

First of all, we would like to appreciate the reviewer's comments and suggestions. Especially, we want to appreciate the reviewer's pointing out errors we made about the budget analysis and figures. Correcting these errors contributed a lot to the quantitative improvement of this manuscript. 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 #2**

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Synopsis:

This study compares a GCM and a CSR simulation of the cloudy marine boundary layer in July off the coast of Mexico under present-day and preindustrial conditions. This study is a follow-on to a recently published study (Lee et al. 2009a) in which the same GCM and CSR are compared using present day aerosol emissions. The present study extends that study by comparing with simulations using pre-industrial aerosols. In both cases the GCM output is used for a 20-day period to force the CSR. One of the principal conclusions of this study is that the CSR and GCM respond very differently to changes in the aerosol concentration. Also, the stratocumulus in the preindustrial CSR has more precipitation and thinner cloud which is attributed to a lower condensation rate.

The use of CSR to better understand the GCM responses and to test the GCM is a promising approach, but there are serious problems with the budgets presented here which raise large doubts about the interpretation.

[We corrected the budget analysis by correcting program errors. See below for more details.](#)

Further, the presentation is lacking some important details. Because of these weaknesses and the fact that the complex results do not add substantially to the original Lee et al. (2009a and 2009b) studies, I cannot recommend publication in ACP.

[We believe that the examination into the different response of cloud properties to the PI-to-PD transition for the CSR and the GCM is important, since it can give us an insight into mechanisms](#)

associated with uncertainties in the prediction of climate changes in the GCM. Although Lee et al. (2009a and 2009b) provides a leverage to explain these mechanisms, they don't give us any quantitative analysis about the discrepancies (thus uncertainties in the GCM) in the prediction of climate change between the CSRM and the GCM. In addition to this, this study compares the role of aerosols to that of environmental condition in the response of clouds to climate changes; as far as we know, this study is a first attempt to quantify the relative importance of aerosol effect to that of environmental effect in the changing cloud property with the PI-to-PD transition. This study also reports the dependence of the effect of aerosols on the type of warm clouds; we believe this dependence is important, since it indicates that the wrong simulation of the type of warm clouds and mechanisms associated with the transition of the type of warm clouds in climate models will result in the misleading calculation of the aerosol indirect effect (as discussed in the text).

Main points:

There appear to be some large problems with the liquid water budget for stratocumulus shown in Table 3 and discussed at length in the paper.

1. From the time-averaged conversion rate profiles of cloud liquid to rain in Figure 12b, one can estimate the cloud-base precip flux by vertically integrating. For the CSRM-PD run, for a 200m thick cloud with a mean production of  $0.03 \text{ g}/(\text{m}^3 \text{ day})$  that makes  $6 \text{ g}/(\text{m}^2 \text{ day})$  or  $0.006 \text{ mm}/\text{day}$ . This is much smaller than the mean cloud-base precip fluxes of  $0.2 \text{ mm}/\text{day}$  (before 00 17 Jul) which could be estimated from Lee et al (2009a) Fig 14.

First of all, we would like to apologize for our mistakes in Fig. 14 in Lee et al. (2009a). The true unit in Fig 14 in Lee et al. (2009a) is  $10^{-3} \text{ mm}/\text{day}$ . In our post-processor, the length-unit conversion is generally performed from "m" to " $\mu\text{m}$ " due to the frequent use of " $\mu\text{m}$ " for cloud-particle size. This conversion is applied for precipitation rate by mistake and the real unit in Fig 14 in Lee et al. (2009a) is  $10^{-3} \text{ mm}/\text{day}$  or  $\mu\text{m}/\text{day}$ .

We had generally run 1-day simulations before simulations presented here were performed. Hence, we did not divide the time- and area-averaged variables associated with cloud-liquid mass budget (to obtain their vertical distribution) by the corresponding number of days in the post-processor. This post-processor is used here by our inadvertent mistake. Hence, in fact, the unit of the distributions shown in Figures 9, 12a, and 12b in the old manuscript is  $\text{g}/\text{m}^3/(16.3 \text{ day})$ ; Figures 9, 12a and 12b in the old manuscript are Figures 11, 13a, and 13b in the new manuscript, respectively.

With corrected units in the figures pointed out here, for the CSRM-PD run, the mean conversion rate is  $\sim 1.84 * 10^{-3} \text{ g}/(\text{m}^3 \text{ day})$  that makes  $\sim 0.37 \text{ g}/(\text{m}^2 \text{ day})$  or  $\sim 0.00037 \text{ mm}/\text{day}$  for a 200m thick cloud (following the reviewer's approximated calculation method). With corrected unit, the mean cloud-base precipitation flux is  $\sim 0.0002 \text{ mm}/\text{day}$  in Figure 14 in Lee et al. (2009a).

