First of all, we would like to 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 reviewer. Each comment of the reviewer (colored black) is listed and followed by our responses (colored blue).

Interactive comment on "Comparison of a global-climate model to a cloud-system resolving model for the long-term response of thin stratocumulus clouds to preindustrial and present-day aerosol conditions" by S. S. Lee and J. E. Penner

Anonymous Referee #1

Received and published: 10 November 2009

General comments

This paper performed the numerical simulations with a GCM and a cloud-system resolving model (CSRM) for aerosol and environmental (meteorological) effects on cloud fields, and compared the results of these two kinds of models. Although the approach of comparing the GCM with CSRM described here may be helpful for identifying what aspect of aerosol-cloud interactions lacks to be represented in GCMs, there are several concerns with fundamental mechanisms responsible for the cloud behavior in CSRM that are not well explained in current manuscript.

Comments about Concerns raised here are responded below.

Another difficulty in this manuscript is quite redundant presentations especially when the authors explain the results in figures, and I couldn't catch the main points until I reached the last section (summary section). The authors should make the presentations much more compact to make it easier for readers to understand what the authors intend to emphasize.

We revised the presentations (see our responses to the last specific comment here for the revision).

I would like to recommend eventual publication of this paper after the authors appropriately addressed my concerns listed below and improved their presentations.

Specific comments

Page 21326, line 22-24: "LWP in the GCM-PD run generally shows much larger temporal fluctuations than the MODIS-observed LWP and the CSRM-PD-run LWP." What is the main reason for the larger fluctuations in GCM run?

As stated in the text, the saturation adjustment scheme in the GCM used here tends to produce ~ 3 times larger condensation as compared to the condensation scheme in the CSRM. It is found that, as clouds deepen, the difference in condensation between the GCM and the CSRM becomes larger. In other words, the difference in condensation and thus LWP becomes larger, as diurnal decoupling weakens during the nighttime when clouds in both the CSRM and the GCM have maximum LWP on daily basis. This indicates that the sensitivity of the scheme associated with condensation in the GCM is more sensitive to the variation of the water-vapor transportation from the surface to the cloud layer, which is controlled by the magnitude of decoupling. The cause of this different sensitivity is that the scheme in the CSRM tends to smooth out supersaturation through interactions between supersaturation and CDNC whereas the scheme in the GCM does not have these interactions allowing the occurrence of very high ratio of water-vapor mixing ratio to saturation water-vapor mixing ratio.

The following is added to state about the cause of the larger fluctuations in LWP in the GCM than in the CSRM.

(LL587-601 in p20)

The consideration of the explicit feedbacks between CDNC and supersaturation tends to smooth out supersaturation and this leads to smaller supersaturation in the CSRM than the diagnosed supersaturation in the GCM in each of the PI run and the PD run. This leads to increased condensation in the GCM-PD (-PI) run as compared to that in the CSRM-PD (-PI) run. This increased condensation is large enough to result in a larger LWP despite the higher conversion efficiency (i.e., the ratio between the conversion of cloud liquid to rain and condensation) in the GCM-PD (-PI) run than in the CSRM-PD (-PI) run during the time when stratocumulus clouds dominate. This results in a better agreement in LWP between the CSRM-PD run and the MODIS observation than between the GCM-PD run and the MODIS observation. The consideration of the explicit feedbacks between CDNC and supersaturation, smoothing out supersaturation, also lowers the sensitivity of LWP to diurnal decoupling and thus the diurnal variation of the transportation of water vapor from the surface to the upper layers in the CSRM runs; the presence of interactions between CDNC and supersaturation acts to damp down (or smooth out) the variation in supersaturation with varying decoupling. This leads to much larger temporal fluctuation (or diurnal variation) in LWP in the GCM runs than in the CSRM runs as shown in Figure 7.

Page 21332, line 20-22 and Page 21333: The authors try to explain the reason why “condensation and evaporation are one to three orders of magnitude larger than autoconversion and accretion” in CSRM runs. Although a theoretical explanation according to cloud physics textbook is provided in page 21333, I’m not sure how these theoretical mechanisms take place in terms of CSRM parameterizations. Can you explain how the model parameterizations represent these mechanisms described in page 21333?

