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Atmospheric
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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.

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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. Each comment of the reviewer is listed and followed by our responses.

Given the complex interactions between microphysical and dynamical feedbacks in the context of convective clouds it is questionable whether the simulations satisfy the goal proposed by the authors on page 5 namely to conduct physically realistic simulations. The potential implications of this restriction for the general outcome of this work should

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be discussed.

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.

Secondly, the authors do not discuss the role of ice crystal shape in their simulations. However, the ice crystal shape is a function of temperature and ice supersaturation

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(Pruppacher and Klett, 1997) and is an important aspect for radiative interactions. At least, the authors should investigate to what extent the conclusions drawn in this manuscript could be affected by assumptions of the ice crystal geometry.

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 around 0.3-0.5, 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

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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 around 14 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 around 17 % (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.

Thirdly, the findings of the manuscript are not summarized very well and are not sufficiently put into context with the results of similar studies such as Lohmann and Diehl (2006) and Lohmann (2008).

The followings are added to discuss about the results of Lohmann and Diehl (2006) and Lohmann (2008).

(LL 843-858 in p28-29 in the new manuscript)

Lohmann (2008) examined the effects of changes in greenhouse gas since industrialization on precipitation using a GCM coupled with double-moment microphysics for both convective and stratiform clouds. She reported the invigoration of convective clouds in a warmer present-day climate, leading to increased precipitation in convective regions. Hence, her results appear to support the hypothesis about the changing relation between CAPE and the convection intensity (and thus cloud-top height) with global warming, suggested above. However, the implications for large-scale aspects of this study will require further study with larger-domain models which is coupled with advanced microphysics and able to resolve convective cells. 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.

(LL 910-919 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

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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 to aerosols deserves the further study.

Finally, the manuscript would benefit from being more concise and from avoiding repetitions. Furthermore, the style of the manuscript needs modifications to improve the flow of the manuscript and its general appeal.

Expressions are revised or removed to avoid repetitions and to enhance the flow of the manuscript.

Revised expression:

The expressions ‘‘Different modulation of LCF between the deep convective MCE and stratiform clouds is mostly due to differences in cloud depth and cloud-top height. This implies different modulation of LCF even among different types of convective clouds with different cloud depth and cloud-top height.‘‘ (LL 561-564 in p19 in the old manuscript) are replaced with

‘‘The crucial role of cloud depth and cloud-top height in the different modulation of LCF for the deep convective MCE and stratiform clouds implies that the modulation of LCF can vary even among different types of convective clouds.‘‘ (LL 577-579 in p19-20 in the new manuscript)

Removed repetitive expressions:

(LL 89-91 in p4 in the old manuscript)

However, stratiform clouds are considered to be resolved by GCM grids and thus represented more explicitly via microphysics parameterization than deep convective clouds.

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(LL 149-151 in p6 in the old manuscript)

Those marine stratiform clouds are simulated using the CSRM with smaller domain and finer resolution as compared to those for the simulation of the MCE.

(LL 624-626 in p21 in the old manuscript)

Due to lower cloud-top height, smaller portion of SCF is counterbalanced by LCF in DEEP (LOW-CU) than in DEEP (CU) (Table 4).

(LL 771-778 in p26 in the old manuscript)

This study demonstrates that different cloud and aerosol effects on radiation among different types of clouds were strongly controlled by cloud vertical extent and cloud-top height. The larger cloud-top height of clouds was the primary cause of large LCF, leading to the larger offset of SCF by LCF in deeper clouds. Also, the larger vertical extent of deeper clouds enabled much more intense low-level downdrafts, leading to substantially increased updrafts and cloud mass at high aerosol as compared to those in comparatively shallower clouds. This led to more offset of increased negative SCF by increased LCF at high aerosol in deeper clouds. Hence,

Specific comments:

The introduction section is rather long and contains many repetitions and tech- nical explanations which may be better suited for a model description section (e.g., the paragraphs starting at line 132 until the end of the introduction). Here, my suggestions is to shorten this section drastically and merge some of the dis- cussion with a model description section in order to make the introduction more concise and more appealing to read.

Parts removed in the introduction.

(LL134-145 in p5-6 in the old manuscript)

The double-moment microphysics predicts cloud particle (i.e., cloud liquid and cloud

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ice) number as well as cloud particle mass. Nucleation is calculated by considering aerosol number, chemical composition and size distribution. This is different from previous bulk schemes coupled with saturation adjustment or empirical nucleation schemes where initial cloud particles are diagnosed with no consideration of aerosols (See Appendix A for the description of the CSRM). Also, homogeneous aerosol (haze particles) and droplet freezing are considered by using size distribution of unactivated aerosols and taking into account evaporation of small droplets during homogeneous freezing, following Phillips et al. (2007). Hence, it is expected that cloud and aerosol effects on radiation in deep convection and stratiform clouds are simulated with better confidence in the CSRM adopted here than that in previous bulk schemes coupled with saturation adjustment or empirical nucleation schemes.