We corrected figures for the unit of  $\text{g}/\text{m}^3/\text{day}^{-1}$ ; in figure 12b (which is now figure 13b in the new manuscript), the conversion of CSRM-E(PD)-A(PI) is calculated again due to a wrong scaling factor applied to the graphic tool for this run.

2. There is an even larger precipitation discrepancy for CSRM-PD between Table 3 and precip rate. Autoconversion + accretion is  $0.00735 \text{ mm} / 16.3 \text{ days} = 4.5 * 10^{-4} \text{ mm}/\text{day}$  compared with  $0.2 \text{ mm}/\text{day}$  in Lee et al (2009a) Fig 14.

We have many versions of models, since we updated models every time we found errors in them. It seems we did use the model with an error in the calculation of cumulative values. We found the error in the program calculating the budget; we updated model by correcting this error but unfortunately, due to our inadvertent mistake, we chose a version of model not updated for this study. The model used with the error did not pass the cumulative values from the restart files to the next continuing simulation correctly in some occasions, since the routine reading the budget values at the last time step of the previous simulations in those restart files was skipped; sometimes, the routine did not recognize that the simulation was a restart simulation for cumulative values. New budget numbers from the corrected program are in table 3 in the new manuscript. However, the qualitative nature of results in this study is not affected by these errors.

In those new budget numbers, the CSRM-PD cumulative autoconversion+accretion is 0.00749, which corresponds to 0.000459 mm/day and, as explained above, the real unit in Fig. 14 in Lee et al. (2009a) is  $10^{-3}$  mm/day. Hence, the averaged precipitation rate in Fig. 14 in Lee et al. (2009a) is  $\sim 0.0002$  mm/day, which is smaller than the conversion rate calculated from CSRM-PD cumulative autoconversion+accretion.

3. In Figure 9a, vertically integrated condensation in CSRM-PD could be estimated as  $200\text{m} * 3 \text{ g}/(\text{m}^3 \text{ day}) = 600 \text{ g}/(\text{m}^2 \text{ day})$  or 0.6 mm/day. Over 16.3 days that should be 10 mm, which is much larger than the 0.34 mm reported in Table 3.

As explained in our response above, the true unit of the distributions shown in Figure 9 is  $\text{g}/\text{m}^3/(16.3 \text{ day})$ . Hence, the estimated integrated condensation (based on the approximated calculation method of the reviewer here) would be  $\sim 0.6 \text{ mm}/(16.3 \text{ days})$ , which is  $\sim 0.6 \text{ mm}$  over 16.3 days. The new cumulative condensation in Table 3 is 0.63 mm. Hence, figure 9a (which is now Figure 11a in the new manuscript) with the corrected unit represents the cumulative condensation in Table 3 well.

4. Again for the CSRM-PD run,  $\langle dqc/dt \rangle = 0.033 \text{ mm}$  indicates that the LWP should be  $33 \text{ g}/\text{m}^2$  bigger at 00 17 Jul than at the start of the run, while the difference in LWP between these times in figure 6 is only about  $4 \text{ g}/\text{m}^2$ . A similar discrepancy is present for the CSRM-PI run.

Budget numbers are corrected by fixing the errors in the routine calculating the cumulative values; the cause of errors is explained in our responses to the comment 2 of the reviewer here.

In the corrected values,  $\langle dqc/dt \rangle = 0.005$  and  $0.002 \text{ mm}$  for CSRM-PD and -PI runs.

I am skeptical but intrigued by the possibility that condensation differences due to aerosol differences are driving the differences in the LWP in the clouds, as was also argued in Lee et al 2009b. However this budget analysis needs to be corrected in order to try and make that point. It appears plausible to me that drizzle fluxes and not condensation rate are causing the LWP differences. The CSRM-PD run has a diurnal mean of roughly 0.2 mm/day of cloudbase precip (Lee et al 2009a fig 14), and the clean case CSRM-E(PD)-(A(PI)) has double precipitation production (autoconversion +accretion) according to Table 3, and therefore double the cloud-base precipitation rate. The difference between the runs of  $5 \text{ W}/\text{m}^2$  heating (cooling) in cloud (below cloud) is not negligible in the energy budget, and could certainly have a significant effect on LWP.

As mentioned in our responses above, the true unit of precipitation is  $10^{-3}$  mm/day in figure 14. Hence, it is not likely that drizzle fluxes have strong impact on LWP.

Another problem with this study is the use of a very unrealistic GCM stratocumulus simulation as the base state. The coarse GCM resolution together with the very strong thermal stratification in the chosen case results in the representation of the entire boundary layer by only one or two vertical grid points.

