Responses to Referee 1

I found their comment on the top of Page 29019 in which they state: "… our simulations suggest that the peak precipitation intensity is more sensitive to thermodynamics than aerosols" to be a very important one. This is especially true in light of the uncertainty of the effects of aerosols on precipitation. I think that their results show that the aerosols affect the timing of rain initiation and maybe the division between the contribution of the cold and warm precipitation processes, but that the total precipitation is more a function of the atmospheric temperature and humidity profiles. I would like to see this important point expanded in the paper.

We appreciate the referee’s suggestion to expand this important point and add the following after the sentence.

Aerosol loading alone affects the collision-coalescence of drops, the formation of ice particles via drop freezing, the partitioning of the contribution from the cold and warm precipitation processes, the intensity of precipitation rate, and the precipitation onset. The atmospheric temperature and moisture profiles not only affect those, but also other microphysical processes. For example, a warmer environment effectively increases the depth of the warm rain processes and allows drops to grow to larger sizes. Therefore, it enhances graupel particles via immersion freezing and produces more precipitation once the graupel particles sediment below the elevated melting level. As a result, both precipitation intensity and duration increase.

I found a few major problems that the authors should address in their paper:

1) The model is axisymmetric and thus cannot account for the effects of wind shear on the development of precipitation. 2D models with shear show that many of the small ice crystals at the upper parts of the clouds are blown away to produce anvils, thus reducing precipitation. In continental clouds this could be a major factor since riming is slower and the ice crystals are smaller. In maritime clouds, where the number of cloud drops is small, the ice crystals that are formed have only very few drops to rime with, thus the ones that do not grow by riming will also remain small and be blown away by the horizontal winds at the upper parts of the clouds.

We agree with the reviewer. However, there are many factors that can affect cloud and precipitation that are difficult to study. In this paper, we present the special case of clouds without wind shear. Even for this special case, there are not many studies of the influencing of aerosol and thermodynamics on precipitation in deep convective clouds with the detailed analysis of the cloud microphysics.

MAC3 is an axisymmetric model and the axisymmetry is a major limitation in terms of dynamics, but a major advantage in terms of microphysics. It cannot be used to simulate clouds in strong wind shear conditions. In a weak wind-shear environment, however, an axi-symmetric model gives more realistic results than a two-dimensional

(2D) slab-symmetric model for simulation of a single-cell cloud. For example, Ogura (1963), Murry (1970) and Soong and Ogura (1973) compared results from 2D slab-symmetric and axisymmetric models. All those studies showed that clouds that developed in an axisymmetric model were more vigorous than those in a 2D slab-symmetric model, and the clouds developed in an axisymmetric model were closer to those in a three dimensional model (Wilhelmson and Ogura, 1972), providing the initial and boundary conditions in the two models were the same (Soong and Ogura, 1973).

We emphasise the limitations in the revised paper, and discuss the limitations of axial symmetry more fully. Since this is the major and only concern of Referee 2, we describe fully the limitations in the responses to Referee 2.

2) The major conclusions of this paper depend on the rate of growth of ice. Namely the number and size of the ice crystals make a big difference in the development of precipitation. However, the paper uses the parameterization of Meyers et al to simulate the development of the ice. This parameterization has been shown to overestimate the ice formation. Although good parameterization of ice formation in clouds is one of the major deficiencies of our understanding clouds and precipitation, I expected the authors to address this point at the beginning and not leave it to the end of the concluding remarks.

We have now addressed the difficulty in the parameterization of ice formation in clouds at the beginning of the conclusions.

3) I think that it will be valuable to estimate the effects of modifying the parameterization of ice formation even by artificially enhancing and decreasing ice formation by a certain factor. Another option is to use another published parameterization of ice nucleation (e.g. recent publication by DeMott which suggests a dependence on total aerosol concentration > 0.5 microns) which leads to lower concentrations of ice crystals. Such evaluation could reveal the sensitivity of the conclusions to the rate of formation of ice.

We considered this issue when designing the runs for the project. We made the decision that since there was so much uncertainty about the formation of ice that it would be difficult to determine sensible variations. We believe we made the right decision. A future study will focus on the formation of ice.

4) Page 29009 – the reference to Levin and Cotton should be: Springer press, 382 pp, 2009 and not the WMO report.

We have changed the reference.

5) Page 29013 – second paragraph – although sulphate formation has been shown to be small, it is important to note that particles coated with sulphate have been measured. It is certainly conceivable that some ice nuclei could be coated thus modifying ice nucleation. Furthermore, some particles that are insoluble and are inefficient CCN could become effective as GCCN. These points should at least be discussed.

