First of all, we would like appreciate the reviewer's comments and suggestions. In response to the reviewer comments, we have made relevant revisions in the manuscript. Listed below are our answers and the changes made to the manuscript according to the questions and suggestions given by the reviewers. Each comment of the reviewer is listed and followed by our responses (between dotted lines).

Interactive comment on "Factors determining the effect of aerosols on cloud mass and the dependence of these factors on liquid-water path" by S. S. Lee and J. E. Penner

Anonymous Referee #1

Received and published: 19 October 2009

Review of "Factors determining the effect of aerosols on cloud mass and the dependence of these factors on liquid-water path", by Lee and Penner

Overview: This paper presents results from a large eddy model showing that, in thin (low LWP) clouds, aerosol-driven differences in condensation/evaporation may have significant impacts upon the cloud radiative properties. In thin clouds these effects may exceed those associated with precipitation suppression (the so-called second aerosol indirect effect). The results are interesting, and complement earlier work (Arnason and Greenfield 1972, Kogan and Martin 1994, Kogan et al. 1995, Wang et al. 2003, Grabowski and Morrison 2006) suggesting important effects of cloud microphysics (and hence aerosols) on cloud dynamics through the finite supersaturation relaxation time and delayed condensation/evaporation, effects that are independent of aerosol effects on sedimentation/precipitation. Some of this important earlier work is not cited which makes me wonder whether the authors are aware of it.

The following is added to cite earlier work mentioned here.

(LL101-104 in p4 in the new manuscript)

The importance of the effect of aerosols on condensation and cloud dynamics in Lee et al. (2009) has also been discussed in previous studies (Arnason and Greenfield, 1972; Kogan and Martin, 1994; Kogan et al., 1995; Wang et al., 2003; Grabowski and Morrison, 2006).

The authors find that in thin clouds, in which precipitation effects are small, increased aerosols may lead to stronger updrafts since condensation and evaporation rates are higher. In some of their model cases this leads to thicker clouds, and in others the opposite is true. This is not entirely surprising since it is likely that the way in which the cloud thickness is changed occurs through changes in entrainment rate, and whether increased entrainment thickens or thins clouds depends upon the environmental conditions and timescale as explored by Randall (1984), Ackerman et al. (2004) and Wood (2007).

I believe that the authors have a result that is very tantalizing since, to my knowledge, no previous study has specifically considered the aerosol indirect effect associated with microphysically-limited condensation. The findings of this work are certainly worthy of publication in Atmospheric Chemistry and Physics. However, the manuscript could be much better: the approach is not particularly well-conceived, the manuscript is sloppy in places, and does not do due justice to previous important work on this subject. For example, statements like "....the role of feedbacks between microphysics and dynamics become more important with the lowering level of LWP" (abstract) give the impression that somehow precipitation-driven aerosol effects do not involve feedbacks between microphysics and dynamics. This is totally untrue as numerous previous studies involving the effects of drizzle have shown. The authors also do not acknowledge the potential and previously-explored problems of supersaturation prediction in cloud resolving models (e.g. Stevens et al. 1996, Grabowski and Morrison, 2006, and see discussion in Reisner and Jeffery 2009) that one might imagine could lead to spurious estimates of microphysics on condensation rate.

The following is added to discuss about the spurious prediction of supersaturation:

(LL623-628 in p21 in the new manuscript)

It has been reported that spuriously high supersaturation can be simulated around cloud top (Stevens et al., 1996; Grabowski and Morrison, 2006; Reisner and Jeffery, 2009). However, most of condensation is affected by supersaturation around the mid-level of clouds. Less than 2 % of condensation is accounted for by supersaturation around cloud-top (i.e., at $z/z_t > 0.95$). Hence, the qualitative nature of results here is not likely to be affected by the spurious supersaturation around cloud top.

I recommend that the authors revise their manuscript to reflect the previous work and to better explore the physical processes driving their liquid water path responses.

Major points:

1) I wouldn't call increasing latent heat flux by a factor of five a "minimized difference in environmental conditions" (P19319, line 5), since LHF increases not only the LWP but also the buoyant driving of the boundary layer. What are the authors trying to show here? If they wish to show that at low LWP, the precipitation is less important, then this could be done by more indirect means such as moistening the free-troposphere and allowing the entrainment of moister air to drive thicker clouds. An alternative would be simply to run with and without precipitation.

