Replay to Reviewer 3.

The authors discussed observations of ice crystal concentrations measured in-situ during the ICE-D field campaign in Cape Verde during August 2015. It was suggested that, based on INP measurements, primary nucleation alone could not explain the high ice crystal concentrations and so secondary ice processes, e.g. rime splintering, occurred in the convective cloud.

Simulations with one or multiple thermals were performed with several configurations of the heterogeneous ice nucleation scheme. The maximum ice crystal concentrations were than compared with the ones measured during aircraft passes through the cloud.

Major Comments

1. The vertical and horizontal extent as well as the lifetime of the modeled cloud are not compared to the observed cloud, for example by utilizing weather radar data.

> **Reply:** A ground-based mobile radar was deployed, but the clouds were 150 – 200 km from the radar and so due to the beam width and curvature of the Earth, it was not possible to perform detailed comparisons. However, the cloud penetrations were made following a ascending cloud top in order to detect the first ice and in the HM zone to measure the secondary ice production. The top of the simulated clouds was close to the observed clouds. Therefore, we could not directly compare the cloud extents.

2. The microphysics of the model are also very sensitive to the initial conditions, especially the vertical profile of water vapor. The authors used initial profiles combined from dropsonde measurements and NCEP/NCAR reanalysis data, but did not show these profile or discuss which parts of the simulated clouds are located in the region approximated with reanalysis data. The authors should put more emphasis on linking observations with model results and discussing uncertainties of initial conditions.

> **Reply:** The initial profile of the potential temperature and the water mixing ratio has been added. In the discussion section, we added the following in the text. "A simulated cloud with a model is sensitive to its initial conditions. A perfect initialisation requires to follow the trajectory of the cloud in time and space to get the vertical variation of thermodynamic variables before its formation. The initial conditions we could get in close proximity to reality was from the aircraft profile run after it took off to reach the clouds. The initialisation based on the combination of aircraft measurement and reanalysis was a source of uncertainty. However, the major conclusion of this study is that the multi thermal is the only way to get enough ice. The initial conditions only have to be roughly correct to get a cloud that goes to correct height and has the same magnitude of updraft velocities and horizontal extent."

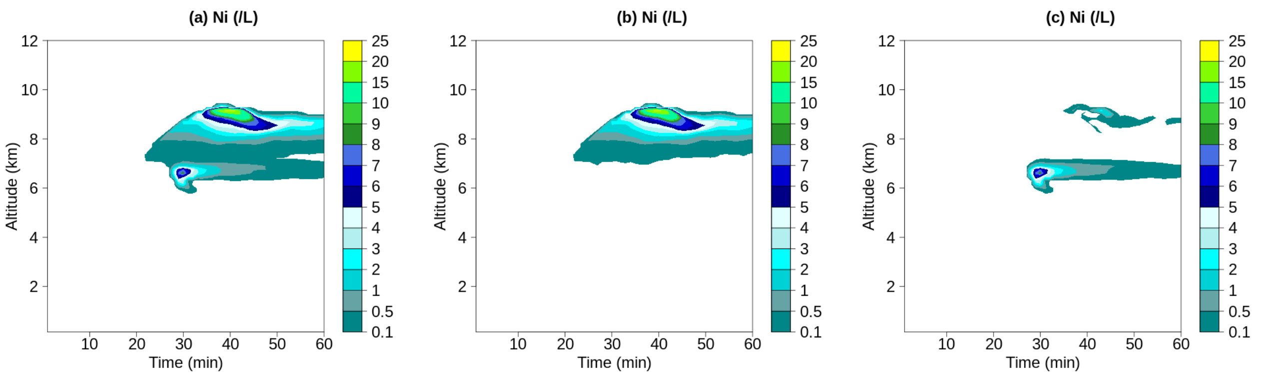
3. A major part of the focuses on evaluating the contribution of secondary ice from rime splintering. The authors identified secondary ice by observing the temperature zone where the Hallett-Mossop (HM) processes is active, e.g. between -3 and -8 °C., and attributed ice crystals in that temperature range to rime splintering. However, transport processes, e.g. advection and sedimentation of ice crystals from the colder part of the cloud into the HM zone, are not discussed.

> **Reply:** As shown in Figure 5d, the high concentrations of ice crystals are in two regions. One is between 27 – 34 min and 6 – 7 km, and the other is above ~ 8 km outside the HM zone.

Figure 5c shows that graupel particles fall into the same region as that in Figure 5d of the high ice concentration in the HM zone. The high ice concentration is indeed by the HM process. The reply to the next point also reinforces this point.

