Interactive comment on “Investigating the Impacts of Saharan Dust on Tropical Deep Convection Using Spectral Bin Microphysics, Part 1: Ice Formation and Cloud Properties” by Matthew Gibbons et al.

Anonymous Referee #1

General Comments: This paper investigates the impact of dust acting as IN on tropical convection – specifically its impacts on ice nucleation and particle size distributions -using numerical simulations. The impacts of dust on tropical convection are still not well understood and studies such as this one are needed. Some aspects of the analysis and discussion need clarification, particularly regarding Figure 7 and some of the physical reasoning for the differences seen in the simulations. These are detailed below.

We thank the reviewer for very thorough and constructive comments. The quality of the manuscript has been improved by these comments and suggestions. Below are our responses (in *Bold)* to the comments. Page and line numbers refer to the original manuscript currently under discussion.

Specific Comments: 1. Page 2, Line 10: It is confusing to state the increased condensation results from greater droplet nucleation since those are two separate processes. More accurately, the higher droplet concentrations induce the greater condensation and heat release.

We have clarified the statement on P2, L10 to read: “The higher droplet concentrations induce the greater condensation and latent heat release, resulting in stronger convective updrafts leading to the formation of taller and wider clouds”

2. Page 5, Lines 12-17: Hasn’t the additional IN prognostic variable been available in the SBM for a number of years now?

We have clarified the statement on P5,L12-17 to acknowledge that the prognostic IN variable has been added in connection with newly implemented set of heterogeneous ice formation mechanisms: “In order to examine IN impacts on clouds and precipitation, an additional prognostic variable for IN particle (dust in this case) number concentration was added to connect our newly implemented heterogeneous ice formation mechanisms with the presence of dust particles in the atmosphere”

3. Page 6, Line 10: Why is the simplest homogeneous nucleation option being used? Presumably the other options represent homogeneous nucleation more accurately.

We have replaced the original statement: “The current results use the H_{thr} threshold based scheme to provide pure drop freezing.” with
“The current results use the H_{thr} threshold based scheme to provide pure drop freezing, which is similar to a number of global climate models. In future studies, we intend to conduct more extensive sensitivity tests related to the different homogeneous freezing mechanisms in conjunction with different partitioning of IN and CCN in the dust layer.”

The Heymsfield and Milosevich (1993) scheme was intended for use in future related studies, but has not yet been extensively tested within the current model setup. Since this scheme not being used in the current simulation, we have removed the references to the Heymsfield and Milosevich (1993) scheme from Section 2.2.1 (P6,L2-11).

In addition, there is an omission in the paragraph relating to the Liu and Penner (2005) aerosol freezing mechanism. The text does not explicitly state that the scheme is not active in the current simulation due to the study focusing on DCC rather than cirrus cloud formation. Since the scheme does not contribute to the results, we have removed the description of this scheme (P6,L13-17)

4. Page 8, Line 20: If the authors feel that our ability to represent ice nucleation in models is limited and poor, how do we know that the results of this study are meaningful and applicable to the real world?

We have added an additional clarifying statement to the end of the paragraph on P8, L20+: "Comparison between simulation results and prior observations of our case study will be used to evaluate the model parameterizations implemented into the model for this study."

5. Page 10, Lines 20-25: I found this part to be confusing. Are the authors simply trying to state that differences in simulated cloud properties are entirely due to dust impacts? I think it is a given that the environment and sea surface are initially the same and therefore do no contribute to differences in the clouds.

To clarify this, we have replaced the statement: "However, the convective cores presented in Fig. 2 are nearly identically located geospatially, occur at the same model time, and possess nearly identical SST values below the cores, limiting the dynamical effects on the clouds in this instance." with:

"However, as all cases are driven by the same initial and boundary conditions, changes to cloud properties noted in Fig. 3 are predominantly affected by changes to microphysical processes, rather than being exclusively a result of differing large scale dynamical conditions."

The statements (P10, L20-25) were intended to emphasize that changes to cloud properties were predominantly a result of microphysical processes rather than being exclusively a result of differing large scale dynamical conditions. However, as SST values are fixed in the simulations, this section is not useful for our discussion. Therefore we have removed these lines (P10, L20-25)

6. Page 11, Line 9: Max updraft speed or mean updraft speed?

It is the averaged maximum updraft velocity over two periods: a) Hour 10-20, a relatively strong convection period; and 2) Hour 20+, a relatively weak convection period).

7. Page 11, Lines 14-to end of page: The logic here is circular. First the authors state that the weaker updrafts limit ice nucleation (also, why is this the case?), but aren't the changes in nucleation ultimately the reason for the weaker updrafts?

