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Atmospheric
Chemistry
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Discussions

Interactive comment on “Cloud and aerosol effects on radiation in deep convective clouds: comparison with warm stratiform clouds” *by* S. S. Lee et al.

S. S. Lee et al.

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First of all, we would like to thank the reviewer for his or her comments and suggestions. In response to the reviewer comments, we have made relevant revisions on the manuscript. Listed below are answers and changes made to the manuscript according to the questions and suggestions given by the reviewer.

Response to specific major comment 1

Following the comments of the reviewer here on climatic aspects of this study, parts associated with climatic implications of this study in the manuscript are removed or revised as follows:

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(LL2-3 in p15293 in the old manuscript)

This has been a cause of large uncertainties in the prediction of climate changes.

(LL8-9 in p15295 in the old manuscript)

, which have garnered much more attention than deep convective clouds in climate studies.

(LL21-22 in p15292 in the old manuscript)

, indicating the assessment of effects of varying cloud types on radiation due to climate changes can be critical to the better prediction of climate.

(LL21 in p15293 - LL9 in p15294 in the old manuscript)

So far, general-circulation model (GCM) studies have mainly focused on the representation of cloud and aerosol effects on radiation in warm stratiform clouds. Cloud and aerosol effects on radiation in deep convective clouds have not been represented as explicitly as stratiform clouds. In GCM studies, stratiform clouds are represented by microphysics parameterization. However, deep convective clouds are considered sub-grid clouds and, thus, represented by cumulus parameterization. Cumulus parameterizations are unable to simulate cloud dynamics and microphysics explicitly. Thus, cumulus parameterization is not able to consider effects of microphysics on radiation and aerosol effects on dynamics, microphysics and thus cloud mass (both cloud liquid and cloud ice) of deep convection explicitly. Hence, the role of microphysics and aerosols in radiative budget in deep convection has not been represented in a physically realistic way in GCM studies. However, stratiform clouds are considered to be resolved by GCM grids and thus represented more explicitly via microphysics parameterization than deep convective clouds. This enables the simulation of changes in the properties of stratiform clouds caused by green house gases and aerosols in a more realistic way as compared to that in sub-grid deep convective clouds. Hence, GCM studies evaluate the variation of cloud radiative forcing due to green house gases and aerosols mostly based on the variation of cloud radiative forcing of stratiform clouds.

(LL20-24 in p15294 in the old manuscript)

Hence, the evaluation of variation of cloud radiative forcing due to green house gases and aerosols is needed to be based on changing radiative properties of deep convective clouds as well as changing radiative properties of stratiform clouds for the better prediction of climate changes; the accurate representation of cloud and aerosol effects on radiation in deep convective clouds in GCMs can be critical to the prediction of climate changes.

(LL27-30 in p15294 in the old manuscript)

This contributes to better understanding of cloud and aerosol effects on climate, which can be used to improve the representation of those effects in GCMs.

2. Parts revised:

‘‘Among the many atmospheric processes that play a role in climate,‘‘ (LL24 in p25292 in the old manuscript) is replaced with

‘‘Among the many atmospheric processes that play a role in the Earth‘s radiation budget,‘‘ (LL56-57 in p3 in the new manuscript)

The following is added in the summary and conclusion to indicate the need of long-term simulations to draw climatic implications.

(LL851-858 in p28-29 in the new manuscript)

Also, it should be pointed out that feedbacks between clouds and their environment for longer time period than that in this study can lead to different cloud and aerosol effects than shown here. Clouds here are simulated only for one day, which is much shorter than the time needed for a radiative-convective equilibrium state (around 30 days) according to Tompkins and Craig (1998). Hence, it is likely that the study here is only able to represent short-term transient behaviors of cloud and aerosol effects. This indicates the need to perform long-term simulations to draw robust climatic implications of this study.