For the assumed gamma size distribution of the cloud droplets, the collection equation (i.e., stochastic collection equation) is solved as in the bin microphysics using realistic collection kernels as described in Section 2 (See Lee et al. (2009a,b) and references therein for more details). Here, there are 36 bins for the calculation of mass changes in each bin via collection processes. With an increase in LWC with an increase in condensation, for a given total cloud-droplet number concentration and a given gamma size distribution of cloud droplets, mean size (and thus characteristic particle size of the gamma size distribution; See Walko et al. (1995, Atmos. Res.) for the details of the characteristic particle size) increases, representing the increase in the cloud-droplet size due to the increase in condensation. This leads to an increase in the average collection efficiency, which in turn leads to an increase in the turbulent collection processes below 80 micron, which induces an increase in autoconversion (i.e., an increase in particles growing above 80 micron (in diameter) through collisions among them); particles larger than 80 micron are considered rain or drizzle. This larger size also induces more collection of droplets by rain by increasing collection efficiencies between droplets and rain.

With very low condensation and LWC associated with thin clouds with the LWP < 50 g m^{-2} in the CSRM runs, the characteristic particle size is small, leading to small collection efficiencies among droplets or among droplets and rain. This contributes to small conversion of cloud droplets to rain, which is substantially smaller than condensation and evaporation.

Page 21335, line 10-12: “The effects of the increased surface area for condensation outweigh the effects of decreased supersaturation” Why is the effect of increase in surface area is larger than that of decrease in supersaturation in CSRM? Is this a direct result of the parameterization formulation?

As explained in 6.4.2, condensation is determined by Eq. (3). Note that CDNC and supersaturation are predicted in this study and the only difference in condensation equation between the microphysics scheme adopted in this study and the bin microphysics is that this study assumes the gamma size distribution of droplets whereas in bin microphysics there is no particular assumption of the size distribution.

As also explained in 6.4.2, the CDNC difference and superaturation difference control most of differences in condensation (and thus LWP difference) between the high- and low-aerosol runs. 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 6.4.2 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 the CSRM runs as shown in the budget analysis in section 6.4.2. 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 the CSRM runs.

Lee et al. (2009b) showed that the competition between CDNC and supersaturation can increase or decrease condensation with increasing aerosols depending on how much aerosols and thus CDNC increase. In Lee et al. (2009b), a case with an increase in CDNC showed a decreasing condensation with increasing aerosols. However, when simulations in this case were repeated with a larger increase in aerosols, condensation increased with increasing aerosols due to a larger increase in CDNC providing more increased surface areas of droplets for condensation. Hence, we can say the CDNC increase is large enough to offset the effect of supesaturation on condensation (leading to larger LWP with the PD aerosols) in the CSRM runs in this study.

Page 21335, line 2-14: Same mechanisms should operate for evaporation process except for an opposite sign. To my understanding, what determines the cloud water budget is a net effect determined by difference between condensation and evaporation, rather than only condensation. Can you discuss a mechanisms for the overall effect of condensation and evaporation?

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, excluding the rain content), 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 the aerosol variation. Since we are interested in explaining the variation in the "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 3 demonstrates that condensation and evaporation variations are the main controls among the microphysical terms determining the variation in the time- and domain-averaged LWP and that the conversion of cloud liquid to rain by autoconversion and the collection of cloud liquid by rain play a minor role in controlling the variation in the time- and domain-averaged LWP as compared to condensation and evaporation of cloud liquid.

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 the cumulative condensation controls the 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 negligible. Larger (smaller) condensation induces larger (smaller) cloud liquid, contributing to the 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 the condensation rate when CDNC is fixed for the condensation term only; this type of experiments with the fixed CDNC are described in more detail in Section 5.4 in Lee et al. (2009b). Differences in evaporation and condensation are only 5 and 9 % of those in the standard high- and low-aerosol runs where the CDNC is predicted for all processes including condensation. 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. 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 condensation not only controls the cloud-liquid mass variations (and therefore the LWC and LWP variations) but also controls the evaporation variations 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 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 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 in Lee et al. (2009b) 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 time- and domain-averaged LWP and its variation due to aerosol changes or the cumulative evaporation and its variation due to aerosol changes.