Large-scale or environmental dynamics impacts the cloud formation and structure and dust loading also impacts those microphysically through CCN activation and heterogeneous nucleation. We wanted to illustrate both dust IN microphysical effect and environmental dynamical impact based on two different large-scale dynamical strength periods and different dust IN loadings. In the revised paper, we clarified this as

"In general, the simulation can be separated into periods of strong (hour 10-20) and weaker (hour 21+) convective activity due to the differing large scale dynamical conditions during these times.

After hour 21, the dust cases feature reduced IN activation and domain averaged updraft intensities no longer exceed the Clean case average when compared to the earlier hour 10-20 time range.”

…

“The generally weaker environmental dynamical activity during this period limit heterogeneous ice formation which in turn reduces the contribution of latent heating to parcel buoyancy. To illustrate how the dust effects are limited by both IN availability and by environmental dynamics, we note the similar heterogeneous ice number and updraft changes in the D1.2 (strong convection period) and D12 (weak convection period) cases. During these two time periods, the dust effects are limited either by IN availability (D1.2) or by number of IN activated (D12) yielding similar increases to heterogeneous ice formation and updraft intensity compared to the Clean case.”

…

8. Page 12, Line 12: What is meant by “three per unit magnitude increase”**?**

We have changed the P12, L12 “three per unit magnitude increase” to: “Graupel formation is enhanced compared to the Clean case, with graupel number in the Dust cases increasing by approximately a factor of three per order of magnitude increase of IN concentration from the D.12 case’s concentration.”

9. Page 13, Line 13: What is meant be “increases up to 30%, proportionally to IN number”?

We have changed statement from: “increases up to 30%, proportionally to IN number” to “ . . . increases in the dust cases between 5-30% higher than the Clean case, proportionally with increasing IN number . . . ”

10. Page 13, Line 25-26: Does this ratio appear in your simulations?

We have included the following statement after the sentence ending on P12, L28 to clarify our model agreement: “Our own simulations possess a similar convective/stratiform ratio (~1:6.5) to the ratio reported by Liu and Fu (2001) when averaged over the simulation time to remove the variation resulting from different stages of convective development.”

11. Page 14 and Figure 7: I don’t understand what is shown in Figure 7. The authors state it is the difference in location before and after gravitational sedimentation. Are both of these fields output by the model? The titles on the figures say “number flux” but the units are 1/L which is not a flux. Lastly, the text suggests that the authors examine this quantity in order to understand how particles are transported, but are the particles not also transported by the winds? And thus this figure does not really tell us where the regions of formation are?

Due to the ambiguities related to this figure with respect to the relative contributions of changes to particle terminal velocities and vertical motion in the dust cases, we have replaced Figure 7 with a new figure of calculated fall rates averaged over the convective or stratiform regimes and their corresponding dust case minus clean case differences. This figure is now Figure 8 in the overall order due to the original Figure 9 (and accompanying text) having been moved earlier in the analysis to be Figure 2.

In addition, the original passage related to Figure 7 (P14, L19 to P15, L2) has been replaced by the following passages, with summary of key points at the beginning of each paragraph:

>>Section addresses that cloud geometry is affected by both dynamical and microphysical processes. Describes Figure 8 and specifies how particle fall speed was determined for the figure.

"Differing cloud geometry in the dust cases is a result of changes to the feedbacks between microphysical and dynamical processes within the cloud during formation and growth. Large scale environmental dynamics will provide the baseline values of a cloud's top height, anvil extent, and lifetime (Futyan and Del Genio, 2007), but aerosol indirect effects will modulate these values up or down depending on the changes to the clouds' microphysical processes (Fan et al. 2007a; Koren et al., 2010b; Li Z et al., 2011; Niu and Li, 2012; Fan et al., 2013; Saleeby et al., 2016), especially with respect to changes in hydrometeor PSDs which in turn affect particle terminal velocities (Fan et al., 2013). As previously noted in Figure 4, cloud top height is lowered in our dust simulations despite the presence of increased updraft velocities over the majority of the simulation's time range. In order to further explore this apparent contradiction, Figure 8 provides the convective (row 1 & 2) and stratiform (row 3 & 4) averaged particle fall rates (cm s^{-1}) for cloud ice (column 1), snow (column 2), and graupel (column 3) particles, averaged over the total simulation time. Dust case minus Clean case differences for convective and stratiform data are presented in row 2 and row 4, respectively. Particle fall rate is determined by combining calculated particle terminal velocities (positive downwards, Khain and Sednev, 1995) with vertical velocity (positive upwards). In Fig. 8 (row 1 and 3), positive numbers indicate motion towards the surface, while negative numbers indicate the opposite."

