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Atmos. Chem. Phys. Discuss., referee comment RC1
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Comment on acp-2022-152

Anonymous Referee #1

We thank the reviewer for their comments. The comments have been constructive, informative and will improve the next version of the submission. Please see responses marked in blue text below.

Referee comment on "Sensitivity analysis of an aerosol aware microphysics scheme in WRF during case studies of fog in Namibia" by Michael Weston et al., Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2022-152-RC1, 2022

The manuscript *"Sensitivity analysis of an aerosol aware microphysics scheme in WRF during case studies of fog in Namibia"* investigates how droplet activation of cloud condensation nuclei (CCN) affects simulated evolution of fogs. The analysis is done for two observed fog cases which are simulated using different assumptions for initial CCN concentrations affect the evolution of fog properties. The paper presents a thorough investigation of the topic and is within the scope of Atmospheric Chemistry and Physics. The main issue with the paper is that it is not clear to me, what is the scientific value of the study and in order to be published, this should be clarified.

Thank you for this comment as the response should help place this study in better context for the reader. Our response is included below and we will integrate this into the introduction in the next submission.

Motivation for the study

Microphysics schemes in mesoscale models are designed with cloud formation in mind, and not necessarily fog formation. Droplet activation is based on a parcel that is lifted and cooled adiabatically to reach saturation, and is therefore most sensitive to the updraft speed. However, fog often occurs under stable conditions where updrafts are low in speed or even negative. Thus, droplet activation is dependent on other processes like non-adiabatic cooling. This point is highlighted by Boutle *et al* (2018) who observe a cooling rate prior to fog formation of 1Khr^{-1} which is equivalent to an updraft speed of 0.04 ms^{-1} assuming a wet adiabatic lapse rate of 6.5Kkm^{-1}. In their case, the minimum updraft speed in the microphysics scheme was 0.1ms^{-1}, and thus would over estimate fog drop activation. To address this issue, Poku et al. (2021) expanded an existing microphysics scheme to allow for non-adiabatic cooling, which allowed for more realistic cloud droplet number concentration in the simulation.

Scientific value

In this paper, we assess an aerosol aware microphysics scheme that uses a minimum updraft speed of 0.01 ms^{-1}, which equates to a cooling rate of 0.23 Khr^{-1}. This minimum updraft speed should solve some of the over activation issues highlighted by Boutle *et al* (2018) and Poku *et al* (2021). The main aim is to see how this scheme performs, before applying major changes in the code to account for non-adiabatic cooling rates or similar. Furthermore, our study site is located in the tropics which we see this as a benefit to the community at large as most fog modelling studies are focused on mid- to high-latitude sites.

In addition, the following points should be addressed:

Major comments:

1. In many cases, the model setups and their effects on results are explained too ambiguously to be understandable for the reader. I was not able to understand properly the description of the setup for initial CCN concentrations. Section 3.3.2 discusses the vertical profiles of CCN and refers to the WRF user guide for an explanation. However, it is still unclear to me how this initial vertical distribution results in such a large difference in CCN over land and over ocean for Case CCN_300. Is the initial column intergral of CCN concentrations (CCN burden) significantly different depending on the terrain? Is the CCN concentration initialized in the beginning of the spin up or at the beginning of the actual simulation?

CCN scenarios

We agree that the description of the CCN vertical profile should be included in the methodology before being discussed in the results. We will introduce these concepts in the methodology in the next submission. We will also expand the description of the various scenarios and the motivation for them.

