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 #3

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This paper examined the impact of condensation and sedimentation on LWP of marine stratocumulus clouds. The authors used Goddard Cumulus Ensemble (GCE) model, and simulated a case of thin marine stratocumulus cloud located off the coast of the western Mexico. The LWP of simulated marine stratocumulus was varied from 73 to 36 g/m2 by modifying the surface latent heat flux. Through a budget analysis of the source and sink terms, the authors found that condensation and evaporation are 1 to 2 orders of magnitude greater than sedimentation, and the effect of aerosol on cloud LWP (mass) is mainly through its impact on condensation instead of sedimentation. The topic of the paper is well suited for Atmospheric Chemistry and Physics, but I have some questions, which are outlined below. I recommend the authors take into consideration the comments and revise the paper.

Major comments:

The current study is quite similar to an earlier paper published by the authors (Lee et al., 2009). Both studies presented simulations of marine stratocumulus with different LWP, and reach the conclusion that for thin marine stratocumulus clouds, the effect of aerosol on cloud LWP (mass) is mainly through its impact on condensation instead of sedimentation. In addition, the discussions of the cases in which LWP decreases with increased aerosol concentration (case LH-D5 in current study, and DRY case in earlier paper) are nearly identical. I'd suggest the authors include more analysis to better understand the physics processes that control LWP as described in the next comment.

The maximum value of the LWP in Lee et al. (2009) is ~ 60 g m^{-2}, while it is ~ 320 g m^{-2} in this study (compare Figure 4 in Lee et al. (2009) to Figure 6 in this study). Associated with this, all simulations have the time- and domain-averaged LWP of smaller than 50 g m^{-2} in Lee et al. (2009), whereas two cases (i.e., CONTROL and LH-M5) have the time- and domain-averaged LWP of larger than 50 g m^{-2}. Based on the classification of Turner et al. (2008), generally, clouds with the LWP smaller than 50 g m^{-2} can be considered thin. This indicates that clouds in Lee et al. (2009) are mostly thin clouds, whereas the significant portion of clouds simulated here is thick. In thick clouds in CONTROL and LH-M5, the conversion efficiency (the ratio of conversion to condensation) is 3 – 15 % which is ~ one order of magnitude larger than that in thin clouds in LH-D5 and LH-D10 and ~ one to two orders of magnitude larger than that in thin clouds in all of cases in Lee et al. (2009).

This demonstrates the obvious differences between cloud type in LH-M5 and CONTROL and that in LH-D5, LH-D10, and cases in Lee et al. (2009) (i.e., WET, MID-WET, and DRY), enabling us to examine how factors controlling aerosol-cloud interactions in warm clouds vary with transition of cloud type from thick clouds to thin clouds in this study. However, in Lee et al. (2009), only thin clouds with extremely low conversion efficiency are simulated, disabling us from the examination of the variation in factors with the transition. Also, want to point out that the averaged-LWP in LH-M5 is in the LWP range of one of the highest observation frequencies reported by McComisky et al. (2009) as discussed in the manuscript, enabling us to study aerosol-cloud interactions in most probable clouds, whereas none of the clouds have this LWP range in Lee et al. (2009).

Although mechanisms explained for the effect of aerosols on clouds with no surface precipitation in this study are similar to those in Lee et al. (2009), the main purpose of this study is to examine the dependence of factors controlling aerosol-cloud interactions in stratocumulus clouds on the cloud thickness represented by the LWP level, whereas the purpose of the study of Lee et al. (2009) is to examine aerosol-cloud interactions only in thin clouds with the LWP < 50 g m^{-2}; as explained above, this study simulates clouds with the LWP > 50 g m^{-2} as well as those with the LWP < 50 g m^{-2} to examine the dependence.

We also want to emphasize that LH-D5 is compared to LH-D10 in this study to show that varying difference in the cloud-base precipitation between the high- and low-aerosol runs with varying cloud thickness can result in the different sign of the effect of aerosols on the LWP in the absence of the surface precipitation. However, Lee et al. (2009) only investigates the case with the decreased LWP with the increased aerosols in the absence of the surface precipitation.

The impacts of aerosol on both condensation and sedimentation/precipitation can change the updraft velocity, which in turn influences condensation. The change in updraft velocity can also influence the entrainment rate. Depending on the RH at the top of the boundary layer, an increased updraft velocity can either increase or decrease LWP. The interactions between microphysics and dynamics are complex. For example, increased aerosol leads to higher LWP in some cases (e.g. LH-10D), but lower LWP in others (LH-5D). To convincingly demonstrate the importance of condensation on LWP, the authors may need to carry out additional simulations to separate the effects of different processes, including using fixed droplet number concentration for condensation (as done in Lee et al., 2009), turning off precipitation/sedimentation, and using same entrainment rate for both low and high aerosol concentration cases .

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).

Minor comments:

In abstract, the sentence “...the role of the feedbacks between microphysics and dynamics becomes more important with the lowing level of LWP” is misleading. Whereas the impact of aerosol on condensation is more important than precipitation/sedimentation, Table 2 shows that the impact of aerosol on condensation (i.e. the difference in condensation rate between PD and PI aerosol cases) deceases with decreasing LWP.

