sensitivity of other parameters, such as total mass of condensate, mass fluxes, etc. were found to be very sensitive to aerosols.

The paper is of interest and can be accepted for publication after major revision. The comments and remarks are presented below.

1. Figure 12a. It is not clear why the sum of liquid and ice contents is equal to zero below ~500m. Under such profiles surface precipitation should be equal to zero. I suspect a mistake in the figure.

Here, liquid water content includes cloud liquid but not rain. This is clarified in text. Inclusion of precipitable hydrometeors does not change the general conclusions of the paper, as exemplified in the following figure, which depicts the time series of the homogeneity of water path which includes rain water path as well as cloud-liquid and –ice water path.



2. It seems that the authors believe that the small effect of aerosols on accumulated rain is the result of the averaging over many clouds and over long time. Note that ccomparatively low (5-15%) sensitivity of precipitation to aerosols was found earlier in simulations of single clouds (Khain et al.2008; Khain 2009; Fan et al. 2009), squall lines (Khain et al. 2009; Tao et al. 2011), supercell storm (Khain and Lynn 2009), etc. Moreover, it was stressed in many of these studies that the comparatively small changes of relative humidity, surface temperature, wind shear and other parameters affect precipitation much stronger than aerosols. Moreover, the change in these parameters can lead to the change of the sign of precipitation response to aerosols. It is desirable to add this comment into the paper.

We appreciate the perspective provided by the reviewer. In the introduction, our goal is to describe a general tendency of the small change in precipitation amount with a 10-fold increase in aerosol for simulations of cloud systems over a long period and a large domain. As the reviewer indicates, single clouds or clouds of short duration could experience both small and large differences in precipitation amount.

It is true that environmental conditions (represented by stability, wind shear, surface temperature and humidity) influence clouds. However, the main interest of this study is not in the effects of these environmental conditions on clouds. Instead, it focuses on aerosol effects on clouds for a well studied tropical convective case study. To indicate this and ongoing work on single cloud and cloud systems using bin and bulk schemes to better understand aerosol effects on deep convective clouds, the following is added in the introduction:

(LL57-74)

Clouds play an important role in climate change by controlling the global radiation budget and hydrological cycle. While environmental conditions are the primary determinant of clouds and convection (Bluestein, 1993; Houze, 1993), aerosol particles have also been shown to play a role. The aerosol can influence different cloud types to varying degrees, and via different mechanisms, including cloud brightening, persistence of clouds, changes in cloud dynamics, and precipitation. The effects of these aerosol-cloud-precipitation interactions on climate have not been quantified adequately and represent one of the largest unknowns in climate forcing (Solomon et al., 2007). Motivated by this uncertainty, this study aims to enhance our understanding of the effect of increasing aerosol on tropical mixed-phase convective clouds. These clouds are one of the important components of the global hydrological cycle and the climate system.

Over the past decades, significant effort has been invested in development of microphysical representations of aerosol-cloud-precipitation interactions in deep convective clouds (e.g., Flossmann, 1991; Respondek et al., 1995; Yin et al., 2002; Khain et al., 2005; van den Heever and Cotton, 2007; Fridlind et al., 2012; Seifert et al., 2012), and to understanding the environmental conditions in which these clouds are likely to respond to aerosol perturbations (e.g., Khain et al., 2008a; Morrison and Grabowski, 2011; Seifert et al., 2012; Tao et al., 2012).

3. the sensitivity of results to the model resolution should be also stressed.

To examine the sensitivity of results here to resolution, the high-aerosol run and the control run are repeated with a horizontal grid length of 300 m (reduced from 500 m) and a vertical grid length of 120 m (reduced from 200 m); the aspect ratio is maintained. These repeated runs are referred to as the high-aerosol-high-res run and the control-high-res run, henceforth. Figures 2c, 3e and 6b for updraft mass flux, WP frequency and homogeneity from these repeated runs and comparisons between these figures and Figures 2a, 3c and 6a from the high-aerosol and control runs demonstrate that the qualitative nature of results is relatively insensitive to varying resolution. These repeated runs are described in a newly added section 4.5

4. This comment concerns the accuracy of the results. In the survey by Khain (2009) it was shown that surface precipitation is a small difference between two large values: generation of condensate (condensation, deposition) and the loss of condensate (evaporation, sublimation). A small error in calculation of any of the components may lead to a very significant change in surface precipitation. Taking into account that any model and any microphysical scheme are not perfect, the conclusion about the negligible effects of aerosols on precipitation amount should be treated with caution (as well as the opposite conclusions about dramatic effects of aerosols on precipitation).

This comment is especially applicable to the bulk-parameterization models which, according to results of many studies, tend to significantly underestimate aerosol effects on precipitation. The errors of different bulk schemes in reproduction of different physical processes are well known. For instance, the errors in reproduction of sedimentation lead to significant errors in calculation of surface precipitation (e.g., Milbrandt and Yau, 2005, Li et al 2009). The huge difference in sensitivity of the mass fluxes to aerosol effects obtained in this study and that of Morrison and Grabowski (2011) supports the statement that different bulk-schemes produce very different results in simulations of the same case studies. Thus, the estimation of 9% precipitation increase that can be obtained by increase in aerosol concentration can be considered as an estimation by order of magnitude.