As stated in the introduction, it is widely recognized that cloud parameterizations and the use of coarse resolutions have been the cause of discrepancies in the prediction of climate change (in which the AIE plays an important role) among the GCMs (Zhang et al., 2003; Cubasch et al., 2001). Note that one of the purposes of this study is to examine the effect of the use of coarse resolutions on the simulation of thin stratocumulus clouds in the GCMs by comparing the GCM simulation to the CSRSM simulation. Also, we want to note that whether the strong thermal stratification is adopted or not, the comparatively deep MBL (with a depth around 2 km) is generally represented by not more than 4 vertical grid points in the GCMs. Thus, we believe that one or two number of vertical grid points used in the MBL is not that extremely low for the GCMs; in fact, in this study two to three vertical grid points are generally used for the cloudy regions in the MBL.

The stratocumulus-topped boundary layer produced in the GCM is extremely and unrealistically shallow (~350m as compared with e.g. ~550-700m for FIRE I, July 1987, 3 degrees to the north of the study location ) more akin to fog than to stratocumulus, with an unrealistically deep (>200m) capping inversion. This provides a very unrealistic initial state for the CSRSM and makes the study of the GCM and CSRSM sensitivity to aerosol less useful.

We don't think clouds simulated here should have the similar cloud depth to that observed in FIRE I site, since FIRE I is for one specific year and one location which are different from those in this study and we believe the year-to-year and location-to-location variation of cloud depth can explain the difference in cloud depth between the GCM run and FIRE I; Jiang et al. (2002) shows that cloud depth varies from ~ 200 m to ~ 500 m even over a day period.

We think the 200-m capping inversion is not that deep, since even 1-km capping inversion is frequently observed (see Guo et al. (2007, ACP) for the 1-km deep capping inversion).

Other points:

How much do the temperature and moisture profiles above the boundary layer in the CSRSM simulations drift from the GCM simulations over the twenty days? Lee et al (2009a) shows that in the clear sky case the the GCM and the CSRSM evolution is fairly similar in the lowest 2km of the simulations. However this may not be the case in the presence of clouds. Ideally the CSRSM profiles of temperature and humidity above the inversion need to stay near to the GCM profiles to make the simulation comparisons meaningful. Temperature/moisture profiles at different stages of the runs should be shown.

Temperature and moisture profiles at 00 LST on July 11<sup>th</sup> and July 15<sup>th</sup> and 16 LST on July 20<sup>th</sup> are shown in Figure 5. As shown in this figure, no significant differences in temperature and moisture above the MBL between the CSRSM-PD run and the GCM-PD run are shown.

The following text is added:

(LL261-269 in p9)

Figures 5a, 5b, and 5c show the vertical profile of the area-averaged potential temperature and humidity at 00 LST on 11 and 15 July and 16 LST on 20 July, respectively, for the CSRM-PD and GCM-PD runs above the MBL. 00 LST on 11 July is around the middle of time integration; 00 LST on 15 July is when the top height of stratocumulus clouds is at its maximum in the CSRM-PD run; 16 LST on 20 July is at the end of simulations (see Figure 7a in Lee et al. (2009a) for the stage of cloud development). These figures indicate nearly identical vertical temperature and humidity in the CSRM-PD run to those in the GCM-PD run. This demonstrates that the comparison between a CSRM run and a GCM run for clouds can be restricted to layers below the top of MBL.

It is unclear from the descriptions here or in Lee et al. (2009a) whether or not meteorological analysis is assimilated into the GCM runs other than for aerosol transport.

As stated in section 5 in Lee et al. (2009a) and in the current manuscript, background meteorological and aerosol conditions are extracted from the GCM runs and then assimilated into the CSRM runs (not the other way around). Hence, the GCM and CSRM runs can be performed under the identical environmental and aerosol conditions.

The comparison with MODIS observed LWP in Figures 6 and 7 appears to be for a specific year. However, from the description on p. 21326 line 18, MODIS is averaged over the years 2001-2008, and is not from a specific year. If the MODIS data is not from a specific year, the MODIS time series should not be plotted, only the mean value and standard deviation for the simulation period.

The time series of the MODIS-observed LWP and effective radius shown in Figures 7 and 8 in the new manuscript are averaged values over the years 2001-2008 “for each of days between ~ 30 June and ~20 July”

The 20m vertical resolution chosen for the CSRM is also relatively coarse to be trusted to realistically study subtle changes in stratocumulus (e.g. Bretherton et al. 1999, Stevens et al. 2005) especially over a long time scale where entrainment differences could have substantial impacts.