Here, we intended to say the decreasing relative importance of the response of conversion and sedimentation to aerosols in the determination of the effect of aerosols on cloud mass to that of condensation, which is determined by feedbacks between microphysics and dynamics, with decreasing cloud thickness represented by the level of the LWP. This decreasing relative importance is represented by the last row of Table 2 showing the decreasing ratio of sedimentation difference to condensation difference between the high- and low-aerosol runs with the decreasing level of LWP.

The sentence pointed out here is revised as follows:

(LL44-47 in p2 in the new manuscript)

Comparisons among these cases show that the relative role of the conversion and sedimentation in the response of cloud mass to aerosols to that of the feedbacks between microphysics and dynamics becomes less important as the level of LWP lowers.

Page 19319, Line 15, please show CCN spectra for both PD and PI emissions.

Figure 4b is added to show the CCN spectra for PD and PI aerosols.

Page 19324 Line 15-16. I disagree that the role of sedimentation is not important. In case LH-5D, the impact of sedimentation on updraft velocity leads to reduced LWP at high aerosol concentration instead.

In the sentence pointed out here, in-cloud sedimentation above the cloud base is used for the comparison to condensation, whereas, sedimentation just below cloud base affects evaporative cooling and thus cloud-base instability for the increased updraft and LWP at low aerosol in LH-D5.

To avoid confusion "in-cloud" is added in the sentence pointed out here.

Page 19325, Line 15-16, I would expect the difference in F_{Re} is also important as it scales with droplet diameter. What is difference in F_{Re} between PD and PI aerosol cases?

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f_{Re} (whose formulation is shown in LL378-379 in p13 in the new manuscript) ranges from 1.0002 to 1.01 with the variation in cloud-droplet diameter from 1 micron to 40 micron, which covers most of the diameter range of cloud liquid in this study. Only less than 1 % increase is shown with the increased diameter in this variation. This leads to less than 1 % variation in $F_{Re.}$

Figure 9 shows that supersaturation is the highest in the case LH-M5. Why is the cloud droplet number concentration in case LH-M5 the lowest among all cases (figure 8)?

McComiskey et al. (2009) showed the near-linear decrease in CDNC with the increasing LWP based on their observation of stratiform clouds if LWP was smaller than ~ 130 g m^{-2} (see figure 4 in McComiskey et al. (2009)). This is due to increasing accretion among droplets or between droplets and rain with increasing LWP; the particle size and thus collection efficiency are larger with the larger LWP mainly due to a larger condensational growth in clouds with a larger LWP, resulting in larger particles. The more collection among droplets (whether autoconversion occurs or not) and that between droplets and rain in clouds with larger LWP reduces CDNC in this study.

Page 19327, Figure 12c and 12d: There appears to be some inconsistencies between figure 12c and 12d. The potential temperatures are the same at the surface for both PD and PI aerosol cases (Fig. 12d). If d (theta)/dz is consistently lower for the PI aerosol case (as shown in Fig. 12c), I would expect the potential temperature at the top of the boundary layer for the PI aerosol case will be lower than that in the PD case. But Fig 12d shows the potential temperatures are the same for both cases at the top of the boundary layer.

If we look at Figure 12c more carefully, d (theta)/dz at the PD aerosol starts to be smaller than that at the PI aerosol from around 0.75, leading to similar potential temperature at the PD aerosol to that at the PI aerosol from ~ 0.8 to the top of clouds.

Page 19328, Line 9-11. Why does stronger vertical motion lead to increased condensation (at same altitude) in this case? As long as the droplet number concentration is lower in the PI case, should the smaller droplet surface area lead to a higher supersaturation (i.e. water vapor mixing ratio), and a lower liquid water content when compared to the PD case at the same altitude?

As explained in the text in Section 5.3, in LH-D5, due to larger cloud-base rain evaporation, there is a larger cloud-base instability developing in the low-aerosol run than in the high-aerosol run. This induces stronger updrafts. Although the droplet surface area is smaller, these increased updrafts increase supersaturation enough to induce more water vapor condensed onto droplets in the low-aerosol run than in the high-aerosol run.

The following is added to explain this:

(LL461-469 in p16 in the new manuscript)

If the effect of cloud-base instability on updrafts were absent, smaller CDNC and thus surface area of droplets and higher supersaturation in LH-D5 would result in lower condensation after 02 LST on July 15th at low aerosol than at high aerosol in LH-D5; as explained above, the effect of the smaller surface area of droplets on condensation tends to outweigh that of supersaturation, leading to smaller condensation at low aerosol. The instability-induced stronger vertical velocity augments supersaturation large enough to induce more water vapor to be condensed onto droplets at low aerosol than at high aerosol in LH-D5.

Table 2: In control case, the different in <Qevap> between high and low aerosol scenarios in control case should be 0.41 instead of 0.38.

Corrected.

Reference:

Lee, S. S, Penner, J. E., and Saleeby, S. M.: Aerosol effects on liquid-water path of thin stratocumulus clouds, J. Geophys. Res., 114, D07204, doi:10.1029/2008JD010513,2009b.