>>Addresses changes to cloud ice fall speed and terminal velocity for the different cases at different altitude ranges. Cloud ice is generally heavier (greater terminal velocity) in the dust cases but is more strongly affected by vertical motion.

"Due to their small sizes, cloud ice fall rate is most affected by changes in vertical motion. The negative values of cloud ice fall rate in the convective average (Fig. 8 row 1a) at altitudes between 3 and 13 km indicate that transport of these small particles is predominantly upwards within the convective updrafts. The associated difference plot (Fig. 8 row 2a) indicate that fall rates between 3 and 9 km are increased for the primary dust cases (D.12; D1.2a; D12), and occur in conjunction with the greater updraft speeds at these altitudes. Cloud ice terminal velocities increase by approximately 0.4 (D.12), 1.7 (D1.2a) and 2.6 (D12) cm s^{-1} between 3-9 km, which signify that the ice particles are becoming heavier due to increased diffusional growth. Above 9 km the fall rates are increased in the D1.2a and D12 cases due to stronger downdraft intensities, as cloud ice terminal velocities are actually reduced by as much as ~1 cm s^{-1} in the dust cases. In the D.12 case cloud ice fall rate and terminal velocities are reduced above 9km when compared with the clean case, while homogeneous freezing is reduced (Table 3). It is reduced by less than one percent in the D.12 case, indicating that many drops are still being transported to temperatures below -38°C and being frozen. While small drop sizes are not necessarily more common in the D.12 case (Fig. 6f), they are also not as significantly reduced as in the D1.2a (Fig. 6g) and D12 (Fig. 6h) cases, leading to a greater number of small ice forming homogeneously near the cloud top and reducing the average cloud ice fall rate. A similar reduction in cloud ice fall rate above 9km is seen in D1.2c. The added CCN in the D1.2c case increases the midlevel liquid content and results in a slightly higher homogeneous freezing number than the base D1.2a case (Table 3). Terminal velocity of the resulting homogeneous cloud ice particles is also slightly reduced compared to the D1.2a case due to the generally smaller sizes of the frozen liquid drops. At altitudes between 3 and 9 km, terminal velocities are nearly identical in both D1.2a and D1.2c cases, with the D1.2c being slightly higher due to increased particle growth. The noticeable difference in fall rate between 6 and 9 km for the D1.2a and D1.2c cases is a result of stronger updrafts in the D1.2c case due to the greater latent heat release from the higher condensate mass. When deposition freezing is removed from the simulation (D1.2b), midlevel ice formation is provided by the immersion freezing mechanism. As

this mechanism freezes liquid drops from the largest sizes to the smallest sizes, the larger drops freeze into graupel rather than cloud ice. Terminal velocities of cloud ice in the D1.2b case is reduced 1-3 cm s^{-1} between 3 and 9 km, which indicates that the large change in fall rate is due to changes in the latent heat profiles affecting vertical motion."

>>Specifies changes to fall rates for snow and graupel. Snow and graupel fall rates are generally reduced between 5 and 10 km and increased above 10km for the primary dust cases. This helps to explain the lowered cloud tops and greater midlevel cloudiness.

"Changes in fall rates of precipitation sizes particles such as snow and graupel will strongly affect eventual surface precipitation accumulation due to changes in downdraft and below-cloud particle residence times and subsequent evaporation. Snow particles tend to grow larger by aggregation processes at warmer temperatures due to greater "stickiness" (Hallgren and Hosler, 1960), which results in fall rates generally increasing towards the surface (Fig. 8 row1b and row 3b). The greater midlevel ice formation in the dust cases results in increased aggregation rates in the 0°C to -38°C temperature range. Larger sizes settle out more quickly and tend to accumulate around the melting level as can be seen between 2 and 5 km. Terminal velocities are increased +15 (D.12) to +60 (D12) cm s^{-1} over this range and are partially countered by stronger updrafts as can be seen in the fall rate differences (Fig. 8 row 2b). At altitudes between 5 and 10 km, snow terminal velocities are decreased between -5 (D.12) and -15 (D12) cm s^{-1} due to more numerous but smaller aggregates, while the resulting fall rates vary between +2 (D.12) to -2 (D12) cm s^{-1} due to the stronger vertical motion in these cases. Above 10 km, terminal velocity and fall rates are increased for the primary dust cases, although D.12 is reduced. In the D.12 case. the most significant ice formation and subsequent aggregation occurs primarily at homogeneous temperatures, yielding smaller aggregates near the cloud top. In the stratiform regime, where vertical motion is weaker, changes in terminal velocity are similar to the convective regime, but are higher overall. This is a result of more active aggregation in the stratiform regime due to the relative lack of liquid water content (for riming) compared to the convective core. When liquid content is significant, graupel forms either by direct freezing of large drops or by riming of existing ice and snow particles. In the primary dust cases (D.12, D1.2a, and D12), stronger updrafts and smaller graupel particles result from the greater midlevel ice concentrations. The graupel fall rates are progressively reduced between 3 and 10 km in both the convective and stratiform regimes as IN concentration is increased. In the D1.2b case, where immersion freezing results in significant formation of graupel from large frozen drops, graupel fall rates are significantly increased. This results in a final accumulated surface precipitation value in the D1.2b case which is 3.7% higher than the Clean case. In contrast, the final values of surface precipitation accumulation are reduced in the primary dust cases (D.12; D1.2a; D12), with the greatest reduction being -6.02% in the D12 case."

