Interactive comment on* "How do changes in warm-phase microphysics affect deep convective clouds?"** ***by **Qian Chen et al.**

Anonymous Referee #2

We thank the reviewer for his thoughtful comments that helped us improve the paper. Please find below a point by point reply to all comments (replies in blue):

This manuscript focuses on how changes to the warm-phase component of a convective cloud is modified by changes to aerosol amount. They simulate a convective cloud system from a field project over the Marshall Islands using WRF. The most interesting aspect of this work is the use of the what they call the VCOG or the combination of the surrounding air velocity and the effective terminal velocity of hydrometeors. This work is well written, easy to read and to follow, the results follow clearly from their analysis and the figures are well chosen and presented.

My recommendation to accept his work with minor revisions

Answer: We are glad that the reviewer found our manuscript interesting and well presented.

Main comments: 1) It would also be beneficial to see a discussion about the applicability of this case to other convective systems. How generalizable are these results?

Answer: Thank you for this comment. Indeed it is very important to discuss the generality of our results. More and more studies (both observational and numerical ones) are accumulating showing clear evidences for invigoration of deep convective clouds. For example numerical studies (using both bin and bulk schemes) of single tropical cloud up to mesoscale convective system like squall line (Sarangi et al, 2015; Storer et al. 2013; Cui et al., 2011; Fan et al., 2013; Khain et al., 2008; Li et al., 2013; Tao et al., 2007; Tao and Li, 2016) and observational studies (Sarangi et al, 2017; Jiang et al, 2016; Storer et al., 2014; Yan et al, 2014; Heiblum et al., 2012; Koren et al., 2005, 2010; Andreae et al., 2004).

We are aware however, that there were numerical studies that showed no clear evidence or even an opposite aerosol effect. They all used bulk microphysical schemes (Lee and Feingold, 2010; Morrison and Grabowski, 2011; Morrison and Grabowski, 2013). We think that due to some inherent properties of the common bulk schemes, such model experiment are significantly less sensitive to aerosol effect. To name some of the main limitations: recent studies of bulk vs. bin schemes comparison show how in-essence saturation-adjustment (Tao et al., 1989) mimics polluted runs even for low aerosol concentration. It is caused by neglecting the time it takes to consume the supersaturation and therefore the bulk schemes dictate excellent condensation efficiency for all runs with limited sensitivity to aerosol concentration (Lebo and Seinfeld 2011; Lebo et al. 2012; Khain et al., 2015; Heiblum et al, 2016). Other comparison studies indicated of bulk schemes limitation of the prescribed hydrometeors size distribution and autoconversion parameterization (Ovchinnikov et al., 2014). Khain et al., (2009, 2015) showed that schemes that prescribe the drop concentration cannot capture correctly the sensitivity of cloud and rain processes to changes in aerosols amount.

To present these points and to make it clearer we have revised Section 3.2 as follows:

"Our results agree with previous numerical studies that reported an aerosol invigoration effect of tropical deep convective clouds (Cui et al., 2011; Fan et al., 2013; Khain et al., 2008; Li et al., 2013; Tao and Li, 2016; Tao et al., 2007). However other numerical studies showed no clear evidence for this effect or even an opposite effect (Lee and Feingold, 2010; Morrison and Grabowski, 2011, 2013). The reasons behind those differences were examined in previous studies that showed the lower sensitivity of cloud and rain processes in bulk schemes to aerosol concentration (Khain et al., 2009, 2015; Lebo and Seinfeld, 2011; Lebo et al., 2012; Heiblum et al., 2016)."

2) The discussion of Figure 2 states that they model CFAD captures the vertical structure and magnitude of the observed CFAD reasonably well. I agree that the highest probabilities (dark red) do look similar between the observations and the model. However, what is the source of the strange peak in the modeled CFAD between 5-7 km that is not present in the observations?