Guo et al. (2008, ACPD) indicated that the development of stratocumulus clouds was sensitive to the vertical resolution. However, Guo et al. (2008, ACPD) found that basic features of the integrations (e.g., the inversion height, LWP and cloud-top radiative cooling) were similar for vertical resolutions of 40 m or finer. Consistent with the finding of Guo et al. (2008, ACPD), an additional set of simulations with a vertical resolution of 5 m for the CSRM-PD and -PI runs (only for period when stratocumulus clouds are dominant cloud type for both runs) show nearly identical results (e.g., LWP and cumulative values of the LWP budget terms) to those with the resolution of 20 m below the top of the MBL. This indicates that the qualitative nature of results here can be considered robust to the vertical resolution.

The following is added to indicate the robustness of results to the vertical resolution:

(LL840-848 in p28)

Stevens et al. (2005) indicated that the 20-m vertical resolution adopted in the CSRMs could not be fine enough to simulate stratocumulus clouds with confidence. However, Guo et al. (2008) found that basic features of the integrations (e.g., the inversion height, LWP and cloud-top radiative cooling) were similar for vertical resolutions of 40 m or finer. Consistent with the finding of Guo et al. (2008), an additional set of simulations with a vertical resolution of 5 m for the CSRMs-PD and -PI runs (only for period when stratocumulus clouds are dominant cloud type for both runs) show nearly identical results (e.g., LWP, effective radius, and cloud fraction) to those with the resolution of 20 m below the top of the MBL. This indicates that the qualitative nature of results here can be considered robust to the vertical resolution.

Minor points:

One can infer from Lee et al. (2009a) that the large scale vertical velocity from the GCM is imposed on the CSRMs. This should be stated here, and the evolution of vertical velocity described for these cases or ideally plotted as this can substantially influence boundary layer evolution.

“vertical velocity” is added in LL193 (in p7) in the revised manuscript.

What was the motivation for selecting this particular location and time period for your study?

The area off the coast of the western Mexico is well-known for persistent development of stratocumulus clouds as reported in Schubert et al. (1979, JAS, pp1286-1307); this persistent development has been confirmed by the satellite observation. We selected this area to simulate stratocumulus clouds, which are not contaminated by other types of clouds when stratocumulus clouds are dominant.

The following is added to indicate the persistent stratocumulus off the coast of the western Mexico:

(LL180 in p7)

where the persistent development of stratocumulus clouds has been observed

Domain averaged vertical profiles of precipitation flux would be very helpful to show in order to understand the CSRMs simulations presented in this study.

We believe Figure 11b depicting the vertical profile of sedimentation-induced cloud mass change can replace the vertical profile of precipitation flux, since we can deduce sedimentation-induced latent-heat changes from Figure 11b.

p.21326 line 17: The GCM runs don't appear to be averaged over 24 hours in Figure 6 as stated. For example the GCM-PD LWP plotted drops to zero twice at days 9.5 and 10.5, which means it couldn't possibly be non-zero at day 10.0. They should be averaged over 24 hours for a better comparison.

The algorithm used for the figure pointed out is checked out and this figure is re-drawn.

p.21328 line 17: The transition would be better described as a change from stratocumulus to cumulus under an elevated stratocumulus deck. The cloud fraction actually increases in the CSRMs-PD run during this period compared with the stratocumulus period.

As reported in Bretherton et al. (1997), cumulus clouds reaching the top of the MBL spread at the top (which is analogous to deep convective clouds reaching the tropopause and spreading to form anvil cirrus clouds). This spreading involves detrained cloud liquid from the cumulus clouds to form the elevated stratocumulus deck at the top of MBL.

The following is added:

(LL341-343 in p12)

These cumulus clouds spread at the top of MBL to form the elevated deck of stratocumulus clouds as shown in Figure 9 in Lee et al. (2009a).

'July' should replace 'June' in many places: p.21332 line 9, p.21335 lines 13 and 18, p. 21338 line 21, p.21340 line 22, p.21342 line 27, Figure 8a top and in the figure caption, Figure 8b top of the figure, Table 2 multiple column headers

“June” in the text pointed out here is replaced with “July”

p.21321 line 15 Is the acronym CDNC defined?

It is defined in LL127 in p5 in the new manuscript.

p.21322 line 8 'represent' p.21330 line 24 should read 'Also, it needs to be pointed out'

Done

p.21331 line 2 Figure 11 is introduced here 2 pages before Figure 9 is. p.21338 line 12

The figure order is corrected following this comment.

It is budget 'terms' shown in Table 3 not the budget 'equation'.

Corrected

p.21347 line 2 should be 'changes'

Corrected

Table 2: 'MODIS' and 'Simulation' should be switched relative to the diagonal line

Done

Table 3: Text 'Domain averaged budget terms...' inside table is redundant. Units (mm) should be in the table caption.

Done

Figure 5: An additional contour level at 0.1 g/kg or 0.2 g/kg would be helpful, as 0.4 g/kg is very large for typical stratocumulus clouds. Figure 11. The fonts in the figure legend and at the top of the plots are too small

Done

References:

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