We think the proposed method (involving the moistening the free-troposphere) by the reviewer here also changes cloud dynamics involving the buoyant driving of the boundary layer as well as the LWP. Hence, we do not believe that this proposed method would enable us to minimize difference in environmental condition more effectively than the method we used.

As mentioned in the introduction (LL13-24 in p 19316 in the old manuscript), small cloud droplets grow to a critical size for (active) collection not only by the turbulent collisions among them but also by condensation; for particles smaller than the critical size, condensational growth is as important as the growth through the turbulent collisions and particles grow via positive feedbacks between the condensational growth and the growth through these turbulent collisions, though, above the critical size, the growth through collection is dominant (Rogers and Yau, 1991). Thus, as clouds get thinner, these feedbacks get weaker and thus the conversion efficiency gets lower, since condensation in thinner clouds with lower LWP is lower. Hence, the conversion of droplets to rain (here, defined as particles whose radius is larger than 40 micron) becomes more inactive to contribute to the decreasing importance of sedimentation as compared to that of condensation as clouds become thinner in this study. Also, Khairoutdinov and Kogan (2000) indicated that the sensitivity of the conversion of cloud liquid to rain to varying CDNC was weaker at low liquid-water content (LWC) than at high LWC based on results from a bin model taking into account the feedbacks between condensation and collisions. This implies that the sensitivity of sedimentation to aerosol changes (leading to CDNC changes) is also weaker at low LWC and thus LWP. This contributes to the decreasing relative importance of sedimentation in the response of LWP to aerosols to that of condensation as clouds become thinner.

We wanted to show the above-explained dependence of the conversion efficiency on condensation (determining the LWP or cloud thickness), leading to the varying role of the conversion and thus sedimentation (or precipitation) with the level of LWP or cloud thickness. Hence, although the LWP increases among four cases in this study are due to increasing condensation and increasing condensation involves increasing updrafts associated with the increasing buoyant driving, the above-explained dependence can be simulated reasonably well. This is because for the examination of the dependence, the level of the LWP and condensation only matters (due to the explained mechanism in the introduction (LL13-24 in p 19316 in the old manuscript) regardless of the effect of dynamics on the LWP and condensation; here, we are interested in the level of LWP and condensation, which can be considered to be final products of cloud processes including dynamics, but not in processes through which this level is determined, since the above-explained feedbacks between the turbulent collisions and condensational growth are a strong function of the level of LWP but not a function of dynamic processes determining this level.

We also want to point out that clouds with higher LWP tend to have higher buoyant drive and thus updrafts in reality; stronger updrafts are in favor of higher LWP through higher condensation. Hence, we believe that clouds with higher LWP involving higher buoyant drive and updrafts simulated here are not that unreasonable. To vary updrafts and thus condensation and LWP among the cases in this study by minimizing the environment differences, varying the surface latent heat flux can be considered effective. This is because we can simulate different clouds with different updrafts and LWP with no variation of environmental conditions above the surface, enabling us to compare clouds with different LWPs (accompanying different dynamics) by excluding the effect of the above-surface environment (such as humidity around cloud-top and large-scale subsidence known to affect clouds and aerosol-cloud interactions) on the comparison.

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2) Condensation rate differences between high and low aerosol runs may be influenced by aerosol-driven precipitation differences because suppressing precipitation drives stronger updrafts (e.g. Stevens et al. 1998, Ackerman et al. 2004, Wood 2007). The paper be far more convincing if these effects were more clearly separated, e.g. by

running cases (a) without precipitation; (b) by fixing supersaturation = 0 for condensation purposes; (c) including both effects.

If we fix supersaturation = 0, clouds are not likely to develop. Hence, to see the contribution of the interactions between CDNC and supersaturation to condensation difference between the high- and low-aerosol runs, simulations are repeated with CDNC fixed in the same manner as described in 5.4 in Lee et al. (2009, JGR).