With regards to the vertical profiles, Fonseca *et al* 2021 (doi: 10.3390/atmos12121687) have documented the equations from the microphysics fortran routine.

$$N(z) = N_1 + N_0\, EXP\left[-\left(\frac{h(z)-h(1)}{1000}\right) N_3\right] \quad (1)$$

with

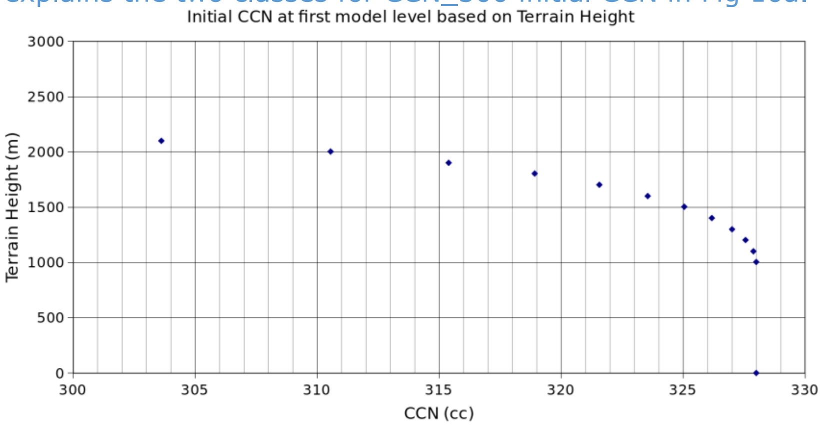
$$N_3 = -\frac{1}{0.8} LOG\left(\frac{N_1}{N_0}\right)\ if\ h(1)\ \leq 1000\ \mathrm{m} \quad (2)$$

$$N_3 = -\frac{1}{0.01} LOG\left(\frac{N_1}{N_0}\right)\ if\ h(1)\ \geq 2500\ \mathrm{m} \quad (3)$$

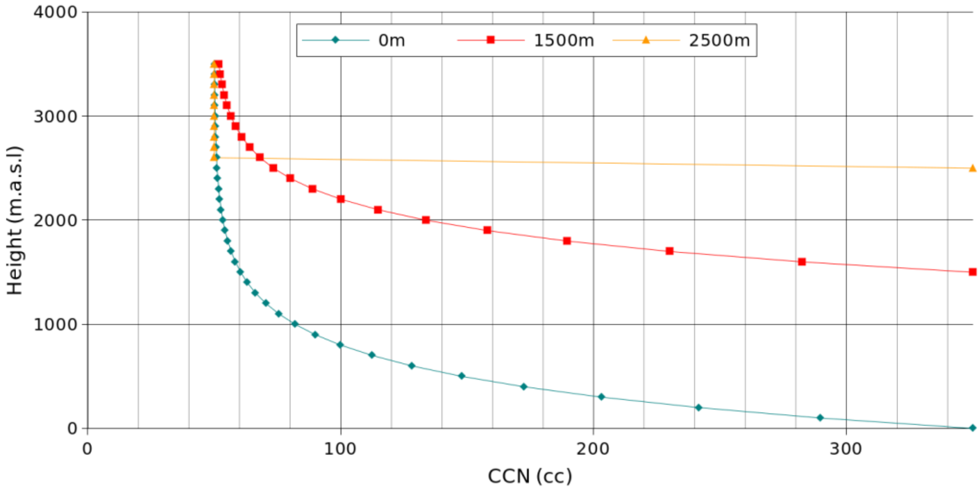
$$N_3 = -\frac{1}{0.8\, COS\,[h(1) \times 0.001 - 1]} LOG\left(\frac{N_1}{N_0}\right)\ if\ 1000\ \mathrm{m} < h(1) < 2500\ \mathrm{m} \quad (4)$$

Fonseca *et al* (2021). *"In the equations above, h(z) is the height of the model level z in meters, with h(1) being the height of the first model level. The constants N1 and N0 are set to 50 × 106 m3 and 300 × 106 m3 for water-friendly aerosols, and 0.5 × 106 m3 and 1.5 × 106 m3 for ice-friendly aerosols, respectively. This definition is based on the premise that aerosols are mostly concentrated in the lowest part of the atmosphere, with a faster decrease with height over the higher terrain, and a profile tailored for the continental United States."*

If we consider different terrain heights (z) and a first model level at z+34 we get the following initial CCN using these equations. Terrain heights of 0 and 1000 m have the same initial CCN, but after 1000 m it decreases. As Namibia has a coastal plain before the escarpment extends beyond 1000 m, the sea and coastal plain has the same initial CCN near the surface, while he terrain above 1000 m has a lower initial CCN concentration. This explains the two classes for CCN_300 initial CCN in Fig 10a.



