<u>Anonymous Referee #1</u> (Review comments in regular**; response in bold**.)

This paper discusses the aerosol cloud life time effect for the diurnal cycle of Stratocumulus clouds over the ARM SGP site, and comparing the results by a cloud resolving model with those of a GCM. They find that entrainment related evaporation can dominate the autoconversion reduction with increasing aerosol concentration, a mechanism not typically observed in GCMs. In general, I find this paper well written, understandable and novel, so I recommend publication in ACP after some questions are addressed.

Particularly, I am worried about the 50 to 100m horizontal resolution of the CRM, and the 30+ m in the vertical; in most LES intercomparisons of SCu, a much higher resolution is used, particularly to resolve the sharp interface of the SCu top entrainment. Do the authors have a good feel for how well their CRM is converged?

Answer: We used two horizontal resolutions for the CRM, 50 m and 100 km, not 100m. The response of LWP to increased aerosol number does change signs when we change dx=50 m to dx=100 km but not dx=100 m.

To test the convergence of the model, ideally one would increase the resolution of the CRM to see if the results still hold. Due to the limited computational resource we have, we run the cases with a decreased horizontal resolution of 100m. Both dx=50m cases and dx=100m cases show the same trend of the LWP, i.e., LWP decreases with increasing aerosol number concentrations. We agree that a resolution with dx=50m and 30+m in the vertical may be somewhat higher than most LES simulations of SCs and a smaller grid size could be better in capturing the cloud top processes and show some quantitative difference in the LWP. But we expect the trend of LWP to the increased aerosol number will be the same. As the main issue we wish to show is how basic processes left out of GCMs can lead to overestimates of the response of LWP to aerosol particle number, the exact change of LWP is less relevant here. Moreover, we never claimed that we were running the simulation at LES resolutions.

The coarse resolution case dx=100km, was a sensitivity study to mimic what occurs in single column CAM model. We chose this coarse resolution to substantially reduce the vertical movement so that the effect from the microphysics would dominate. By doing this we isolate the microphysics effect from the entrainment effect at the cloud top and demonstrate that using a reduced autoconversion rate in the CRM also increases the LWP when the aerosol number concentrations are increased, which is similar to the response in the GCM.

The other major question that I have is about the case that they chose. It is a complicated SCu case, with a strong diurnal cycle, and an a-typical qt profile. So why this case, and do you feel it is representative for cloud life time effects across the globe? Perhaps a slightly less generic title would help to lower the expectations here.

Answer: One of the targeted goals of our funded project was to use the relatively less frequently used IOPs from the SGP site. Thus we chose to use the forcing data derived from the Midlatitude Continental Convective Clouds Experiment (MC3E) which was the most recently conducted experiment near the ARM Southern Great Plains (SGP) site. For this study, May 27th, 2011, was selected because middle and

high clouds were absent during a low cloud period observed near noon. We agree that such a case may not be representative enough for SCs across the globe. But the finding (i.e., the absence of cloud-top entrainment effect in GCMs may lead to an overestimated LWP for increased aerosol numbers) should be applicable to SCs with dry air above the cloud top across the globe. To make the title less generic, we change the title from "Why do GCMs overestimate the aerosol cloud lifetime effect? A comparison of CAM5 and a CRM" to "Why do GCMs overestimate the aerosol cloud lifetime effect? A case study comparing CAM5 and a CRM".

Other points:

1) It is not very clear from your introduction that you are talking about Stratocumulus, and probably of the kind that barely precipitates. I would make that more clear in the introduction.

Answer: Done.

2) How does your work compare with the DYCOMS results, and the papers by Andy Ackerman et al? (e.g., Nature, 2005 and MWR, 2009)

Answer: Our case is similar to some extend to the DYCOMS-II case in Ackerman et al. (2004) but with even less drizzling. This makes the increased entrainment effect even more dominant than the decreased drizzling effect in our case and explains why we only see decreased LWP with increasing aerosol concentrations. We now mentioned this in the discussion in the revised manuscript.