Two pairs of additional simulations, each of which is composed of the high- and low-aerosol runs, in each of the four cases in this study are performed. Each pair of simulations adopts the identical CDNC only for condensation; N_d in Eq. (3) is fixed at a constant value and forced to be the same for the high- and low-aerosol runs, though predicted N_d is allowed to be used in the other processes. The first pair of simulations is referred to as the high-aerosol run (CDNC-high fixed) and low-aerosol run (CDNC-high fixed) in each of the four cases. The high-aerosol run (CDNC-high fixed) and low-aerosol run (CDNC-high fixed) in each of LH-M5, CONTROL, LH-D5, and LH-D10 adopt an averaged CDNC in the high-aerosol run in each of LH-M5, CONTROL, LH-D5, and LH-D10 as a fixed value only for condensation as described in Table 1. The second pair of simulations in each of the four cases adopts the averaged CDNC in the low-aerosol run in each of the four cases as a fixed value only for condensation and is referred to as the high-aerosol run (CDNC-low fixed) and low-aerosol run (CDNC-low fixed).

The budget numbers of Eq. (2) for these additional simulations are shown in Table 3. Time- and domain-averaged LWPs in the high-aerosol run (CDNC-high fixed) and low-aerosol run (CDNC-high fixed) are 75.5 and 74.3 g m^{-2}, respectively, in LH-M5. In CONTROL, the LWPs are 62.3 and 61.5 g m^{-2} in the high-aerosol run (CDNC-high fixed) and low-aerosol run (CDNC-high fixed), respectively. The LWPs in the low-aerosol runs (CDNC-high fixed) increase significantly as compared to LWPs in the low-aerosol runs, resulting in negligible differences in LWP between the high-aerosol run (CDNC-high fixed) and low-aerosol run (CDNC-high fixed) in each of CONTROL and LH-M5. This is mainly due to larger CDNCs in the low-aerosol runs (CDNC-high fixed) than average CDNCs in the low-aerosol runs, leading to increased condensation as compared to that in the low-aerosol runs (Table 3). The LWP differences between the high-aerosol run (CDNC-low fixed) and low-aerosol run (CDNC-low fixed) are also negligible as compared to those in the high- and low-aerosol runs in each of LH-M5 and CONTROL. LWPs in the high-aerosol run (CDNC-low fixed) and low-aerosol run (CDNC-low fixed) are 62.4 (52.9) and 61.3 (52.1) g m^{-2}, respectively, in LH-M5 (CONTROL). LWPs in the high-aerosol runs (CDNC-low fixed) decreases significantly as compared to LWPs in the high-aerosol runs, resulting in negligible differences in LWP between the high-aerosol run (CDNC-low fixed) and low-aerosol run (CDNC-low fixed) in each of LH-M5 and CONTROL. This is mainly due to smaller CDNCs in the high-aerosol runs (CDNC-low fixed) than average CDNC in the high-aerosol runs, leading to less condensation than in the high-aerosol runs. These additional simulations indicate that the LWP responses to aerosols can be nearly the same for the high- and low-aerosol runs only by making CDNC for condensation identical. This demonstrates the most crucial role of CDNC impacts on condensation in the LWP responses to aerosols. This also demonstrates that the impacts of aerosols and thus CDNC on the other processes such as the sedimentation of cloud liquid, the conversion of cloud liquid to rain, thus, the sedimentation and evaporation of rain do not play an important role in the LWP responses in thin clouds with the surface precipitation here.

These additional simulations for LH-D5 with the absence of the surface precipitation show a larger increase in LWP at low aerosol due to the absence of increased interactions between CDNC and supersaturation at high aerosol than that at low aerosol. These simulations for LH-D10 also with the absence of the surface precipitation show an increase in LWP at low aerosol due to the absence of increased interactions between CDNC and supersaturation at high aerosol, contrary to the decrease in LWP in the low-aerosol run.