Answer: The model overestimates the reflectivity values above 4.8 km (the environmental ZTL) and there is a sharp decrease in reflectivity below it. This can be attributed to overestimation of big ice particles above 5 km (mostly graupels, but snow particles as well). It is a result of the relatively simple melting scheme used by the model that allows immediate melting of ice particles when falling across the ZTL. So large graupel and ice particles (as indicated by their large effective terminal velocity presented in Figures 6j,k) melt while crossing the ZTL and breakup immediately into smaller drops. Part of these drops is pushed upward by the updraft and contributes to the additional growth by riming of the graupels. And indeed 70% of the mass located above 5 km in voxels with reflectivity values higher than 35 dBZ are graupel particles. So there is an overestimation of big graupel (and snow) particles above 5 km. Below the ZTL there is a sharp decrease in reflectivity because the drops are smaller (compared to the large graupel particles above the ZTL) and they fall faster so their concentration in the volume is reduced (hence form a reduced reflectivity). Thank to this remark we added the text (sections 3.1 and 3.3) parts that highlights the limitation of the melting scheme and explain the feedbacks caused by it.

The additions to section 3.1: *"There is an overestimation of the modeled reflectivity above the ZTL (4.8 km) compared to the observed one. It can be explained by an overestimation of large ice hydrometeors (mostly graupel, but snow particles as well) above the ZTL. This is due to feedbacks caused by the simple melting scheme used by the model (see section 3.3)."*

The changes in section 3.3: *"Note that the simple melting scheme used by the model allowed immediate melting of ice particles while crossing the ZTL. The resulted drops formed by the melting of big graupel (and snow) particles broke up immediately into smaller drops and part of them was carried up again by the updraft and froze by riming. So there may be an overestimation of big grauple particles above the ZTL (as shown in Figure 2b)."*

3) For Figure 8, what is the source of the smooth nature of the clean curve in 8a and c vs. the more variable semipolluted and polluted curves?

Answer: Thank you for this great observation. Following this comment, we revised section 3.4 to point out and explain this variance:

"This impacted the variance of the mass-flux, which was larger in the more polluted

cases (Figure 9c). The increased variance is driven by the enhancement of the fields' dynamics by aerosol, as shown throughout this study. Polluted clouds exhibited larger updrafts with larger variance (as shown in Figure 8), larger updraft area (Figure 9d) and larger mass fluxes, all of which tend to increase the variance in the upward mass-flux".

Line by line comments: Line 164: "Aerosol effects on clouds' macroscale" is strange wording. Perhaps "Aerosol effects on macroscale cloud properties" would be a better section header.

Answer: Thank you. We changed it to "*Aerosol effects on clouds' macrophysical properties*".

Line 166-167: "vertical profiles of a cloud fraction" - I don't think you need the "a"

Answer: Thank you. Corrected.

Line 167-168: What is a "Voxel"? I have never heard this term before.

Line 184: Voxel again... once it's introduced earlier this would be fine.

Answer: It is the abbreviation of volume pixel, which is the smallest unit of three-dimensional grid-space. Here it means a grid volume. Explanation has been added in the text: "Figure 3a,c,e shows the evolution of the vertical profiles of a cloud fraction for the three runs (calculated as the ratio between the number of cloudy *volume pixels (voxels)*, i.e., total condensate exceeding 0.01 g kg^{-1}, at each vertical level and the total horizontal number of voxels)."

Line 296: VCOG - "COG" should be subscripted

Line 298: VCOG - "COG" should be subscripted

Line 299: VCOG - "COG" should be subscripted

Line 300: VCOG - "COG" should be subscripted

Answer: Thank you. Corrected.

Figure comments: General: Most of the figures appear to have bolded text for the axes and color bars, for some (specifically the color bar on Figure 3 b,d,f) is blurry due to this. The text in figure 7 is also very blurry.

Answer: Thank you. Revised.

Figure 4b) The insert is hard to see, perhaps switch the location of the legend and the zoomed in insert so that the insert can be made larger.

Answer: Thank you. Revised.

Figure 5a,b,c) including the ZTL as a dashed line on these figures would be helpful.

Answer: Thank you. The ZTL lines have been added into figures 5,6 and 7.

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