If you see equation (2), the cumulative condensation minus cumulative evaporation is equal to the conversion (i.e., autoconversion + accretion) plus cloud liquid amount suspended at the end of time integration, which is 00 LST on 17 July; in case there is no suspended cloud liquid at the end of time integration, the cumulative condensation minus cumulative evaporation is equal only to the conversion (i.e., autoconversion + accretion). The cloud liquid amount suspended at the end of time integration is represented by the storage term on the left hand side of equation (2); if we insert $\frac{\partial q_c}{\partial t}$ in (1), we can see the meaning of the domain-averaged cumulative value of $\frac{\partial q_c}{\partial t}$ more clearly. $<\frac{\partial q_c}{\partial t}>$ is just the averaged LWP of suspended cloud liquid at the end of the simulations in case there is no suspended cloud liquid at the beginning of the simulations. In case there is suspended cloud liquid at the beginning of the simulations, $<\frac{\partial q_c}{\partial t}>$ is the difference in the averaged LWP of suspended cloud liquid between the end of the simulations and the beginning of the simulations. Hence, condensation minus evaporation does not give us any information about the relative importance of terms associated with cloud liquid. The traditional concept proposed by Albrecht stated that the conversion controlled the response of LWP to aerosol changes. This study indicates that the source of LWP (i.e., condensation) plays much more important roles in this response than the conversion. It is also possible to say that evaporation plays much more important roles in this response than the conversion. However, increasing evaporation with increasing aerosols is not able to explain increasing LWP with increasing aerosols. Condensation increase best explains the LWP increase 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.

Page 21335, line 23-24: “The effects of condensation on LWC outweigh those of evaporation and entrainment, leading to the increased LWP in the PD run.” What is the reason for this excess of condensation effect over evaporation effect?

As explained above, the budget analysis showed predominantly more important roles condensation and evaporation play in the aerosol-induced LWP variation and only condensation increase can explain the LWP increase with an increase in aerosols in this study. Hence, for the increased LWP with increased aerosols, condensation should increase, if the variation in the conversion with increased aerosols is negligible.

If environmental conditions are different than adopted here, condensation and thus LWP can decrease with increased aerosols, in other words, the effect of evaporation and entrainment on the LWP can outweigh those of condensation on LWP. For example, in case the cloud-top humidity is extremely dry, entrainment increases with increased aerosols can lead to decreasing condensation and LWP as reported in Ackerman et al. (2004). However, the cloud-top humidity is high enough to lead to the increased condensation and LWP with increased aerosols in this study.

Page 21336, line 26-29: "the larger cloud-base instability is outweighted by the weaker interactions among CDNC, supersaturation, and condensation in the CSRM-PI run compared to those in the CSRM-PD run." I didn't understand what this part means. Can the author explain in more comprehensive way what they mean by this part?

A larger rain evaporation (due to decreasing aerosols) around cloud base (in case precipitation does not reach the surface) induces a larger MBL instability in the CSRM-PI run than in the CSRM-PD run. This tends to increase condensation and thus LWP in the CSRM-PI run. However, as explained in 6.4.3, interactions among CDNC, condensation, and dynamics increase with increasing aerosols and thus these interactions tend to increase condensation and thus LWP in the CSRM-PD run. In summary, with the increasing (decreasing) aerosols, the cloud-base instability and associated condensation decrease (increase), whereas interactions between CDNC, supersaturation, and dynamics and associated condensation increase (decrease). In the CSRM runs in this study, the decreasing interactions among CDNC, supersaturation, and dynamics play more important roles in the determination of condensation and LWP than the increasing cloud-base instability with decreasing aerosols. In other words, the magnitude of the decreased condensation due to the decreasing interactions (among CDNC, supersaturation, and dynamics) is larger than that of the increased condensation due to the increasing cloud-base instability with the decreasing aerosols in the CSRM-PI run. This resulted in smaller LWP in the CSRM-PI run.

The sentence pointed out here is revised as follows:

(LL626-634 in p21-22)

The increased cloud-base instability tends to increase condensation in the CSRM-PI run by inducing an increase in the intensity of updrafts. However, with the increasing (decreasing) aerosols, interactions between CDNC, supersaturation, and dynamics and associated condensation increase (decrease) as explained in the previous section. In the CSRM runs, the magnitude of the decreased condensation due to the decreasing interactions (among CDNC, supersaturation, and dynamics) is larger than that of the increased condensation due to the increasing cloud-base instability with the decreasing aerosols in the CSRM-PI run. This explains the smaller time- and domain-averaged updrafts, condensation and thus LWP in the CSRM-PI run than in the CSRM-PD run during the time when stratocumulus clouds dominate.

Page 21337, last line: "the effects of the increased aerosols on CDNC and thus condensation outweigh the effects of the increased cloud-base instability". Can you also explain the reason why the aerosol effects are larger than instability effects in the CSRM?