The high- and low-aerosol runs are repeated for all of the four cases again by turning off sedimentation and evaporation of rain to investigate the role of rain evaporation and sedimentation in thin clouds and their responses to aerosols and referred to as the high-aerosol run (rain-off) and the low-aerosol run (rain-off). As shown in Table 4, the qualitative nature of the results described for the high- and low-aerosol runs does not change with whether rain evaporation and sedimentation operate in LH-M5 and CONTROL. However, condensation and LWP increase in the high-aerosol run (rain-off) in LH-D5 due to the absence of cloud-base evaporation and its effect on the cloud-system instability in LH-D5, contrary to their decrease in the high-aerosol run. The absence of cloud-base evaporation and its effect on the cloud-system instability leads to larger increases in condensation and LWP in the high-aerosol run (rain-off) than those in the high-aerosol run in LH-D10.

We found that it was not viable to set the entrainment rates to be identical, since entrainment is none other than a part of the predicted dynamic and turbulence fields which we can't control. In LH-M5 and CONTROL, stronger interactions among CDNC, supersaturation, and condensation (leading to more evaporation) induce a larger entrainment at high aerosol than at low aerosol. Simulations with identical CDNC for condensation for each of these two cases have nearly identical entrainment rates due to nearly identical interactions among CDNC, supersaturation, and dynamics. Hence, variation in entrainment is controlled by that in interactions among CDNC, supersaturation, and dynamics with varying aerosols and the condensation increase (due to increased interactions among CDNC, supersaturation, and dynamics) is large enough to offset the effect of increasing entrainment, leading to larger LWP at high aerosol in LH-M5 and CONTROL. In LH-D5 and LH-D10 with no surface precipitation, both interactions among CDNC, supersaturation, and dynamics and those between cloud-base rain evaporation and instability affect entrainment (by affecting condensation and cloud-liquid evaporation). Simulations with identical CDNC for condensation for each of these two cases show larger entrainment at low aerosol due to increased cloud-base instability (leading to increased condensation and evaporation), indicating the feedbacks between cloud-base instability and dynamics play a role in the entrainment variation with varying aerosols. In LH-D5, the condensation increase from interactions between cloud-base rain evaporation and instability is large enough to offset the effect of entrainment increase also from these interactions, leading to larger LWP in the low-aerosol run than in the high-aerosol run. In LH-D10, the condensation increase from interactions among CDNC, supersaturation, and dynamics (offsetting the effect of decreasing interactions between cloud-base rain evaporation and instability) is large enough to offset the effect of increasing entrainment, leading to larger LWP in the high-aerosol run than in the low-aerosol run.

Section 5.4 and 5.5 are added to describe the above-described additional simulations (for the sake of brevity, the high- and low aerosol runs (CDNC-high fixed) are included and the high- and low aerosol runs (CDNC-low fixed) are excluded in the text):

The dominant role of condensation over entrainment in simulations with increased condensation and LWP is mentioned in the text (LL407-411 in p14 in the new manuscript).

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3) Introduction, P19315, line 25, and numerous other places. It is not just surface

precipitation that is important for AIEs. Surface precipitation affects the BL moisture budget, but cloud base precipitation affects the cloud dynamics and entrainment (e.g. Ackerman et al. 2004, Wood 2007). Thus, an assessment of whether precipitation is relevant to the AIE problem requires knowledge of the cloud base precipitation.

We mentioned the surface precipitation in Introduction simply to indicate the very low conversion of cloud liquid to rain in thin clouds as explained in the following sentences (LL26-28 and LL1-6 in p19315-19316 in the old manuscript). To avoid confusion, we removed "with a very small surface precipitation of ~0.01 mm day^{-1} or less" in Introduction (LL25-26 in p19315 in the old manuscript) and add "of ~ 0.01 mm day^{-1} or no surface precipitation but with cloud-base precipitation" after "resulting in very small surface precipitation" (LL92 in p4 in the new manuscript).

We already explained the importance of cloud-base precipitation when there is no surface precipitation in the text (LL9-16 in p19327 in the old manuscript).

Also, the following is added to indicate the importance of cloud-base precipitation:

(LL99-101 in p4 in the new manuscript)

This response of condensation to aerosols is affected by aerosol-induced changes in interactions between cloud-base precipitation and dynamics when precipitation does not reach the surface.

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4) Fig 7: Passive broad-channel radiometers such as MODIS cannot accurately measure temperature and moisture profiles in the boundary layer. No instrument can currently do this with the accuracy required to evaluate the model in question. If this accuracy could be attained with MODIS, we wouldn't need radiosondes, AIRS, COSMIC, and other profiling satellite sensors. The agreement with observations must be almost entirely fortuitous.