Response to specific major comment 2

As the reviewer here pointed out, in stratocumulus, boundary layer processes, cloud-top radiative cooling, and entrainment at cloud top are key controlling factors in the stably stratified large-scale environment. The modification of those processes due to aerosol increases is associated with changes in evaporation, condensation and dynamics (i.e., updrafts and downdrafts) in stratiform clouds. However, as reported in Lee et al. (2008b) and shown in this study, the aerosol-induced modification of updrafts (involving the modification of those processes in stratiform clouds) is not as significant as the modification of updrafts in deep convective clouds. Lee et al. (2008b) found that the aerosol-induced changes in the temporal evolution of updrafts (controlling the changes in condensation and thereby cloud mass) was strongly controlled by the cloud depth, determining the acceleration of downdrafts and updrafts. In shallow stratiform clouds, changes in downdrafts in stratiform, led by those in boundary layer processes, cloud-top radiative cooling, and entrainment at cloud top through those in evaporation, could not be magnified as much as in changes in downdrafts in deep convective clouds due to shorter path between level of cloud-liquid evaporation and the surface which downdrafts took as they descended to the surface. This led to smaller changes in near-surface convergence and updrafts; the shorter path from the surface to the cloud-top also contributed to the further decreases in aerosol-induced changes in updrafts and thus cloud mass. In contrast, aerosol-induced changes in downdrafts in deep convective clouds could take longer path to the surface, enabling them to be accelerated more to result in larger aerosol-induced changes in near-surface convergence, updrafts and cloud mass than in shallow clouds.

Lee et al. (2008a) simulated the same deep convective case as simulated here. However, Lee et al. (2008a) focused on the analysis of dynamics and precipitation budget to understand precipitation increases at high aerosol while this study focused on aerosol effects on cloud mass and radiation budget. Lee et al. (2008a) found that increased cloud liquid due to delayed autoconversion at the initial stage of cloud development enhanced evaporative cooling of cloud liquid and downdrafts for the development of stronger low-level convergence and updrafts, leading to more condensation and precipitation. They found that the intensification of updrafts was primarily caused by increased evaporative cooling and thereby low-level convergence and the effects of increased freezing played a secondary role in the intensification of updrafts; the simulations with no ice physics showed the similar intensification of updrafts and increased precipitation to those in simulations with ice physics (refer to section 4.4 in Lee et al. (2008a) for more detail).

Modification of boundary layer processes, radiative cooling and entrainment in stratiform clouds play an important role in that of dynamics in stratiform clouds. Freezing in deep convective clouds play an important role in that of dynamics in deep clouds. However, they are not main causes of the differences in dynamics and cloud mass between deep and shallow clouds and those differences are primarily determined by the cloud depth. The presence of well-known effective interactions between evaporation and gust front (i.e., near-surface convergence) through downdrafts in deep convection, sustaining strong updrafts, is made possible by the large depth of clouds in deep convective clouds (Houze,1983). The presence of those effective interactions made it possible for the aerosol-induced changes in microphysics to change updrafts more effectively in deep convective clouds than those in shallow clouds.

Response to specific major comment 3

1. Ice crystal shape

As can be seen figure 3b, the large portion of mass of cloud ice is concentrated around or above the level of homogeneous freezing (around 10 km) where the conversion of cloud ice to precipitable snow is known to very inefficient due to the absence of liquid-phase particles. Hence, although we assumed the collection efficiency of 1 for collisions between cloud ice and liquid-phase particles, it is found that just around 5% of the ice formed by deposition is converted into snow in this study according to budget analysis. As indicated in Pruppacher and Klett (1978), different crystal habits lead to different collection efficiency. This indicates that different crystal habits lead to different removal of cloud ice through precipitation as snow, which in turn can change the mass of cloud ice and thus radiative properties of deep clouds. However, the low conversion efficiency of cloud ice, which is around 5 %, even with the collection efficiency of 1 indicates that there will be negligible changes in the mass of cloud ice with different crystal habits assumed. As an extreme case, if we assume a crystal habit having the efficiency of 0.1, it is expected that around 0.5 % of cloud ice is converted into snow. This brings only around 4.5 % change in the mass of cloud ice to the mass of cloud ice simulated in this study.