The reviewer here raised the issue of representation of aerosol-cloud interactions. While we appreciate the fact that bin methods are inherently superior to bulk methods because they do not approximate the size distributions with basis functions, we believe that for long time/large domain simulations, bulk methods are a particularly attractive option. In the simulations here, parameters such as surface precipitation are largely driven by the largescale forcing (See Fridlind et al. 2012) so that biases such as those described in Li et al. 2009 will not be a concern. Perhaps the primary question is whether the nature of the cloud and rain fields (e.g., PDFs of WP, homogeneity, rainrate) is influenced by bin vs bulk.

We have not compared our results with bin microphysics, but do note that the microphysics scheme is based on bin microphysics simulations. In other words, within the assumption of a two moment representation of microphysics with a prescribed basis function (gamma), the method mimics bin microphysics. Nevertheless we do understand that these basis functions do not provide the same flexibility as a bin method. Bulk schemes enable larger domains, finer resolution, and longer simulations, and these are important factors when dealing with convection.

Fan et al. (2012) compared pdf of rainrate simulated by a bulk scheme to that by a bin scheme for a mesoscale convective system over China. Both the bulk and bin schemes show very similar decreasing or increasing trends of rainrate frequency with increasing aerosol in each of rainrate classes, although magnitudes of the increase or decrease in the frequency are different between the bulk and bin schemes. This indicates that qualitative nature of aerosol effects on the rain field is not influenced much by bin vs. bulk.

5. As regards to the model and the bulk-scheme used, it would be important to present
some results characterizing the accuracy of the method. For instance, DBZ distribution would be useful. What is the relation between convective and stratiform rain in the simulations? Can the authors to compare their results with observations?

Accuracy of the method is now evaluated relative to observations. When we compare cloud fraction for each of low-, mid-, high-cloud regions, there is a good consistency between the control run and observation. The cloud fraction is 45, 55, and 78% for low clouds (0-5 km), mid clouds (5-10 km), and high-clouds (10-15 km), respectively, for the control run and these are just a few percent different from observed values. Observed values are 43, 52 and 81% for low-, mid-, and high-cloud regions. The simulated average cloud-top height over the simulation period is 8.5 km and this is ~ 8% different from the observed height. The observed height is 7.8 km. The time- and domain-averaged LWP and IWP are 920 and 85 g m^{-2}, respectively, which are ~ 11% and 9% different from observed values, respectively. The observed LWP and IWP are 819 and 77 g m^{-2}, respectively. This indicates that the overall MCE structure is simulated reasonably well.

The following is added:

(LL188-197)

The simulated cloud fractions for low clouds (0-5 km), mid clouds (5-10 km), and high clouds (10-15 km), are within a few percent of observations: 45% (low), 55% (mid), and 78% (high) in the control run compared to 43% (low), 52% (mid) and 81% (high) in the observations. The simulated average cloud-top height over the simulation period is 8.5 km, while the observed height is 7.8 km (~ 8% difference). The time- and domain-averaged liquid-water path (LWP) and ice-water path (IWP) are 920 and 85 g m^{-2}, respectively, which are ~ 11% and 9% different from the observed LWP (819) and IWP (77 g m^{-2}), respectively. These comparisons provide confidence that the overall MCE structure is simulated reasonably well.

The relationship between convective and stratiform clouds is described in Figures 2, 3 and 4 in Lee and Feingold (2010).

Radar reflectivity (dBZ_e) from a millimeter wave cloud radar (MMCR) during the observation period is available. The MMCR is a zenith-pointing radar and provides the vertical distribution of reflectivity at the center of the TWP-ICE observation domain during the observation period and this vertical distribution represents the average vertical distribution over the whole observation domain. Hence, for comparison, simulated radar reflectivity is averaged over the domain and compared to the MMCR counterpart. The comparison between reflectivity averaged over time and domain from the control run and averaged over time from MMCR is made in Figure 3b.

The following is added:

(LL265-269)

To evaluate the model simulation of cloud particles (e.g., cloud-liquid and cloud–ice particles), radar reflectivity from a millimeter wave cloud radar (MMCR) (Seo and Liu, 2006) is compared to the simulated radar reflectivity for the control run (Figure 3b). Figure 3b demonstrates that simulated radar reflectivity follows the vertical distribution of the MMCR reasonably well.

6. The process of the cloud-aerosol interaction is not described in the paper. How are aerosols activated? Aerosols are depleted by nucleation scavenging. The process of the scavenging is very efficient.

To describe the activation process, the following is added:

(LL130-136)

Aerosol is represented by a single scalar (number mixing ratio) and the assumption of a fixed (lognormal) size distribution and a fixed composition (ammonium sulfate). With this assumption, droplet nucleation is calculated based on predicted supersaturation. The cloud droplet nucleation parameterization of Abdul-Razzak and Ghan (2000, 2002), which is based on Köhler theory, is used. Aerosol particles with critical supersaturation smaller than the model-calculated supersaturation are activated to droplets.