We agree that the coated dust could become effective as GCCN. However, the coating of dust with sulphuric acid has other effects.

For example, Sullivan et al. (2010) found the irreversible loss of ice nucleation active sites in mineral dust particles caused by sulphuric acid condensation. Furthermore, GCCN can enhance the warm rain processes. We have stated in the manuscript that “Teller and Levin (2005) found that the increased rainfall due to GCCN is mainly a result of the increased graupel mass in the cloud, which partially offsets the decrease in rainfall due to pollution (increased CCN). To avoid the entangled offset effect caused by increasing CCN and GCCN, we restrict the meaning of increasing aerosol to increasing aerosol in the lower troposphere without increasing GCCN.”

To make it clearer, we added “Although the sulphate formation has been shown to be small, the coating of mineral dust with sulphuric acid could change the properties of ice nuclei and the coated dust particles could be served as GCCN. However, the effect of coatings on heterogeneous ice nucleation needs further study (e.g., Sullivan et al. (2010).”.

6) Section 4.1 – why is the range of CCN in the maritime clouds larger than in the continental ones?

We stated in the sentence “The range of cloud base CDNC of 50-1900 ~cm^{-3} for marine tropical clouds and 50-1850 ~cm^{-3} for continental clouds *MORE THAN* covers typically observed concentrations.” The CCN in the maritime and continental clouds were designed to have similar ranges: low end is about 50 for both and the high end is roughly same (1900 vs. 1850) so that the results can be compared in a similar parameter space in terms of aerosol loading.

7) Although ice multiplication and condensation-freezing is included in the model, why is there no discussion of the contribution of these processes to the ice formation and the precipitation development? This could certainly be important in maritime clouds.

In Cui et al. (2006), we discussed the dominant freezing mode and found immersion freezing is the most important one. For the maritime clouds in our study, the temperature zone for the Hallet-Mossop process is around 5 km. Within the temperature zone, the lack of coexistence of both small and large droplets means the secondary ice production is very weak. To clarify, we added “The dominant ice production in our study is immersion freezing although other processes may be important in other cases”.

8) Page 29018 – The contribution of graupel particles in the development of precipitation is an important point that has been discussed in other publications (e.g. Teller and Levin, ACP, 2006; Yin et al, Atmos. Res., 2000) and should be referred to here.

We added “The contribution of graupel particles in the development of precipitation has been discussed before (e.g. Teller and Levin, 2006; Yin et al, 2000).” after the sentence “The precipitation, mainly from the melting graupel particles (see discussion of Fig. 7 for detail), therefore, delays.”

Minor point:

Caption of Table 3: Should be maxima

We have made the change.

References

Murry, F. W., 1970: Numerical models of a tropical cumulus cloud with bilateral and axial symmetry. *Mon. Wea. Rev.*, **98**, 14-28.

Ogura, Y., 1963: The evolution of a moist convective element in a shallow, conditionally unstable atmosphere: A numerical calculation. *J. Atmos. Sci.,* **20,** 407-424.

Soong, S-T, and Y. Ogura, 1973: A comparison between axi-symmetric and slab-symmetric cumulus cloud models, *J. Atmos. Sci.,* **30,** 879-893.

Sullivan, R. C., Petters, M. D., DeMott, P. J., Kreidenweis, S. M., Wex, H., Niedermeier, D., Hartmann, S., Clauss, T., Stratmann, F., Reitz, P., Schneider, J., and Sierau, B.: Irreversible loss of ice nucleation active sites in mineral dust particles caused by sulphuric acid condensation, Atmos. Chem. Phys., 10, 11471-11487, doi:10.5194/acp-10-11471-2010, 2010.

Teller, A. and Levin, Z.: The effects of aerosols on precipitation and dimensions of subtropical clouds: a sensitivity study using a numerical cloud model, Atmos. Chem. Phys., 6, 67–80, doi:10.5194/acp-6-67-2006, 2006.

Wilhelmson, R., and Y. Ogura, 1972: The pressure perturbation and the numerical modeling of a cloud. *J. Atmos. Sci.,* **29,** 1295-1307.

Yin, Y., Levin, Z., Reisin, T., and Tzivion, S.: The effects of giant cloud condensational nuclei on the development of precipitation in convective clouds: a numerical study, Atmos. Res., 53, 91–116, 2000.