Parts in the introduction moved to the other sections

Parts ‘‘To better isolate the different role of clouds and aerosols in radiation, differences in environmental conditions between those two types of clouds needs to be minimized. For this, those two types of clouds are simulated for the same LST (local solar time) period at the same latitude on the same date. Hence, the nearly same incident solar radiation is applied to those two types of clouds. Also, calculations described in the following section 3.1 show the difference in surface longwave radiation flux between two types of clouds is within around 5 % relative to the flux in deep convective MCE. Thus, both types of clouds are affected by similar radiation input from the top of the atmosphere (TOA) and the surface.‘‘ (LL 152-160 in p6 in the old manuscript) are moved to the section 2 in the new manuscript (LL170-179 in p6-7 in the new manuscript)

Parts ‘‘Aerosols in high-aerosol run for the case of marine stratiform clouds showed similar aerosol concentration at the surface to that for the case of the MCE. This is because those stratiform clouds are simulated in near-coastal regions just off the coast of Virginia where significant increases in aerosols advected from the continent were observed since industrialization. Hence, the comparison of the high- and low-aerosol runs for the case of stratiform clouds identifies aerosol effects for the similar transition

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of aerosol levels to that for the case of the MCE. This indicates the MCE and stratiform clouds both are affected by similar aerosol environment, minimizing differences in aerosol level to contribute to the better isolation of the role of different cloud and aerosol effects on radiation between two types of clouds.‘‘ (LL 175-184 in p7 in the new manuscript) are moved to the section 2 (LL219-228 in p8 in the new manuscript).

Parts ‘‘the comparison of the high- and low-aerosol runs identifies how a transition from maritime aerosols to rather polluted continental aerosols affect radiation‘‘ (LL173-174 in p7 in the old manuscript) are moved to the section 2 (LL238-240 in p8-9 in the new manuscript).

Responses to comments on P.4, l.89

Added statements to indicate the use of the double-moment microphyiscs for convective clouds (LL 843-845 in p31 in the new manuscript):

‘‘Lohmann (2008) examined the effects of changes in greenhouse gas since industrialization on precipitation using a GCM coupled with double-moment microphysics for both convective and stratiform clouds.‘‘

Responses to comments on P.7, l.170

For the assumed log-normal size distribution with the identical standard deviation and mode radius here, the ratio of aerosol mass partitioned into each bin of size distribution to total aerosol mass does not vary with total aerosol mass. Hence, decreased total aerosol mass by a factor of 10 leads to 10-fold decreases in aerosol mass in all size bins in the low-aerosol run. This also leads to 10-fold decrease in aerosol number, since the identical particle density of each aerosol species is used for the high- and low-aerosol runs. The following is added to clarify this interdependence:

(LL229-237 in p8 in the new manuscript)

‘‘The low-aerosol runs are conducted with aerosol profiles obtained by reducing aerosol masses used for high-aerosol run by a factor of 10. For the assumed log-normal size distribution with the constant standard deviation and mode radius here, the ratio of aerosol mass partitioned into each size bin of the distribution to total aerosol mass does not vary with total aerosol mass. Hence, decreased total aerosol mass by a factor of 10 leads to 10-fold decreases in the partitioned aerosol mass in all size bins in the low-aerosol runs. This also leads to 10-fold decreases in aerosol number in each bin of the size distribution, since the identical particle density of each aerosol species is used for the high- and low-aerosol runs.‘‘

Responses to comments on P.8, l.202

‘‘in a physically realistic way‘‘ in LL 127-129 in p5 in the old manuscript is removed.

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

Responses to comments on P.9, l.247

Black carbon is considered as ice nuclei but not as cloud condensation nuclei in this study as stated in the section 2 in the new manuscript (LL205-207 in p7 in the new manuscript).

As can be seen in figure 1a, the mass of black carbon is one to three orders of magnitude smaller than the mass of aerosol particles assumed to act as CCN. Accordingly, number concentration of black carbon is around two orders of magnitude smaller than that of aerosol particles acting ac CCN below the freezing level. Even among ice nuclei, black carbon accounts for very small portion of ice nuclei as can be seen in figure 1a and as reported by DeMott et al. (2003, PNAS).

Although black carbon can act as CCN after coated by the sulfate, the very small mass and number of black carbon below the freezing level justifies that it can be neglected for droplet nucleation.