If we plot these equations for different terrain heights (z) we get the following curves (Thompson and Eidhammer 2014 also show this curve but for much higher initial CCN concentration). Height intervals (dots) are 100 m. The decrease in CCN concentration between level z and z+1 is larger if the starting terrain height is 1500 m than 0 m. Thus, as vertical mixing takes place over time, we expect the surface concentration over a higher terrain point to decrease more than a lower terrain point. This partly explains why the CCN over land in Fig 10b can decrease more than the CCN over the ocean when compared to the initial CCN.



We hope this explanation is helpful.

2. Page 15, Line 310 says that *"The initial CCN concentration for scenario CCN_300_landsea shows a clear contrast, with lower concentration over the ocean than the land (Fig. 10c). The lower concentration over the ocean counteracts the accumulation of CCN over time, as seen in CCN_300, resulting in a more balanced mean CCN concentration between land and ocean (Fig. 10d)."* Is the accumulation of CCN in CCN_300 only because there are more CCN than in CCN_landsea? In what way there is a more balanced mean CCN concentration between land and ocean? The land-sea contrast at the south boundary seems quite high also in CCN_300_landsea.

We assume that accumulation is occurring in both CCN_300 and CCN_300_landsea as the only difference is the initial CCN over the sea. We will try rephrase line 310 to indicate this.

However, the accumulated CCN over the ocean in CCN_300_landsea should be about a third of CCN_300. In CCN_300, the mean CCN over the ocean (Fig 10b) is higher than over the land, which we expect is not realistic as ocean air usually has lower CCN concentrations than continental air. While in CCN_300_landsea, the mean CCN concentration over the ocean are lower or similar to the coastal area of Namibia, which we think is more realistic. The boundary conditions were the same for CCN_300 and CCN_300_landsea, which may explain the similar contrast at the southern boundary.

3. The droplet activation parameterization is shown in Figure 2 to be sensitive to CCN concentration and updraft velocity. However, fog formation is also affected by nonadiabatic cooling. Poku et al., (2021) have suggested that instead of using simulated updrafts, it would be better to calculate the change in saturation due to non-adiabatic processes. In the current paper, only the effect of changing the minimum updraft speed was tested. Wouldn't it have been fairly straight forward to for example convert the cooling rates to corresponding updraft speeds to have a more physical representation of fog droplet activation? On Page 21, Line 392 it is said *"Their proposed work around is to include cooling tendency as proxy for updraft speed and then assigning a speed that will activate the appropriate number of droplets. This may come with a new set of problems in terms of early activation but this remains to be seen."* To me this seems a very good approach and if there is a new set of problems, would that point to problems in other physical processes of the model and in itself is not a good justification for not using this approach?

Yes, we agree that the approach of Poku et al 2021 is sound and a good approach moving forward. For our case, we needed to work backwards, and see which updraft would achieve a suitable activation given realistic CCN concentrations. From this we can work backwards to calculate the equivalent cooling rate required to reach this activation.

Both reviewers have made this point that the non-adiabatic cooling rate may be responsible for the cloud droplet activation and we should present the equivalent cooling rate for our applied minimum updraft speed. We thank the reviewers for highlighting this point. Our response is below and will be incorporated into the next version of the submission.