The effect of crystal habit on crystal optical properties and thus radiation is a function of the aspect ratio of ice particles (Fu, 2007, JAS); the difference in the effects of crystal habit on radiation is proportional to that of aspect ratio characterizing the crystal habit. This study assumed the columnar shape of ice crystals for the calculation of radiative fluxes, following Phillips et al. (2007). The columnar shape has an aspect ratio of around0.3-0.5, which corresponds to lower end of aspect ratio among ratios of ice particles. Fu (2008, JAS) showed the increase in reflected solar fluxes by cirrus clouds by around 10 % when crystal habit changed from columnar shape to plate or dendrites having aspect ratio around 0.7-1.0, corresponding to upper end of aspect ratio. Wendisch et al. (2007,JGR) showed the dependence of LCF on crystal shape at TOA for high cirrus. For the high cirrus between 13 and 15 km, the change from column to plate or dendrite led to around 14 % increase in LCF, whereas this change brought around 20 % increase in LCF in the low cirrus between 6 and 8 km in their scenario of constant ice water content; they varied crystal habit with no changes in ice water content in this scenario. Since cirrus clouds simulated here are located between the high and low clouds in Wendisch et al. (2007), it is likely that the increase in LCF with the change of crystal habit is between around14 and around 20 %. Hence, the results of Fu (2008) and Wendisch et al. (2007) suggest that both negative SCF and positive LCF increase at TOA for the change of crystal habit from column to plate or dendrite, which can represent an extreme case of the change in crystal habit. For this change in the habit, if we assume that SCF and LCF at TOA change by around 10 % and around17 % (a mid-value between 14 and 20 %) in DEEP based on Fu (2008) and Wendisch et al. (2007), respectively, 48 % (86 %) of SCF is counterbalanced by LCF in the high-aerosol run (low-aerosol run) and 29 % of an increase of negative SCF due to aerosol increases is offset by that of LCF. With columnar shape assumed in this study, 45 % (81 %) of SCF is counterbalanced by LCF in the high-aerosol run (low-aerosol run) and 28 % of an increase of negative SCF due to aerosol increases is offset by that of LCF. Hence, less than 5 % changes in the offset of SCF by LCF are shown with varying crystal habit from column to plate or dendrite. This demonstrates that the qualitative nature of results of this study does not depend on the crystal habit.

The following is added in the summary and discussion to discuss about the effects of crystal habit on the results here (LL 1004-1035 in p33-34 in the new manuscript).

As can be seen in Figure 3b, the large portion of mass of cloud ice is concentrated around or above the level of homogeneous freezing (around 10 km) where the conversion of cloud ice to precipitable snow is known to very inefficient due to the absence of liquid-phase particles. Hence, although we assumed the collection efficiency of 1 for collisions between cloud ice and liquid-phase particles, just around 5% of the ice formed by deposition was converted into snow in this study. Different crystal habits lead to different collection efficiencies (Pruppacher and Klett, 1978). This indicates that different crystal habits lead to different removal of cloud ice through precipitation as snow, which in turn can change the mass of cloud ice and thus radiative properties of deep clouds. However, the low conversion efficiency of cloud ice, which is around 5 %, even with the collection efficiency of 1 demonstrates that there will be negligible changes in the mass of cloud ice with different crystal habits assumed. As an extreme case, if we assume a crystal habit having the efficiency of 0.1, it is expected that around 0.5 % of cloud ice is converted into snow. This brings only around 4.5 % change to the mass of cloud ice simulated in this study. This indicates that results here are not likely to depend on changes in the mass of cloud ice induced by different conversion of ice crystals to snow due to the variation of an assumed crystal habit for collection processes. The dependence of crystal optical properties on the crystal habit is a function of the aspect ratio of ice particles (Fu, 2008); the difference in the crystal optical properties is proportional to that in the aspect ratio characterizing the crystal habit. This study assumed the columnar shape of ice crystals for the characterization of the optical properties and thus calculation of radiative fluxes, following Phillips et al. (2007). The columnar shape has an aspect ratio of around 0.3-0.5, which corresponds to the lower range of aspect ratio of ice particles. Fu (2008) showed the increase in reflected solar fluxes by cirrus clouds by around 10 % when the crystal habit changes from the columnar shape to the plate or dendrites having aspect ratio around 0.7-1.0, corresponding to the upper range of the aspect ratio. Wendisch et al. (2007) showed that that change in the habit leads to around 14 - 20 % increases in LCF. These changes in SCF and LCF bring only less than 5 % change to the percentage offset of SCF by LCF in each of the high- and low-aerosols runs and to the offset of varying SCF by varying LCF between the high- and low-aerosol runs shown in Table 1. This demonstrates that the qualitative nature of results of this study does not depend on crystal optical properties varying with the crystal habit.