The following is added to clarify that black carbon aerosols are used only as IN .

Dust and BC aerosols are assumed to act only as ice nuclei (IN), since this study does not consider dust and BC aerosols coated by the sulfate which can act as CCN (LL205-207 in p7 in the new manuscript).

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Responses to comments on P.10, l.278

We only considered aerosol effects on nucleation of cloud particles and interactions between aerosols and radiation are not taken into account.

Interactions among microphyiscs, radiation and dynamics are taken into account. As shown in Lee et al. (2008,QJRMS), different effects of aerosols on clouds lead to different radiative heating (Lee et al. (2008,QJRMS) simulated the same deep convective case as simulated here. However, Lee et al. (2008,QJRMS) 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). Mainly due to larger mass of cloud liquid at high aerosol, there is less and more cooling around the base and top of liquid cloud, respectively, at high aerosol. This lead to greater instability for more intense interactions between microphysics and dynamics, contributing larger precipitation at high aerosol.

The following is added to clarify the sentences pointed out here (LL248-252 in p9 in the new manuscript).

This study focuses on aerosol effects on the nucleation of cloud particles and thereby cloud microphysical and radiative properties and, thus, does not take into account aerosol direct effects on radiation. In other words, aerosols do not have any effects on radiation before their activation and their impacts on cloud-particle properties after their activation are only taken into account.

Responses to comments on P.15, l.417

In fact, figure 3c shows that rain amount increases with increased aerosols due to interactions between microphysics and dynamics as shown in Lee et al. (2008,QJRMS), leading to increased precipitation at high aerosol. Lee et al. (2008,QJRMS) found that increased cloud liquid due to delayed autoconversion at the initial stage of cloud development enhances evaporative cooling and downdrafts for the development of stronger low-level convergence and updrafts, leading to more condensation, rain and surface precipitation.

Responses to comments on P.15, l.419

The bottom of the figure 4a does not correspond to the surface but to the lowest grid point of the atmosphere, whose height is around 250 m. During time integration, heights of cloud bases vary mostly from around 0.25 km to around 2 km due to spatiotemporally varying large-scale forcing and perturbed humidity and temperature fields by preexisting clouds. Hence, the lowest level of time-averaged cloud liquid is at the bottom of the figure.

The freezing level is around 4 km

The following is added to the caption of figures 2, 3, 4, 7, 9, and 10 to indicate the bottom of those figures corresponds to the lowest grid point of the atmosphere.

The bottom of each figure corresponds to the lowest grid point of the atmosphere which is 250 (20) m for DEEP (SHALLOW).

The following is added to indicate the cloud-base height and freezing level (LL 338-342 in p12 in the new manuscript).

During time integration, heights of cloud bases vary mostly from around 0.25 km (corresponding to the bottom of figures 2a-c and 3a-d) to around 2 km due to spatiotemporally varying large-scale forcing and perturbed humidity and temperature fields by preexisting clouds. The freezing level is around 4 km.

Responses to comments on P.16, l.450

As discussed above, the rain amount increases with increasing aerosols. Lee et al. (2008,QJRMS) shows that rain evaporation plays a negligible role in the intensification of downdrafts as compared to that played by evaporation of cloud liquid at high aerosol. For more detail, see section 4.3 in Lee et al. (2008,QJRMS).

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Responses to comments on P.16, l.455

The relative contribution of the aerosols to domain-averaged mass flux looks similar for deep convective and shallow clouds (figures 5a and 5b). However, when mass fluxes are conditionally averaged over grid points in clouds, DEEP shows around 4 times larger relative increases in mass fluxes at high aerosol than those in SHALLOW. Since DEEP shows around 3-4 times smaller cloud fraction, when mass fluxes are averaged over the entire domain, the relative differences in mass fluxes between the high- and low-aerosol runs decreases to be similar to those in SHALLOW. This larger relative increases in in-cloud averaged mass fluxes, associated with the larger domain-averaged increases in mass fluxes, lead to larger relative increases in cloud mass shown in figure 3.

The following is added to indicate the larger relative increases in in-cloud mass fluxes at high aerosol in DEEP than in SHALLOW (LL 459-462 in p16 in the new manuscript).

the differences in in-cloud averaged increases of mass fluxes at high aerosol between DEEP and SHALLOW are around 4 times larger than those shown in Figures 5a and 5b, indicating there is a larger relative increase in mass fluxes at high aerosol in cloud regions in DEEP than in SHALLOW.

Responses to technical comments

We corrected grammatical and typographic errors. To improve the flow, the repetitive expressions are revised or removed (see our responses to the last general comment for details)

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