3) P2, l 14: Make sure to name your models, and to expand properly

Answer: Done. We now gave the full name in the abstract.

4) P3: I am missing a description of your boundary layer scheme here. This is likely a crucial part of information for the CRM entrainment (or lack thereof).

Answer: Whereas CAM has a shallow convection scheme to parameterize the subgrid transport of heat, moisture, momentum and tracers by asymmetric turbulence within the PBL and a separate moist turbulence scheme for vertical transport by symmetric turbulence (Park and Bretherton 2009), in the CRM, subgrid-scale (turbulent) processes are parameterized using a scheme based on Klemp and Wilhelmson (1978) and Soong and Ogura (1980). The effects of both dry and moist processes on the generation of subgrid-scale kinetic energy have been incorporated. We added this information in the revised manuscript.

5) Since your resolution is on the lower side for the cloud top: What is your advection scheme in GCE?

Answer: GCE uses a positive definite advection scheme for scalar variables (Smolarkiewicz and Grabowski 1990).

6) Also, I have to ask: Is the fact that you are using a bulk micro physics scheme an issue here?

Answer: We used a 2-moment bulk microphysics scheme which predicts both number and mass mixing ratios of cloud droplets. This scheme has the capability to simulate the

effect of aerosol indirect effects even though a bin microphysics may follow some of the details more thoroughly.

7) P5, 10: The linear decrease in aerosol means that you have a decreased CCN concentration in the Boundary Layer of about 5%, if my math is correct. Why make that change?

Answer:

Yes, there is a small decrease of CCN with height in the Bounday Layer. This decrease followed the model's default set-up (the aerosol profile is fixed). We agree that the aerosol number should be (well mixed within PBL. But the small decrease assumed in the model should have a very minor impact and will not change the model behavior.

8) P7, 1: Could you plot the cloud cover as well? The dynamics may very well change as a function of aerosol (or model), for instance moving between cumulus and stratocumulus here.

Answer: We checked the cloud coverage. The change is negligible when we increase the aerosol number and could not be distinguished any change visually from a height-time plot. All clouds are stratus clouds without any cumulus cloud. In the CAM's microphysics scheme for the rain budget in warm clouds, the source terms of rain include autoconversion and accretion of cloud droplets and the only sink term is the evaporation term of rain. The relatively large decrease of surface precipitation when the aerosol number is increased from 250 to 500 cm^{-3} is a combination of decreased autoconversion/accretion and increased evaporation of rain. When the aerosol number is increased from 250 to 500 cm^{-3}, the sum of autoconversion/accretion decreases. Meanwhile since there is less rain falling through the unsaturated sub-cloud layers, the final fraction of rain which can survive evaporation also decreases. The relatively large decrease of surface precipitation is peculiar to the aerosol numbers and environmental conditions. We added a statement to this effect in the manuscript.

9) P7, l 18: To mitigate concerns about this particular case, it could be nice to quickly look at a second one as well. But at the very least, a bit more discussion about the dynamics of this case would be appreciated. (e.g., is it decoupled? What is the w2 profile? How much precipitation do you observe as a function of height).

Answer: We were not sure whether you were asking about the cases associated with number concentrations or the single day we report in the paper.

For number concentration: We checked all cases with different aerosol number concentrations and they have similar structures as showed in Fig. 2b. Fig. 2b actually already presents the results from two cases 250 cm^{-3} (dash-dotted curves) and 1000 cm^{-3} (solid curves). But the curves are overlapped. An enlarged portion to distinguish them is presented in Figure S3.

Below is a figure showing the profiles of potential temperature, specific humidity, cloud water mixing ratio, rain mixing ratio and w^2. From the profiles of θ and q_t, we can see the clouds are not decoupled at 14:00 and 15:00. The clouds at 13:00 are a little more

complicated. The abrupt decrease of w^2 at 1.3 km and the more smooth change of cloud water q_c and larger q_t, at this height suggests the clouds above 1.3 km above may not be fully coupled to the sub-cloud layer.