"Figure 7 demonstrates that simulated potential temperature and humidity also show a good agreement with the MODIS observations." is replaced with "Figure 7 indicates that simulated potential temperature and humidity also show a good agreement with the MODIS observations. However, a high uncertainty exists in the retrieval of the profile as discussed in Menzel and Gumley (1998). Hence, this agreement should be considered as a rough assessment of model performance"

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5) Sloppiness: What time of day are the MODIS LWP observations made for the comparison with the model? Line 10, P19321 is vague.

The following (LL239-243 in p8-9 in the new manuscript) is added:

The simulated LWP in the high-aerosol run is compared to observation by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite to assess the ability of the model to simulate stratiform clouds. The MODIS-observation is provided as averaged values over the period from 14:00 LST on 14 July to 14:00 LST on 15 July in 2002 (for the 10:30 AM and 10:30 PM crossing).

Also, in the sentence: "...the small contribution of autoconversion and accretion to LWC implies that the role of sedimentation of cloud particles in the determination of LWC is not as significant as that of condensation." Cloud particles do not require autoconversion and accretion to sediment. I think the authors mean the sedimentation of cloud+drizzle particles.

In the previous manuscript, cloud particles mean "cloud liquid (or droplets)+rain" except for cloud particles in p19331 meaning only droplets. To avoid confusion, cloud particles in p19331 are replaced with cloud droplets. Also, the following is added to indicate the definition of cloud particles:

(LL86-87 in p3 in the new manuscript)

Cloud particles in this study include both cloud liquid (or droplets) and rain.

Also, although condensation is the only source of LWC in clouds, it is not the determining factor for LWP since in steady-state non-precipitating clouds the evaporation rate has to balance the condensation rate. Any precipitation is the imbalance between the condensation and evaporation. Since we know that precipitation can result in either more or less liquid water path (Ackerman et al. 2004, Wood 2007, see also satellite study by Coakley and Walsh 2002), this proves that the use of a liquid water budget does not help in determining the key terms affecting the liquid water path. This is the heart of the Albrecht argument, i.e. that a greater sink of LWC should lead to thinner clouds. It doesn't work.

The budget analysis in this study was carried out to find out which microphysical terms dominate in determining the liquid-water content (LWC). Although the budget analysis does not enable us to find the cause of the higher LWP (the vertical integration of LWC (only including cloud liquid, excluding rain)), it is at least able to find the dominant microphysical terms determining the rate of change of the LWC and thereby the LWP variation due to aerosols. Note that there are only four terms controlling LWC and LWP, which are condensation, evaporation, autoconversion, and accretion. The LWC sink in Albrecht's argument is about the depletion of cloud-liquid mass via autoconversion and accretion (forming rain). Albrecht argued that decreasing autoconversion and accretion with increasing aerosols led to increasing LWC and LWP.

Since we are interested in explaining the variation in "time- and domain-averaged LWP" with varying aerosols, all of the cumulative microphysical terms in the LWC tendency, which are averaged over the domain, are obtained. The budget analysis shown in Table 2 demonstrates that variations in cumulative condensation and evaporation are the main controls among the four microphysical terms determining the variation in the time- and domain-averaged LWP and that the cumulative conversion of cloud liquid to rain by autoconversion and the accretion of cloud liquid by rain play a minor role in controlling the variations in the time- and domain-averaged LWP as compared to condensation and evaporation of cloud liquid. Hence, Albrecht's autoconversion and accretion do not play an important role in the response of the time- and domain-averaged LWP to aerosol changes in simulations here.

Cloud liquid formed by condensation eventually disappears via evaporation and very small portion of cloud liquid converts to rain via autoconversion and accretion before its disappearance in this study. This indicates that (cumulative) condensation controls (cumulative) evaporation by determining the amount of source (i.e., cloud liquid) of evaporation; the role of autoconversion, accretion, and sedimentation in the determination of the source is not significant. Larger (smaller) cumulative condensation induces larger (smaller) cloud liquid, contributing to larger (smaller) time- and domain-averaged LWP. Larger (smaller) cloud liquid eventually disappears and this disappearance should involve larger (smaller) cumulative evaporation for larger (smaller) cloud liquid (produced by larger (smaller) condensation).