Scavenging processes are described in LL143-145

The authors use the periodic boundary conditions.
So, the boundaries are not serve as the aerosol sources. Does the aerosol concentration decrease with time in the computational area? If so clouds become more and

more "maritime", and effects of precipitation on aerosols decreases.

In this study, there is no source of aerosol, so aerosol concentration decreases with time. This was addressed in great detail by Lee and Feingold GRL 2010. We note that the timescale for readjustment of the perturbed (high-aerosol) simulation back to its initial state is about 7-17 days (depending on altitude) so that over the two day period, the high vs low aerosol contrast is still very distinct. Details can be found in Lee and Feingold, GRL 2010, Table 1.

Does a source of aerosols exist in the model? The treatment of aerosols can significantly affect the results.

No, there is no aerosol source, as mentioned above. However our tests on this case in the past indicate very weak sensitivity to whether an aerosol source exists or not over these relatively short (vis-à-vis aerosol) simulations.

7. How do the results of this study compare with the observed data by Koren et al. (2012) showing a significant increase in precipitation in Tropics with the increase in aerosol concentration?

Koren et al. (2012) did not address total precipitation amounts because they observed snapshots of the system at a fixed tome (13:30). Because they looked at TRMM radar, they observed only the higher rainrates. They too saw a shift in the PDF of rainrates to larger P, in agreement with this study. This is noted in Section 4.2, along with discussion of other studies.

8. The authors explain relatively low sensitivity of precipitation to aerosol by the compensation of the decrease in autoconversion rate by the increase in the accretion rate. What are values of ice content in this case? It seems that Figure 12 does not show a significant increase in ice mass content with increase in the aerosol concentration.

Associated with ~ one order of magnitude smaller differences in ice-water content than those in liquid-water content between the control and high-aerosol runs as shown in Figure 12, microphysical terms involving cloud ice in a precipitation budget equation make ~ one to two orders of magnitude smaller contributions to the difference in total precipitation amount between the runs as compared to those terms involving cloud liquid; note that ice-water content and liquid-water content in Figure 12 include only cloud ice and cloud liquid, respectively, and the time- and domain-averaged cloud-ice content is ~0.02 and ~0.04 g m^{-3} in the control and high-aerosol runs, respectively. Stated differently, the compensation is mainly due to accretion of cloud liquid by precipitable hydrometeors such as rain, snow, hail and graupel. To reflect this, text (LL13-15 in p3003 in the old manuscript) is revised as follows:

(LL208-216)

Among the sources and sinks, autoconversion and terms associated with accretion of cloud liquid account for the primary differences in the precipitation amount (Lee et al. 2008b; Lee and Feingold 2010). Autoconversion is suppressed, whereas accretion of cloud water increases in response to the aerosol perturbation. The increase in accretion is supported by substantial increases in condensation (30-40%) and associated cloud liquid (Lee et al. 2008b). Accretion of cloud ice by precipitation also increases with increasing aerosol however this increase is ~ one order of magnitude smaller than the cloud liquid accretion increase.

9. Last question. Why 9% increase in precipitation over large area is considered as negligible? The increase by 9% means the increase in the latent heat release by 9%. While this value is negligible, when we are talking about the weather forecast, this effect on climate can be significant.

We regard this increase as small relative to the 10-fold increase in aerosol. A 9% increase in surface rain is something hard to measure with confidence. The implications of this 9% change in surface rain rate are indeed interesting, which is what this paper has shown (changes in mass flux, homogeneity of cloud fields, etc.)

Minor remarks:

1) The sentence: "Two-day two-dimensional simulations of an observed mesoscale cloud ensemble (MCE; Houze, 1993) are performed over a two-day period. "two day" is used twice .

Corrected.

2) The text said: "Cloud system studies of long duration or encompassing large domains have demonstrated that total precipitation amount is predominantly determined by radiative-convective equilibrium (RCE) or the applied large-scale forcing, which leads to negligible variations of the precipitation amount with varying aerosol". This statement is not obvious, because aerosols represent not a passive component, but possibly an important component affecting radiative-convective equilibrium. You simulate a hypothetic scenario when aerosol concentration increases ten times in Tropics (or in some region of Tropics). In this extreme case the radiative-convective equilibrium will be different.

We have not performed simulations with RCE, however, Khairoutdinov and Yang (2013) and van den Heever et al. (2011) have shown that with a 10-fold increase in aerosol concentration, the domain-averaged properties of a deep convective system (e.g., precipitation amount) in RCE show a very weak response to the aerosol increase. It is true that there are aerosol-induced changes in environmental conditions such as SST and stability and associated changes in cloud properties such as precipitation amount in RCE in Khairoutdinov and Yang (2013) and van den Heever et al. (2011). This indicates there is some active role played by aerosol in modifying the RCE environment and associated cloud properties. However, the fact that domain-average cloud properties change very slightly supports the idea that overall cloud response to aerosol is constrained by given environmental conditions in RCE despite the presence of some active role by the aerosol increase.

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LETTERS

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