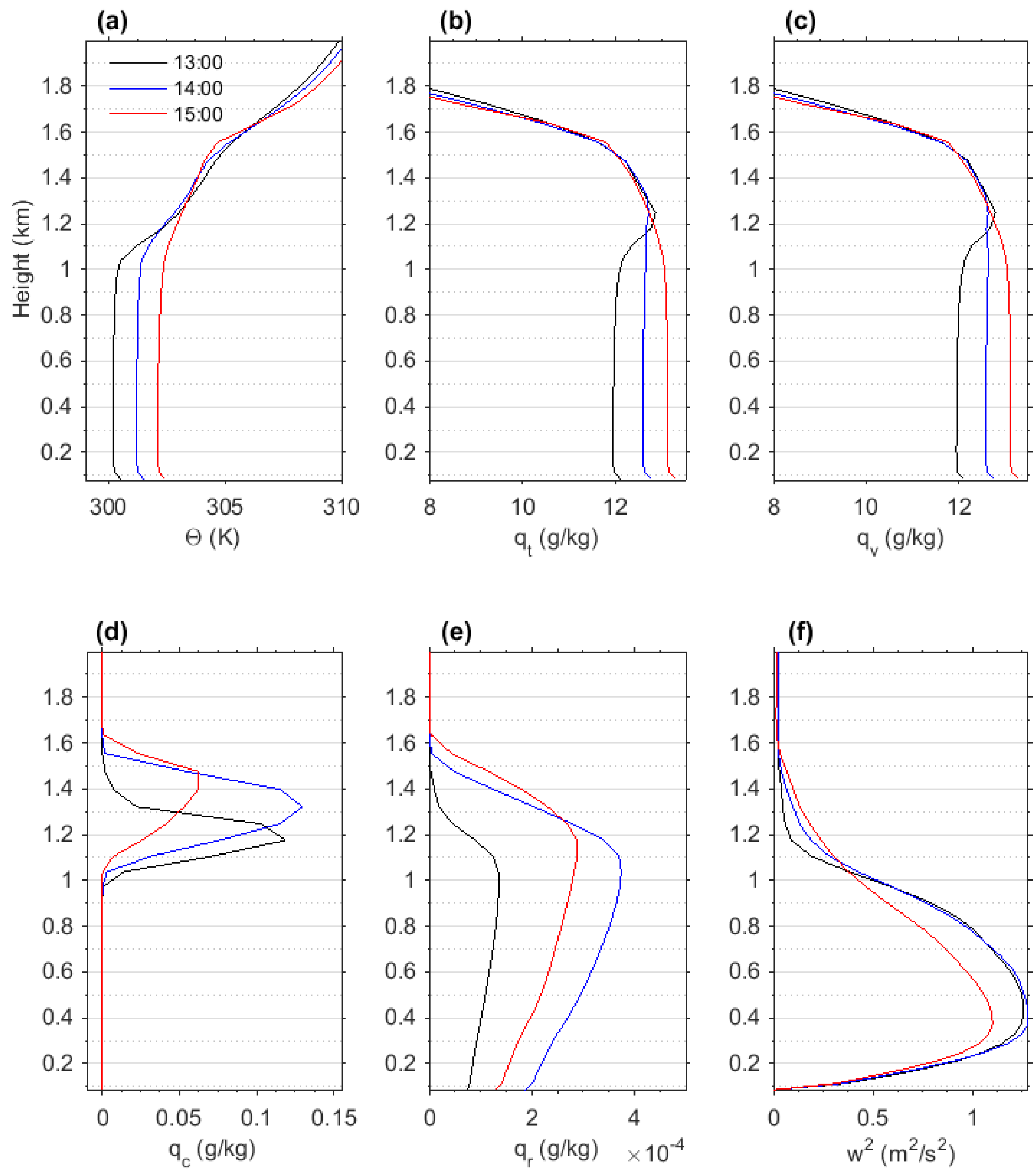

Figure 1 (a) Domain averaged potential temperatures (θ), (b) total water specific humidity (q_t), (c) specific humidity (q_v), (d) cloud water content (q_c), (e) rain mixing ratio (q_r) and (f) square of w at three times (13:00, 14:00 and 15:00) from the GCE case with surface aerosol numbers equal to 1000 cm^{-3}.

10) Why do the observations in Figure 1 show no diurnal cycle?

Answer: The clouds are modulated by advected water vapor and heat fluxes. The fluxes are showed in Fig. S1.

11) P8, l 22: You state that some differences are likely because of details in the microphysical model. I understand that you cannot get those perfectly identical, but did you do a parameter study to get a feel of this sensitivity?

Answer: Since aerosol number affects cloud droplet number and thus directly affects the autoconversion rate, we tested the behavior the autoconversion rate to the increasing aerosol number in the two models. As showed in Figure 2 below, autoconversion rates are functions of in-cloud cloud mass mixing ratio and number mixing ratio in both models. Compared to CAM's scheme, autoconversion rates from GCE overall have a smaller dependence on cloud droplet number but larger dependence on cloud mass mixing ratio. We extracted the two pairs of in-cloud droplet number/mass mixing ratios ([26 cm^{-3}, 0.167 g/kg] and [122 cm^{-3}, 0.293 g/kg]) from the center layer of clouds at 11:30 hour from the two CAM cases in which the surface aerosol number increasing from 250 cm^{-3} to 1000 cm^{-3}. The autoconversion rate from the Khairoutdinov and Kogan [2000] scheme used in CAM decreases from 1.86e-9 to 4.67e-10 kg/kg/s. When we applied the GCE's scheme to these two pairs of data the autoconversion rate only decreases from 1.57e-9 to 1.48e-9 kg/kg/s.