An updraft speed of 0.1 ms^{-1} equates to a cooling rate of 3.51 Khr^{-1} (2.34 Khr^{-1}) at the dry (wet) adiabatic lapse rate. Our observed cooling rate at 2 m air temperature is below 1 Khr^{-1} prior to the fog formation (Fig. 3). A cooling rate of 1 Khr^{-1} equates to an updraft speed between 0.028 to 0.04 ms^{-1} at the dry and wet adiabat respectively. The modelled updraft speed is below 0.02 ms^{-1} prior to fog formation and therefore in line with the observed cooling rate. Therefore, the use of a minimum updraft speed of 0.1 ms^{-1} does not have a physical basis in our simulation and is used only as part of the sensitivity analysis. It is also clear that if we use a physical basis for the minimum updraft speed that the model will not activate enough cloud droplets and that another physical process must be manifesting the droplet activation.

In our case, we assume that the observed fog events are due to cloud base lowering (CBL). The satellite images in figures 4 and 5 indicate cloud is present over the site before fog is observed in the surface observations (Fig 3). The surface observations indicate that fog starts at 02h43 and 04h00 UTC on the 9th and 10th of September respectively (Fig 3). Cloud is visible from the satellite from 01h00 on 9 September and even 16h00 UTC on 9 September prior to the fog on 10 September. From the literature, cloud base lowering fog events do not show the same cooling rate at the surface as radiation fog, as the overhead cloud inhibits cooling (e.g. Roman-Cascon 2019). Furthermore, the influence of the maritime environment at the site will dampen cooling from the desert surface. Thus, our observed cooling rates are low which is to be expected. The observed droplet number may then be due to the descent of a mature cloud to the surface, which was initially formed under conditions different to the surface observations.

We note that the model does not show this mechanism of CBL. Instead, droplets form in the lowest model level first and the fog layer thickens over time (Fig 22). Thus, the model is missing the initial stratus cloud formation (or advection) and subsequent cloud base lowering. As indicated in Fig 7, the model has a cold bias at the surface and as a result over estimates relative humidity in the lowest model levels (Fig 9). This highlights the complexity of the study site which is at the intersection of contrasting land cover and air mass types (ocean and desert) and that the planetary boundary layer scheme has struggled to simulate this land-sea interface. Adequate modelling of this interface is perhaps an ambitious task and was not the focus of this study from the outset. As a result the microphysics scheme has activated at a lower altitude that the observations.

Minor comments:

Page 6, Figure 2: Is the activation sensitivity the activated fraction of CCN?

Yes. We will rephrase to "Activated fraction is response to …"

Page 11, Line 266: *"Therefore, assigning a minimum updraft speed of 0.1 m s-1 can be a reasonable assumption, as it falls within the median of activation at the site 0.56"* Did you compare the distributions of activated fractions for different minimum updrafts?

No we did not. We imagine the result would yield the same curve as Figure 2b.

Page 15, Line 307: "Furthermore, the boundary conditions for scenario CCN_300 had relatively lower concentrations of CCN." Lower concentrations compared to what? Why are they lower?

Lower than the ambient CCN concentration and therefore has a dilution effect on CCN. Why this is lower is a good question. This must be due to the parent domain, which we will investigate and comment on in the text.

Page 21, Line 391: *"In addition, the threshold updraft speed is often higher than the 0.01 ms-1 used in the T14 scheme, which effectively results in a higher super saturation and excess droplet activation than would be expected for a fog event."* Please add references to such studies / approaches.

We will move the references from the previous line (Boutle et al., 2018; Poku et al., 2019) to this line.

The motivation for showing Figures 13-16 is not clear to me.

The motivation for these figures is to give some indication of the spatial dynamics which are influencing the site, as most of the results are comparisons with *in-situ* data at the site. These figures are included to help the reader understand the context of the comparison with *in-situ* data.

Technical comments:

Fonts in figures are extremely small.

The following figures have been updated. Font size and scale bars have been increased.
* Fig 3 log scale for Visibility
* Fig 6 labels and titles
* Fig 7 axis and label titles
* Fig 11 scale bar
* Fig 12 and 13 scale bar
* Fig 14 scale bar
* Fig 15 scale bar
* Fig 16 scale bar
* Fig 17 Axis titles, date consistency on d and e.
* Fig 22 all fonts