Differences in evaporation between the high- and low-aerosol runs decrease substantially as does those in condensation when CDNC is fixed for the condensation term only; experiments with the fixed CDNC are described in our responses to the comment 2. Differences in evaporation and condensation are only ~ 27 (18) and ~ 30 (21) % of those in the standard high- and low-aerosol runs where the CDNC is predicted for all processes including condensation in LH-M5 (CONTROL) where the effect of the cloud-base rain evaporation on the instability is absent. In the standard high- and low-aerosol runs where the CDNC is predicted for all processes including condensation, larger cloud-liquid mass eventually contributes to larger evaporation when the cloud liquid is detrained from the updrafts into the sub-saturated areas (as can be seen from the budget analysis using cumulative values at the end of time integration). When CDNC is fixed for condensation, differences in the cloud-liquid mass decrease due to the reduced differences in the production of cloud liquid by condensation between the high- and low-aerosol runs in LH-M5 and CONTROL. This leads to reduced differences in the detrained mass of cloud-liquid into the sub-saturated areas and thereby to reduced differences in evaporation of cloud liquid. This confirms the above argument that cumulative condensation not only controls the time- and domain-averaged cloud-liquid mass variations (and therefore the time- and domain-averaged LWP variations) but also controls the variations in cumulative evaporation due to aerosols.

In summary, the variation in the time- and domain-averaged LWP is mostly controlled by the variations in the cumulative condensation and the cumulative evaporation of cloud liquid and the variation in the cumulative evaporation of cloud liquid is controlled by the variation in the cumulative condensation which provides the source for the evaporation of cloud liquid; here, we want to stress that the time series of the domain-averaged differences in condensation and evaporation between the high- and low-aerosol runs showed much larger values than those from autoconversion and the collection of cloud liquid by rain throughout simulation periods, indicating that the cumulative values of these processes at the end of time integration can represent situations during the time integration reasonably well. From the budget analysis (using the cumulative values), we can see condensation and evaporation are two major terms controlling the cloud-liquid mass and autoconversion and accretion play an insignificant role in the determination of the cloud-liquid mass. It is the cumulative condensation (evaporation) which increases (decreases) the time- and domain-averaged LWP and our additional simulations with the fixed CDNC demonstrate that the cumulative evaporation is controlled by the cumulative condensation. Hence, we can say that the LWP which is averaged over time and domain is determined by the cumulative condensation which eventually affects the cumulative evaporation and, thus, we can only use the cumulative condensation to explain the LWP and its variation due to aerosol changes or the cumulative evaporation and its variation due to aerosol changes. It is also possible to say that evaporation plays much more important roles in the response of the LWP to aerosol changes than the conversion. However, increasing evaporation with the variation in aerosols is not able to explain increasing LWP with the aerosol variation. The increase in the cumulative condensation best explains the increase in the time- and domain-averaged LWP with the negligible conversion in this study. This is why this study performed comparison between condensation and conversion but not between evaporation and conversion. Also, by showing much larger condensation and its variation with aerosols than the conversion and its variation, we can simultaneously explain larger evaporation and its variation with aerosols than the conversion and its variation due to the connections between condensation and evaporation as explained above. Hence, we analyzed the terms determining the condensation rate in section 5.3 and found that the CDNC and supersaturation variations dominate the condensation variation. Supersaturation represents the dynamical and thermodynamical impacts on condensation, since it is affected by the updraft intensity, temperature and moisture in air parcels. The analysis in section 5.3 showed that the impact of changes in microphysical factors (i.e.,CDNC) on condensation can offset that in dynamical and thermodynamical factors, represented by supersaturation, by changing the surface areas of droplets. Here, we want to stress that it is obvious that condensation is controlled by variables in Eq. (3) and, as expected, the ventilation coefficient and the saturation water vapor mixing ratio showed negligible differences between the high- and low-aerosol runs as compared to those in supersaturation and CDNC. Thus, the supersaturation and CDNC changes explain the cause of the larger condensation resulting in larger LWC and LWP at high aerosol in CONTROL and LH-D5 as shown in the budget analysis in section 5.2. The CDNC and supersaturation effects on condensation offset each other as explained in the text and the CDNC effects are larger than the supersaturation effects, leading to more condensation and LWC (and thus LWP) at high aerosol in CONTROL and LH-D5. As explained in the text, in LH-D5 and LH-D10, the interactions between cloud-base rain evaporation and cloud-base instability interplay with those between CDNC and supersaturation due to the absence of the surface precipitation, resulting in larger LWP at low aerosol in LH-D5 and smaller LWP differences than those which would have been simulated with the presence of the surface precipitation in LH-D10.