We added following after the above referenced sentence:

"Since the autoconversion rate is directly affected by the aerosol number, we used an offline model to compare the autoconversion rates from the GCE and those from the Khairoutdinov and Kogan [2000] scheme used in CAM. The results are shown in Fig. S4. Compared to CAM's scheme, autoconversion rates from the GCE are less sensitive to the droplet number concentrations when the number concentrations are less than 100 cm^{-3} and the cloud mass mixing ratio is above 0.1 g kg^{-1}. When the cloud number concentrations are larger than 200 cm^{-3}, the autoconversion rates from GCE have a larger dependence on the number concentrations than those from the CAM scheme. However, they have a larger dependence on cloud mass mixing ratio than those from the CAM model. So increasing aerosol number tends to decrease the autoconversion rate more in CAM than in GCE. As an example, we extracted the two pairs of in-cloud droplet number concentrations and mass mixing ratios ([26 cm^{-3}, 0.167 g kg^{-1}] and [122 cm^{-3}, 0.293 g kg^{-1}]) from the center layer of clouds at the 11:30 hour from the two CAM cases in which the surface aerosol number increased from 250 cm^{-3} to 1000 cm^{-3}. When applying CAM's scheme to these two pairs of data, the autoconversion rate decreases from 1.86×10^{-9} to 4.67×10^{-10} kg kg^{-1} s^{-1}. In GCE's scheme, the autoconversion rate only decreases from 1.57×10^{-9} to 1.48×10^{-9} kg kg^{-1} s^{-1}. "