12. The authors distinguish between heterogeneous and homogeneous ice throughout the paper. This is based just on the air temperature? But it is possible for heterogeneously nucleated ice to be transported higher in the atmosphere where homogeneous nucleation is dominant, yes? And likewise homogeneously nucleated ice can fall to lower levels. It seems to me that the two types of nucleated ice can't be easily distinguished and that the labels are perhaps misleading.

Yes, heterogeneous and homogeneous regimes are based on the air temperature, and ice particles formed from two different regimes/temperature ranges are transported by the wind. The variables for ice nucleation rates (Fig. 2; Table 3) are not transported by the wind field or gravitational settling, which allows us to determine the location and number of initial ice formation and any relative changes due to dust effects.

To account for the fact that ice may be transported after formation, the statement of P12, L8-10 has been changed from: "A comparison between the ice number concentration, vertical motion, and CTH for the two convective periods is provided in Table 3. Changes in liquid drop and graupel number have also been provided in Table 3 for the heterogeneous temperature range. " to

"A comparison between the dust case minus Clean case hydrometeor number concentration, vertical motion, and CTH for the two convective periods is provided in Table 4. Hydrometeor number concentrations are averaged over the specified temperature ranges. We note that these averages do not directly account for particle transport between different temperature ranges, but rather indicate more generally how the vertical profile of the different hydrometeors are being affected by the different IN concentrations."

We have retitled "homogeneous ice number" to "T <-38ºC ice number" and "heterogeneous . . . number" to -38ºC < T < 0ºC . . . number" in Table 4 to clarify that these are temperature based averages.

13. In Figures 5 and 6, I understand why showing values on a log scale is useful, but I don't understand why the authors add 10 – this just makes the values more difficult to interpret. Also, it is worth pointing out that in the difference of two log10 values is the log10 value of the ratio, i.e. log(x)-log(y)=log(x/y), in order to give more physical meaning to these plots.

We have removed the scaling factor in Fig. 5 and Fig. 6 to allow the contours to directly represent the $\log_{10}$ values and have clarified that the differences represent the $\log_{10}$ values of the Dust/Clean ratio.

14. The changes in relative importance of nucleation mechanisms is interesting. I would suggest moving this discussion to earlier in the results section. Changes in nucleation is the first step in the chain of events that lead to the changes in cloud properties, so it seems natural to include this discussion first rather than last in the results section.

Thank you for your suggestion. We have moved the relevant sections related to initial ice nucleation from section 4.4 to section 4.1 and renumbered the Figures and Tables in the text with the new order.

15. There have been several studies examining the impacts of dust on tropical convection, particularly in hurricanes, yet in general only those studies by Min et al. are cited. Better citation of other relevant literature is needed.

We have expanded our references to account for other relevant studies, including:
MCS/TC studies: Dunion and Velden (2004), Evan et al (2006), Lau et al (2009), Zhang et al (2009), Braun (2010), Carrio and Cotton (2011), Cotton et al (2012), Storer and Van Den Heever (2013) and Storer et al (2014)

Cold pool effects: Altaratz et al. 2007, Berg et al. 2008, Storer et al 2010, Lim et al. 2011, May et al. 2011, Morrison 2012, Grant and Van den Heever, 2015

Observations of convective invigoration: Koren et al (2005, 2009); Wall et al (2014)

16. The lower cloud top heights despite stronger updrafts is a bit confusing, though the authors do give some reasons. I’m wondering if the cloud tops are lower only in the stratiform regions, whereas the strongest updrafts are of course in the convective cores? Perhaps the cloud tops in the convective cores are more similar?

We have clarified P10, L20: “... stratiform height is lowered” to “Stratiform height is also lowered, despite a similar convective core height. This is consistent with the findings of Min and Li (2010) which described higher convective core heights, shown in their Figure 2, but a lowering of the cloud top heights overall.”

We have also changed P10,L27“... lowered cloud top height ...” to “lowered overall cloud top height . . . ”