P19326, line 26. Why do increased condensation rates necessarily lead to increased LWP? Stronger condensation rates should lead to greater LWC in the updrafts, but this also drives stronger entrainment which evaporates LWC and reduces the LWC in the downdrafts. Essentially then, in marine stratocumulus, the LWP is not determined only by the rate of condensation, but by the rate at which the MBL is moistened, warmed, and deepened by the entrainment and surface fluxes.

As explained in our responses to one of the above comments, autoconversion and accretion do not play an important role in the determination of the LWP and condensation and evaporation are the only two remaining processes affecting the LWP determination significantly. Note that the budget analysis used to extract the important role of condensation and evaporation is based on cumulative values of terms associated with “the time- and domain-averaged LWP” determination. Entrainment and surface fluxes affect cloud dynamics and thermodynamics and then affect condensation and evaporation. Regardless of how entrainment and surface fluxes affect condensation and evaporation, it is obvious that condensation and evaporation show much larger cumulative values than autoconversion and accretion from the budget analysis and that the cumulative condensation increases the time- and domain-averaged LWP and the cumulative evaporation decreases the time- and domain-averaged LWP; condensation and evaporation in the budget analysis are determined by all associated processes including entrainment and surface fluxes, in other words, the cumulative values of condensation and evaporation are the final product of these associated processes involving entrainment and surface fluxes. Also, as explained in our responses to one of the above comments, evaporation is determined by condensation when we restrict our discussion to the cumulative values of evaporation and condensation; increasing cumulative condensation increases cumulative evaporation (by increasing the source of evaporation) as well as the time- and domain-averaged LWP.

In summary, from the budget analysis (using the cumulative values), we can see condensation and evaporation are two major terms controlling the time- and domain-averaged LWP and autoconversion and accretion play a negligible role in the determination of the cloud-liquid mass. It is the cumulative condensation (evaporation) which increases (decreases) the time- and domain-averaged LWP and our additional simulations with the fixed CDNC demonstrate that the cumulative evaporation is controlled by the cumulative condensation. Hence, we can say that the LWP which is averaged over time and domain is determined by the cumulative condensation which eventually affects the cumulative evaporation.

P19327, line 9: Precipitation stabilizes the boundary layer as a whole since it warms the cloud layer and cools the subcloud layer.

As shown by Paluch and Lenschow (1991) and Feingold et al. (1996) and as explained in the text (LL428-435 in p15), when precipitation does not reach the surface, its evaporation cools places only around cloud base but not whole subcloud layer. This cloud-base cooling from rain evaporation can increase instability which induces stronger updrafts and thus larger condensation.

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6) The authors make a good point that parameterizations should include microphysical limitations to condensation as well as to precipitation. Wang et al. (2003) offers some ideas as to how this might be done in a bulk model.

The following is added to show the parameterization suggested by Wang et al. (2003)

(LL618-622 in p21)

Wang et al. (2003) also found the importance of interactions between microphysics and dynamics in determining cloud structure. They proposed to simulate these interactions by parameterizaing liquid water flux in terms of the downgradient transport, microphysical contribution, turbulent mixing timescale, and condensation timescale in climate models.

Minor points:

1) P19316, line 2: What "critical size" are you referring to? The sedimentation of cloud mass is controlled by the mass-times-terminal velocity weighted radius. This will be similar to the volume radius in clouds with relatively narrow size distributions.