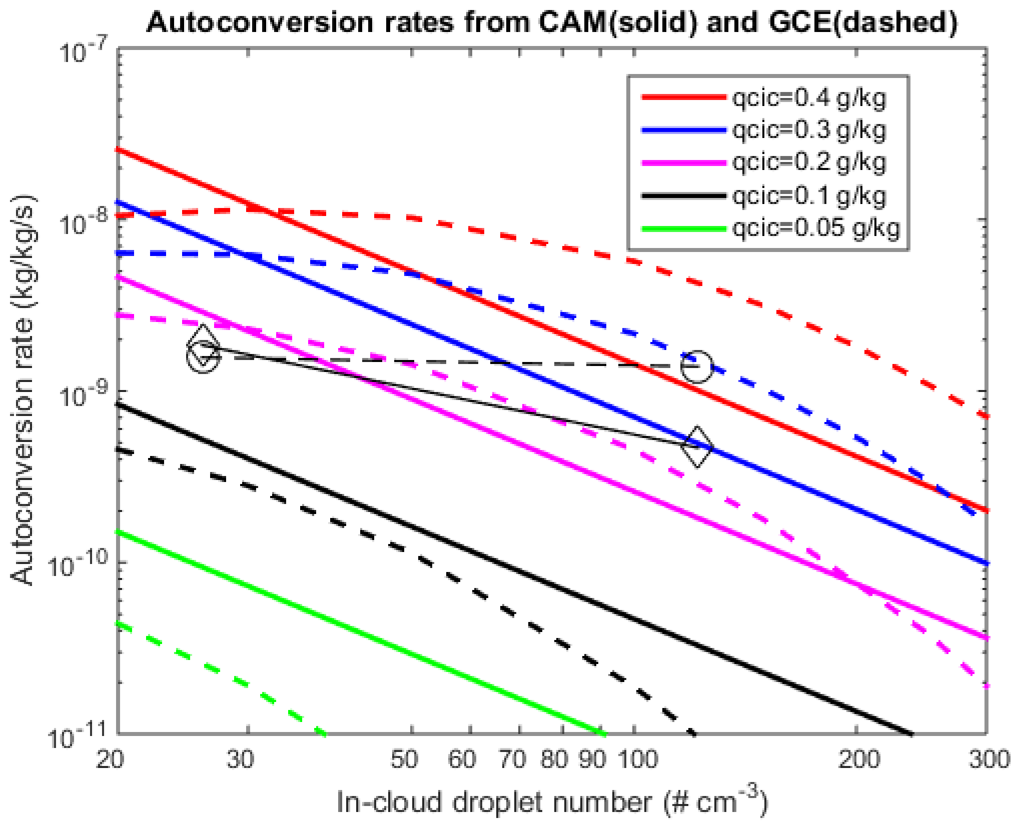

Figure 2. Autoconversion rates from the Khairoutdinov and Kogan [2000] scheme used in CAM (solid curves) and from the stochastic collection equation solutions used in GCE (dashed curves) as functions of in-cloud cloud mass mixing ratio and number mixing ratio. An air density of 1.0 kg/m3 is used. The two pairs of diamond and circle points are autoconversion rates from the two different schemes (diamond: CAM, circle: GCE) using simulated in-cloud droplet number/mass mixing ratios ([26 cm^{-3}, 0.167 g/kg] and [122 cm^{-3}, 0.293 g/kg]) which are extracted from the center layer of clouds at the 11:30 hour from the two CAM cases with surface aerosol number equal to 250 cm^{-3} and 1000 cm^{-3}, respectively.

12) P9, l 21: "..50m to 100km: : :" Should be meter, (I hope)

Answer: It is 100 km. We choose this coarse resolution on purpose to substantially reduce the vertical movement within the CRM so that the effect from the microphysics would dominate. By doing this we isolated the microphysics effect from the entrainment effect at the cloud top and demonstrated that the reduced autoconversion in the CRM would also increase the LWP when the aerosol number concentrations are increased, which is similar to that in the GCM.

Reference

Smolarkiewicz, P. K., and W. W. Grabowski, 1990: The multidimensional positive advection transport algorithm: Nonoscillatory option. J. Comput. Phys., 86, 355–375.