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Interactive comment

Interactive comment on "The effects of cloud-aerosol-interaction complexity on simulations of presummer rainfall over southern China" *by* Kalli Furtado et al.

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Author replies to anonymous Referee #4

Major changes:

1. "A more detailed .. discussion on the microphyical processes". We've significantly rewritten and expanded the text on p9 to provide a more methodical discussion warm and mixed-phase processes. The new structure is based on discussion of 3 possible 'scenarios' of cloud aerosols interaction: (1) warm-rain-processes dominated: more droplets implies reduced auto-conversion and fewer rain drops. (2) cloud-droplet freez-

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ing dominated: more cloud-droplets leads to more ice particles (via ice nucleation); this leads to more rain drops due to melting snow as aerosol increases (3) mixed-phased-feedback dominated: the rate of riming is the dominant factor; more cloud droplets number leads to less riming (because the droplets are larger), less graupel, and fewer rain drops from melting graupel.

We discuss the relative merits of each scenario in turn. (2) can be ruled out because it is not consistent with the simulated changes in ice- and rain numbers (see text). To some extent (2) and (3) cannot be disambiguated, because both affect rain-number in the same direction. However, we note that (2) is not consistent with the orders-of-magnitude of the changes in rain and graupel: the graupel-number changes are much too small to explain the changes in rain-drop number. Further, we've added to Fig. 4 a new experiment ("5e6_ACC") in which Na=5e6 but auto-conversion and rain-cloud accretion are both turned off (for T>-4C). In this experiment, the only possible aerosol-indirect effects are via changes in mixed-phase or ice process. The results show that 5e6F_ACC is similar to 5e7, not to 5e6. This strongly suggest the cloud-aerosol effects seen are very similar to the effects of suppressing warm-rain processes. This supports the conclusion that warm-rain processes are essential for simulating the cloud-responses seen in the full-microphysics simulations. It does not, of course, completely rule out the additional importance of mixed-phase processes, and this is noted in the revised text.

Figure 5. Specifically the co-dependencies of ice-water path and rainfall rate. Firstly note that in each experiment, the surface rainfall rate will always be correlated with ice-water path, because heavier rainfall occurs underneath convective cells with larger water contents. The effects of aerosols can only be seen by stratifying the cloud properties based on rain rate (as shown by the different colors in Fig. 5). A new subsection 3.1.3 (p12) has been added specifically discussing the possible effects of ice-phase processes on rain- and ice-water paths. To paraphrase what is written there, we cannot completely rule out the role of ice-phase processes (and this is fully acknowledge

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in the text), but the simulation without warm-rain process has rain- and ice-water paths that are very similar to the (more polluted) 5e8F simulations, which at least points to warm-rain processes being crucial for capturing the aerosol-effects.

p6.L14 “1s0dp has more rain, but less snow”. These difference are now dealt with in the new sub-section 3.1.1 (p12): “The number of ice crystals (green [lines in Figs 4(a-d)]) is smaller in simulations with fewer cloud droplets aloft. This is consistent with fewer cloud droplets leading to less nucleation of ice, via either homogeneous freezing or heterogeneous (immersion) freezing.”

p9.L16-17. “Some of the discussion of the ice phase processes may be wrong . . . there is more graupel in the low aerosol experiment . . . ”. Your suggestion is that the number of rain drops may be changing in response to a change in the number of melting graupel particles. This is a possibility, but it is difficult to justify because the change in graupel numbers is much smaller than the change in rain drops. This possibility is introduced and more carefully discussed in the revised Section 3 (see “scenario 3”, above. It cannot be completely discounted on the basis of the current experiments, but it struggles to explain the mismatch between graupel- and rain-number changes. Moreover, the ‘no-warm-rain processes’ experiment (5e6_ACC) includes the effects of changes in cloud-drop number on graupel, but does not reproduce the rain differences between the full-microphysics experiments.

p9.L14-15. “Is is hard to understand this sentence”. Agreed! Moreover, I don’t think the sentence was useful, I’ve removed it from the revised version.

p9. Rain water content and surface rainfall rate responses to aerosols. The revised Section 3 address the changes in number, condensed mass and rain-fall rate, systematically and in a more logical sequence. Number changes are dealt with first (Sec. 3.1.1). The responses of water paths then have their own subsection (3.1.2), where the reasons why rain-water path, cloud-water path and rainfall rate varying together are explained. We agree that the responses of rain-water path to aerosol are less readily understood than those of rain-drop number. The responses are explained in Sec. 3.1.2. The basic mechanism here is that larger drops fall faster so if the rain water is held constant then the precipitation rate will increase as the number of rain-drops increases. Similarly, if the rainfall rate is constant, the a larger number concentrations requires a large rain-water path to balance this precipitation flux. These mechanisms can also be put on a mathematical basis by considering mass-balance in the steady updraft. This argument is (we believe) relatively well known, but we've added short appendix (A1) given the details.

p9.L12. "the 'minimum' cloud droplet concentration." 'Minimum' referred to the lowest values of cloud-drop number attained in each column of the model the grid. However, I now think this sentence was unnecessary (and a bit confusing) –so we've removed it entirely, as part of the re-organizing in response to your comment 1. As requested, the large reduction in cloud-droplet number in 1s0dp, compared to 5e7F, is now emphasized in the abstract & conclusions.

2. Model description. (Section 2.1.) We've now described the choice of immersion freezing parametrization in more detail on p5: "This fraction is a function only of temperature and is independent of the number of interstitial aerosol particles. Ice-crystal number concentration can be indirectly affected by the number of aerosol particles, because the number of cloud droplets can affect the number of ice crystals." We've now described the ice-cloud responses seen in vertical profile (Fig. 4) on p9: "The number of ice crystals (green) is smaller in simulations with fewer cloud droplets aloft. This is consistent with fewer cloud droplets leading to less nucleation of ice, via either homogeneous freezing or heterogeneous (immersion) freezing."

The choice of aerosol concentrations is now discussed on p5: "For the fixed-aerosol experiments we consider reductions N_a in decades, from approximately 500/cm^3. This range is selected to span the range of concentrations generated in 1s0dP. For reference, some of the plots also include an unrealistic, 'limiting' case with N_a=50^5 -/kg."

We agree 5e5F is unrealistically clean, we still think it's worth including as a 'limiting case'.

Regarding the rainfall rate variations: we agree the sensitivity of these to aerosol perturbations is not large across the range considered. In fact, this a conclusion of this study: rainfall intensity and area change, but in a way that keeps rainfall amount (rain rate) approximately constant.

3. Abstract. We've modified the abstract to be more specific about the paper's conclusions. The new part reads: "It is shown that in-cloud processing of aerosols can change the vertical structure of the storm by using up aerosols within the core of line, thereby maintaining a relatively clean environment which propagates with the heaviest rainfall. This induces changes in the statistics of surface rainfall, with a cleaner environment being associated with less intense but more frequent rainfall. These effects are shown to be related to a shortening of the timescale for converting cloud-droplets to rain as the aerosol-number concentration is decreased. The simulations are compared to satellite-derived estimates of surface rainfall, condensed-water path and the outgoing flux of short-wave radiation. Simulations with fewer aerosol particles out-perform the more polluted simulations for surface rainfall, but give poorer representations of top-of-atmosphere radiation."

Minors changes:

Figs 1–3; text size. I'm not in favour of increasing this; it's a trade off between text size and picture size. I think the text is readable.

Fig. 7. the 20pc criteria is only used to demarcate ice clouds on the plot – it is not used in a statistical analysis.

Fig. 8. labels corrected.

Various typos corrected.

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