In cloud physics, it is well-known that the collection efficiencies for collector drops less than about 20-40 micron in radius (referred to as "critical size in this study) are quite small (Rogers and Yau, 1983). Also, as shown by numerous studies including the study of Khairoutdinov and Kogan (2000), the drops with radii less than the critical size are always collected, while the drops larger than the critical size gain mass by collecting smaller drops. This is mainly due to the negligibly small terminal velocity of the drops smaller than the critical size; this is the basis of Kessler's methodology which partitioned the liquid water into cloud liquid (corresponding to the drops smaller than the critical size) and rain (corresponding to the drops larger than the critical size) where cloud liquid is assumed to have zero terminal velocity. Hence, the contribution of the drops smaller than the critical size to the sedimentation of cloud mass is known to be much smaller than that of drops larger than the critical size. In the sentence pointed out here, we intend to indicate this small contribution of the drops smaller than the critical size to the sedimentation of cloud mass; this study showed that the very low conversion efficiency (leading to the very low formation of drops larger than the critical size and, thus, the very high ratio of cloud-liquid mass to rain mass) results in the very low sedimentation as compared to condensation due to the negligibly small terminal velocity of cloud-liquid (or drops smaller than the critical size).

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2) Section 3: Why not show CCN-supersaturation spectra used? Why are they changing with time? Are the aerosols interactive?

Figure 4b showing the CCN-supersaturation spectra is added for the initial background aerosols. These spectra for background aerosols do change with time as explained in Section 3 mainly due to the large-scale advection of aerosols. In clouds, total aerosol number changes as compared to a given background aerosols for a corresponding time as explained in Section 3 and thus all of the cumulative values of CCN over the supersaturation range in Figure 4b scales up or down based on the ratio of total aerosol number in clouds to that in background when aerosols are in clouds.

The following is added to indicate the cause of the time variation of background aerosols.

(LL178-179 in p6)
The time variation of background aerosols in Figure 4a is mainly due to the large-scale advection.

The following is added to explain figure 4b.

(LL180-182 in p6-7)
Also, Figure 4b shows the variation of the total activated aerosols with supersaturation between 0.01 and 0.3 %. Figure 4b is obtained using initial background aerosols and temperature at the surface.

“Assumptions of aerosols follow those adopted in Lee et al. (2009b) (see section 5 in Lee et al. (2009b) for the details of these assumptions).” in LL14-15 in p19319 in the old manuscript is replaced with “ is replaced with “The aerosol is predicted within clouds and reset to the background value at all levels outside cloud. Within clouds, aerosols are advected, diffused, and depleted by nucleation of droplets (nucleation scavenging). Initially, the aerosol number is set equal to its background value everywhere.” in LL183-186 in p7 in the new manuscript to explain the interactive aerosols.

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3) Fig. 10. Why not show condensation rates for all cases? Fig 10 shows the condensation rate in the anomalous case where PI condensation is higher than PD. Why is this case different? I notice that the condensation rate is higher in PD earlier, but then it flips sign. The reason for this, I suspect, is that entrainment changes are a significant sink of buoyant motion that are not isolated in this analysis.

In the cases except for LH-D5, the PD cumulative condensation is always higher than the PI cumulative condensation during the time integration. Hence, we think showing figures for condensation for all of these cases is redundant, since Table 2 already provides information of the larger PD condensation than the PI condensation. Figure 10 for condensation for LH-D5 is shown, since the PD condensation becomes smaller than the PI condensation at a time point unlike the other cases.

To indicate the larger PD cumulative condensation always higher than the PI cumulative condensation during the time integration, the following is added.

(LL388-389 in p14)

during the time integration

Simulations in LH-D5 are repeated with rain evaporation turned off as described above and it is found that the PD condensation is larger leading to larger LWP in the high aerosol run (rain-off). This is because an increase in the cloud-base instability due to an increase in cloud-base rain evaporation in the absence of the surface precipitation is absent in the low-aerosol run (rain-off) in these repeated simulations. This indicates that increased entrainment in the high-aerosol run dose not lead to smaller condensation than that in the low-aerosol run in LH-D5 and it is the effect of rain evaporation on the cloud-base instability that enables the start of the larger cumulative condensation in the low-aerosol run during the simulation.

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