2. Fall speed of ice crystal

The following is included in the section 3.5.1 in the new manuscript to discuss about the impact of the parameterization of the ice-crystal fall speed.

(LL690-713 in p23-24 in the new manuscript)

The fall speed of ice crystal is taken into account in this study. The fall speed is parameterized in the same manner as in Phillips et al. (2007). This parameterization is based on the fall-speed power law relating the crystal maximum length to the fall speed through a couple of coefficients, representing the crystal habit. Those coefficients are ai and bi in Phillips et al. (2007) (See section 2d in Phillips et al. (2007) for more detail). According to Khvorostyanov and Curry (2002), generally ai varies 0.33-1.23 and bi varies 60-2250 with the varying crystal habit assumed. In this study, crystals are assumed to be columnar for the purpose of calculating the fall speed. To examine the impacts of the fall speed of ice crystals on results here, simulations in DEEP are repeated with each of the following four pairs of values of those coefficients:

1. ai =0.33, bi=60 2. ai =0.33 bi=2250 3. ai =1.23 bi=60 4. ai =1.23 bi=2250

Values of the four pairs correspond to the upper and lower ends of the general variation of those coefficients. Hence, the impacts of the extreme variation of the fall speed can be examined through the comparisons of those four pairs of experiments. All simulations caused less than 3 % changes in the mass of cloud ice as compared to those presented in the section 3.2 for each of high- and low-aerosol runs, resulting in nearly the same radiative fluxes as compared to those in Table 1. Hence, the qualitative nature of results here do not depend on the assumed crystal habit for the parameterization of the fall speed of ice crystals.

3. Thresholds for conversion of rimed snow to graupel

As mention in the response to the comment on the crystal habit, it is found that just around 5 % of the ice formed by deposition is converted into snow. This indicates that the conversion of cloud ice to snow and then to graupel through rimed snow is highly inefficient; less than 1 % of the ice is converted into graupel through rimed snow according to the budget analysis. Hence, although we assumed a threshold of snow mass of 0.5 g m-3, the mass of cloud ice is not likely to be sensitive to this threshold, considering very inefficient conversion of cloud ice to snow and graupel. To confirm this, additional simulations are performed for DEEP. The first (second) set of those simulations adopts the threshold increased (decreased) tenfold from 0.5 g m-3. These variations of threshold just bring less than 5 % change in the mass of cloud ice as

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compared to presented in the paper for each of high- and low-aerosol runs, resulting in nearly the same radiative fluxes as those presented in the paper. This indicates the results in this study are robust to the threshold adopted.

The following is included in the section 3.5.2 in the new manuscript to discuss about the impact of the thresholds.

