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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Cloud Droplet Growth in Shallow Cumulus Clouds Considering 1D and 3D Thermal Radiative Effects" *by* Carolin Klinger et al.

Anonymous Referee #1

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This study explores the effect of radiation on cloud droplet growth in shallow cumulus clouds. Using an offline parcel model it is found that radiative cooling affects droplet growth mostly for drop sizes larger than 10 μm and that the effect is stronger for 3D than for 1D radiation. Recirculating parcel meet several of the criteria that are found to be favorable for a strong effect of radiative cooling on cloud droplet growth and hence contribute more strongly to rain production than if radiative effects on diffusional droplet growth is not taken into account. In a sencond part, a fully coupled LES simulation with bin microphysics is used to unravel effects of 1D and 3D radiation on the dynamics and the diffusional growth. Although the differences in rain production are overall small, the authors conclude that radiative effects on microphysics increase the rain fraction but that a dynamic evaporation-circulation feedback can decrease rain amount.

The topic of the study is very interesting and relevant for ACP. The manuscript is overall written well and the plots illustrate their content well. However, I have two issue with the study in its present form: First, the authors themselves argue that because in the parcel model raindrops are not allowed to fall out of their parcel, the parcel model is not appropriate to analyze rain formation. Nevertheless parts of their analysis (Fig. 6, 7, 9, 12) focuses on drops of sizes that have considerable fall speed and on rain rate. Second, the differences in the coupled LES simulations are very small. Because simulated precipitation from shallow clouds is such a sensitive variable, I am sceptical that these small differences are robust and due to physical causes rather than random fluctuations due to different realisations. I comment on these two issues in more detail below followed by some specific and technical comments.

1) In the method section you argue (and I agree) that the methodology is only valid until the onset of drizzle. Analysing the rain rate (Fig. 12) is therefore not appropriate. In Fig. 6 and 9 the main differences are seen for drops larger than 20 μm radius, which is just the size where cloud droplets turn into drizzle (e.g., Sant et al., 2013, JAS). Even with a less conservative estimate drops with a radius of 40 μm develop considerable fall speed. In the parcel model, those larger drops do not fall out but instead keep on interacting with the smaller drops in their parcel, which is unphysical. Because of the interaction of the large drops with the small droplets, changes in the smaller part of the drop size spectrum are not independent of this issue as soon as some larger drops form.

2) In the coupled LES simulations overall differences are small (e.g., Fig. 14 and 15) and I am wondering whether they are actually causally related to the changes in the radiation. My null-hypothesis would be that the differences in the runs are due to random fluctuations in different realisations. One way to test this is to run an ensemble of simulations for each of the five modifications and analyze whether those ensembles (and their spread) are significantly different from each other.

Specific comments:

- While I found the rest of the paper well-written and clear, Section 2 was confusing to me. I am not a radiation expert and as other reader might not be either, some improvement is needed here. Please, help the reader by systematically arguing why you need each equation and what it is leading to. E.g., why do you need the forcing term tau and in which equation does it go? On p.5 l.11 you arrive at the same expression you already had on p.3 l.20. Which equation do you use in your model? Also, make sure you explain all variables and constants (see also my technical comment).

- In the first line of Eq 4, why is there no sum over the different sizes of m within the bin range of bin k? Under which assumptions does the approximation hold? Please use $\approx$ where necessary to indicate the approximation.

- p.6 l.2: Are the trajectories run as tracers that go with the flow or is an average fall velocity of particles size distribution taken into account? From what I read later, I assume they are calculated as tracers of the flow. This would be helpful to specify already here.

- How are the cloud droplet size distributions initialised in the offline parcel model?

- Is the analyzed parcel in Fig 4 and 5 the same? This is not clear from the text.

- Fig. 7, tau: It would be interesting to calculate the overall contribution to droplet growth for each of the three sizes from the dynamic and the radiative term. The values of the radiative forcing are much smaller than the dynamic terms but the dynamical forcing also has substantial negative contributions.

- p.13 l.8: This sentence is not clear to me: "The radiative cooling does not seem to cause droplet growth in individual parcels beyond the NR case..." Are you saying that in parcels where there are no cloud droplets for NR, also no cloud droplets will grow with 1DR or 3DR?

- Fig 12 and 13: Is this the rain rate at the surface or integrated over all heights? I assume the latter. Please clarify. However, given the restriction of the method to the

onset of drizzle, I do not think it is appropriate to analyze the rain rate (see my general comment).

- p.16 l.20: How long do the parcels need to be in an environment with qc less than 0.01 g/kg to be called a recirculation? Do your statistics substantially change if you increase or decrease a threshold in time a bit?

- To quantify how much recirculation parcels contribute, I think it makes more sense to normalize by the total rain rate for each simulation, e.g., RR_1DR_recirculating/RR_1DR_total. Otherwise you combine the effect of radiation and recirculation.

- p.18 l.9 and elsewhere: Please do not use "significant" when you did not test for significance. "considerable" or "substantial" might be alternatives.

- Fig. 14,15,18: Why don't you combine those three figures into one? If I am not mistaken you just need to add one line in Fig. 14. It would allow the reader to compare simulation pairs, which the manuscript does not focus on. Also, I do not see the advantage of comparing different time periods for the different simulations in Fig. 17 and 19. If the results are robust, I would expect the results to be qualitatively the same for other time periods. Then Fig. 17 and 19 could be combined and show all five simulations. Also, show all five simulations in Fig. 16.

- Section 4: If the results turn out to be robust (see my general comment), my interpretation here would be that applying radiative cooling to microphysics leads to larger cloud droplets and drizzle drops especially at the cloud edges, which then can lead to two opposing effect: 1) The larger drops re-enter the cloud and have a better chance to form rain than if they had not grown by radiation. Therefore rain formation is enhanced. 2) The larger drops decrease evaporation at the cloud edge, which via the evaporation-circulation feedback leads to weaker updrafts and hence less rain formation. Going from 1DD to 1DD_1DM effect 1 seems to dominate; going from 3DD to 3DD_3DM effect 2 seems to dominate. If you agree with this interpretation, I think it would be worth to make this opposing effects clearer in the manuscript. Here, it would strengthen your point if you analyze the evaporation rates for all simulations (Fig. 16). Also, I suggest to contrast the difference in evaporative cooling at the cloud edge with the difference in radiative cooling rates at cloud edge to unravel whether a decrease in evaporative cooling or the increase in radiative cooling dominates if you go from 1DD to 3DD_3DM.

- p.1 l.11 "Small amounts of rain are ..." and p. 24 l.12 "... rain covers a larger area": I do not see that these sentences are true for 3DD to 3DD_3DM (Fig. 14).

Technical comments:

- Please check the standards of the journal. Usually references should be ordered by year (e.g., p.3 l.6 or l.10, check elsewhere) and brackets in brackets are not allowed.

- pay attention if you place variables (math mode) in the text, e.g., T_inf on p.3 l.17 or q on l.27

- make sure to explain all variables and constants, e.g., D and e_s on p.3 l.28 or t_f on p.4 l.13

- p.6 l.7: Harrington et al. (2000)

- caption Fig.4: where there parcel stays -> where the parcel stays

- Fig 4: What the color scale of qc in b-d? It seems not the be the same as for the trajectory in a.

- p.11 l.4: four -> three

- p.12 l.12: the the -> the

- p.18 l.24: stronger stronger -> stronger

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