As explained in one of our responses to one of the above comments, in the CSRM runs in this study, the decreasing interactions among CDNC, supersaturation, and dynamics with decreasing aerosols play more important roles in the determination of condensation and LWP than the increasing cloud-base instability. In other words, the magnitude of the decreased condensation due to the decreasing interactions (among CDNC, supersaturation, and dynamics) is larger than that of the increased condensation due to the increasing cloud-base instability with the decreasing aerosols in the CSRM-PI run. This resulted in smaller LWP in the CSRM-PI run and in the CSRM-E(PD)-A(PI) as compared to that in the CSRM-PD run..

Lee et al. (2009b) examined the competition between the interactions among CDNC, supersaturation, and dynamics and those between cloud-base rain evaporation and instability by varying aerosols in Section 5.6. They showed that as aerosol increases significantly the interactions among CDNC, supersaturation, and dynamics become dominant over those between cloud-base rain evaporation and instability leading to increasing condensation and LWP with increasing aerosols. They also showed that when aerosol increase is not significant, the increasing interactions among CDNC, supersaturation, and dynamics is not large enough to be dominant over those between cloud-base rain evaporation and instability, leading to decreasing condensation and LWP with increasing aerosols. Hence, in this study, the aerosol increase is large enough to induce significantly increased interactions among CDNC, supersaturation, and dynamics which dominate over those between cloud-base rain evaporation and instability, leading to increased LWP in the CSRM-PD run.

Page 21341, line 2-4: "This leads to increased condensation in the GCM-PD (-PI) run as compared to that in the CSRM-PD (-PI) run. This increased condensation is large enough to result in a larger LWP despite the higher conversion efficiency." It may be interesting to show water budget analysis for GCM as well as CSRM and to compare the numbers of them.

The budget analysis of the GCM runs is added in Table 3.

Page 21345, line 16-22: This is an interesting diagnosis of the CSRM and GCM results, and, I believe, is a main finding of this study which should be shown in more pronounced way throughout the paper. I didn't catch this message until reaching here. Can authors make a significant change in presentation style for emphasizing this finding?

We added the finding pointed out here in the abstract.

In section 6.2, we try to explain quantitative differences in variables associated with cloud radiative properties between the GCM runs and the CSRM runs and to compare these runs with the MODIS observation. Also, in this section, we show that the LWP plays the most important role in the change in the cloud radiative properties among the runs. Hence, section 6.2 acts to show the necessity of the analysis of the LWP to understand the change in radiative properties. Section 6.2 also acts to motivate the budget analysis of the LWP to explain the different LWPs between the GCM runs and the CSRM runs; this explanation is to understand why the CSRM run shows a better agreement with the MODIS observation. Motivated by results shown in section 6.2, we move to the following sections explaining mechanisms leading to the different LWPs. In the following sections, we try to explain differences in the results between the CSRM runs and the GCM runs in terms of the two lines of complication (proposed by Zhang et al. (2003) as explained in the summary and conclusion), which are resolution and microphysics parameterizations, since we believe the reviewer here thinks the association of the different results between the CSRM and the GCM with these two lines is one of the most important findings in this study; this is because the comment of this reviewer says that "I couldn't catch the main points until I reached the last section (summary section)" and the summary section is mainly about the association.

We believe the transition of stratocumulus to cumulus in the CSRM-PD run which is not simulated in the GCM-PD run is as important a finding as the finding pointed out here by the reviewer. Hence, we revised the manuscript to emphasize these two findings. We first explained the transition to cumulus clouds in section 6.3 and then explained the finding pointed out here by the reviewer in section 6.4; we think the finding of the different role of the conversion of cloud liquid to rain between the CSRM and the GCM due to the consideration of spectral information for collection in the CSRM is also important and this finding is elaborated in section 6.4.1. To explain the finding pointed out by the reviewer here, we can't help but explain interactions among CDNC, supersaturation and dynamics using the budget analysis and figures before we move to the finding itself in section 6.4.2; in section 6.4.2, we also explained the cause of the different condensation response to the PI-to-PD change between the CSRM and the GCM for stratocumulus clouds, which is another important finding.

In sections 6.4.3, 6.4.4 and 6.5, the comparatively minor findings about the effects of cloud-base instability and environmental conditions on LWP, and the dependence of the LWP responses to aerosols on cloud type are explained.

Technical corrections
Page 21328, line 1: clouds fractions -> cloud fractions

Corrected

Page 21333, line 15: Figure 9a and b shows -> Figures 9a and b show (Similar errors are found throughout the manuscript. Please check.)

Corrected