(LL718-731 in p24 in the new manuscript)

It is found that just around 5 % of the ice formed by deposition is converted into snow. This indicates that the conversion of ice to graupel through the rimed snow is very inefficient; less than 1 % of the ice is converted into graupel through rimed snow. Hence, it is not likely that the mass of cloud ice (controlling the radiative fluxes) is sensitive to the threshold of snow mass used in the parameterization of the conversion of rimed snow to graupel (See section 2h in Phillips et al. (2007) for more detail); in this study the threshold of 0.5 g m-3 is used following Phillips et al. (2007). To confirm this, additional simulations are performed for DEEP. The first (second) set of those simulations, composed of the high- and low-aerosol runs, adopts the threshold increased (decreased) tenfold from 0.5 g m-3. These variations of threshold just bring less than 5 % changes in the mass of cloud ice as compared to those presented in the section 3.2 for each of high- and low-aerosol runs. This leads to negligible differences in TOA and SFC radiative fluxes between these additional simulations and those with the threshold of 0.5 g m-3.This indicates the results in this study are robust to the threshold adopted.

4. Rain/snow/graupel size distribution parameters

The following is included in the section 3.5.3 in the new manuscript to discuss about the impact of the size distribution parameters.

(LL735-760 in p25 in the new manuscript)

The size distribution of precipitable hydrometeors obeys the exponential distribution

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described in Lin et al. (1983); an intercept parameter controls the shape of the exponential distribution for a given mixing ratio of preicipitable hydrometeors. In this study, the parameters are set to 8 x 10**6, 3 x 10**7, and 4 x 10**4 m-4 for rain, snow, and graupel, respectively. For a given mixing ratio of a precipitable hydrometeor, a lower (higher) intercept parameter results in a higher (lower) mass-weighted mean diameter and thus higher (lower) fall speeds. Hence, it is expected that a higher (lower) intercept parameter results in less (more) depletion of cloud liquid and cloud ice through collisions between cloud particles (cloud liquid and cloud ice) and precipitable hydrometeors. The high- and low-aerosol runs in DEEP are repeated with all of the intercept parameters increased by a factor of 10 to examine the sensitivity of results to the intercept parameters. As expected, the mass of cloud ice and cloud liquid is larger than those shown in section 3.2. The increases in cloud mass are around 2 (5) and 8 (13) % for cloud ice and cloud liquid, respectively, in the low- (high-) aerosol run. This leads to the increase of around 10 % in the percentage offset of SCF by LCF in each of the high- and low-aerosol runs than that presented in Table 1. Due to larger increases in cloud mass in the high-aerosol run than in the low-aerosol run, around 5 % larger percentage offset of the increased negative SCF by increased LCF occurs than the percentage offset shown in Table 1. When the simulations in DEEP are repeated with the parameters decreased by a factor of 10, cloud mass decreases. Those lead to around 7 % smaller percentage offset of SCF by LCF in each of the high- and low-aerosol runs and around 3 % smaller percentage offset of the increased SCF by increased LCF at high aerosol, as compared to those shown in Table 1. However, those variations in the offsets (whether due to increases or decreases in the intercept parameters) are much smaller than those between stratiform clouds and deep convective clouds described in the previous sections. This demonstrates the qualitative nature of results here dose not depend on the size-distribution parameters.

5. The impacts of the use of 2D domain.

The following is added to discuss the potential implications of 2-d restriction for the

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results here in summary and discussion.

(LL980-1003 in p33 in the new manuscript)

Use of a two-dimensional, rather than three-dimensional, cloud-system model affords substantial computational advantages but, as Phillips and Donner (2007) note, some aspects of the dynamics and microphysics in deep convection differ in two- and three-dimensional models. Phillips and Donner (2007) found that vertical velocities and mass fluxes in deep convective updrafts, and downdraft mass fluxes, were larger in three dimensions than two dimensions. Downdrafts play an important role in the interactions among dynamics, microphysics and radiation in deep convection described in this paper. Phillips and Donner‘s (2007) results suggest that this mechanism may have been underestimated in two dimensions. Conversely, Phillips and Donner (2007) also found that comparatively weak convective clouds were more numerous in two dimensions. To the extent these clouds play a role, they may be overestimated in two dimensions. Guo et al. (2007) showed that basic features of the integrations (e.g., the CDNC, LWP and effective size) were similar for two and three dimensional simulations of warm stratocumulus clouds. The results of Guo et al. (2007) suggest that responses of radiation to clouds and aerosols in warm startiform clouds are robust to dimensionality of domain. A three-dimensional version of simulations of the same cases of deep convective system (the 1997 ARM case) and warm stratiform clouds (the 2002 case off the coast of Virginia) as simulated here has also been conducted. For this simulation, single-moment microphysics, similar to Phillips and Donner (2007), was used. The radiation in each of the high- and low-aerosol run in these cases behaved similarly to that in this study. Also, the high-aerosol runs in these cases behaved relative to the low-aerosol runs similarly to the high-aerosol runs in this study with similar radiation responses to aerosols. Although the microphysics is highly simplified in the three-dimensional experiment, this result suggests that the qualitative character of the results here does not depend on the dimensionality of the experiments.

6. The impact of the resolution

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The following is added in the summary and conclusion to discuss the sensitivity of results to the resolution adopted.

(LL1036-1044 in p34-35 in the new manuscript)

As does the choice of two dimensions, the choice of resolution (2 km horizontal, 500 m vertical) affords substantial computational advantages. Donner et al. (1999) reported a series of test calculations with a similar cloud-system model with resolutions ranging from 500 m to 5 km. They found basic features of the integrations (e.g., patterns of vertical velocity) were similar for horizontal resolutions of 2 km or finer for convective clouds. Simulations in DEEP are repeated with the vertical resolution of 100 m to test the sensitivity of results to the vertical resolution. It is found that the principal aspects of results with the 100-m vertical resolution are similar to those with the 500-m vertical resolution.

7. The impact of treatment of ice nucleation

The following is added in the summary and conclusion to discuss the impact of the treatment of heterogeneous ice nucleation.

(LL910-919 in p30-31 in the new manuscript)

Lee et al. (2008a) showed that differences in the mass of ice particles (and thereby the offset of SCF by LCF) between the high- and low-aerosol runs were not significant before stronger updrafts were triggered by enhanced evaporative cooling of cloud liquid at high aerosol. The more intense feedback between updrafts and depositional heating after the development of stronger updrafts played a crucial role in the substantially increased ice mass at high aerosol. However, this does not preclude other interactions as controls on the responses of ice mass to aerosols. For example, Lohmann and Diehl (2006) indicated that different interactions between IN and nucleation (per se) in mixed-phase and ice clouds can lead to the significant variation of the offset of SFC by LCF with aerosol increases. The role of those interactions in responses of ice particles

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to aerosols deserves the further study.

The following is added in the summary and conclusion to discuss the impact of the treatment of homogeneous ice nucleation.

(LL1080-1095 in p36 in the new manuscript)

Homogeneous freezing of haze particles in this study is assumed to occur instantaneously when a size- and temperature-dependent critical supersaturation with respect to ice is exceeded. The critical supersaturation is determined by a look-up table also used in Phillips et al. (2007). For the construction of the look-up table, aerosols dissolved in haze particles are assumed to be ammonium sulphate. Mangold et al. (2005) reported that the critical supersaturation could be lowered by 30 % from that for the ammonium sulphate maximally with varying chemical compositions of aerosols. With a lower critical supersaturation, more aerosol particles can be nucleated for the identical size distribution of haze particles and ambient temperature. Repeated simulations with the critical supersaturation, which is forced to be lowered by 30 % (every time there is the homogeneous freezing of haze particles), showed that more ice particles were formed than shown in section 3.2. This led to more offset of SCF by LCF than that with the ammonium-sulphate haze particles in each of the high- and low-aerosol runs. This increase in the offset was larger at high aerosol than at low aerosol. This led to larger offset of the increasing negative SCF by increasing LCF than that shown with ammonium-sulphate haze particles at high aerosol.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 15291, 2008.

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