4, Furthermore a majority of the sensitivity experiments increased the onset freezing temperature from -8 °C to – 3 °C or higher, hence heterogeneous nucleation is now possible inside the HM zone. This makes it very difficult to distinguish between ice from rime splintering and primary nucleation in that temperature range. The authors should build a stronger argument that increased ice crystal concentrations in the HM zone did indeed originate from enhanced rime splintering. For example sensitivity simulations without rime splintering could be performed and included in the comparisons.

Reply: We have conducted an additional simulation without the rime splintering process. The figure below shows the time-height variation of the ice crystal number concentration in (a) the *early onset1* run in which the onset freezing temperature being -3 ºC, rather than -8 ºC, (b) *the early onset1* & noHM run in which the onset freezing temperature being -3 ºC, rather than -8 ºC, but the HM process was switched off, and (c) the difference between the simulation with the HM process and the simulation without the HM process. The increase in ice number concentration is clearly seen between 27 – 34 min and 6 – 7 km in (a) and (c), but not in (b). This clearly indicates that the increased ice crystal concentrations in the HM zone did indeed originate from enhanced rime splintering. We also have added the simulation in Figure 6.



Reply: It has been changed to "The INP concentrations are highly variable at a temperature depending on aerosol properties, dynamic and humidity conditions."

Line 76: there are also newer review papers relevant for secondary ice processes e.g. Korolvel et al. (2020)

Reply: Two papers have been added here. It has been changed to "see Field et al. (2017), Korolev and Leisner (2020), and Korolev et al. (2020). "

Line 93: missing full stop after Field et Al

Reply: The sentences have been deleted as suggested by another reviewer.

Line 119: missing full stop after aerosol

Reply: It has been added.

Line 134-143: there are a few mismatches in the figure references

Reply: All mismatches have been corrected.

Line 151-153: Fig. 3 does not provide information about temperature. The statement that ice appeared only at T < -10 °C is supported with Fig. 2.

Reply: It has been changed. The following has been added: "The observation indicates that the ice concentrations were a few tens per litre at derived temperatures in cloud between 0 and −2 °C (Lloyd et al., 2020). Therefore, secondary ice production most likely occurred"

Line 153-154: this section has to be expanded to support the statement that measured ice concentrations were lower than what primary nucleation would suggest since Fig. 2 and 3 do not show INP concentrations

Reply: It has been changed to "much higher than the predicted by most primary ice production parameterisation schames."

Line 164: other relevant microphysical processes, which do not require interaction of cloud particles, like sedimentation and particle growth by deposition of water vapor should be mentioned. Also the Hallett-Mossop temperature zone is mentioned multiple times in this work and the temperature range should be explicitly stated in this section

Reply: The processes of sedimentation and particle growth by deposition of water vapour have been added. The temperature range of the HM process has been added too. The text has been changed to "The microphysical processes include drop activation, condensation, evaporation, collision and coalescence, sedimentation of cloud particles, particle growth by deposition of water vapour, primary freezing modes of deposition/condensation, contact, and immersion, and secondary freezing through the riming-splintering (the Hallett-Mossop) process (Hallett and Mossop, 1974; Cotton et al., 1986), in the temperature range of -3 to -8 °C with a maximum at -5 °C, and the transition and interaction between different species."

Line 191-193: include information about model time steps and intervals of writing output. The latter is important for how clearly you can identify nucleation events in your data.

Reply: The following has been added: "The time-step is 2 sec, and the output frequency is 1 min."

Line 209: -14 °C instead of -14C

Reply: It has been changed.

Line 213: misspelled graupel

Reply: It has been changed.

Line 216: check grammar of last sentence in this line

Reply: It has been corrected.

Line 221: parenthesis without content

Reply: It has been deleted.

Line 266: this statement should be better connected to the figure, that actually shows the increase in ice crystal concentrations

Reply: The sentences from the beginning of the paragraph have been changed to "Sensitivity tests were used to investigate the effect of varying the onset freezing temperature and freezing efficiency on secondary ice production. The differences of several microphysical properties between a sensitivity and the control simulations are examined. There was a significantly higher concentration of secondary ice particles produced in *early onset1 & Cooper10x* compared to the *control* run. Figure 7 shows the detailed differences between the two runs."

Line 288: misspelled increase

Reply: It has been changed.

Line 332: remove 'also' before 'approximately'

Reply: It has been deleted.

Line 334: remove space between m and s^{-1}

Reply: It has been deleted.

Line 340: check grammar in second part of the sentence

Reply: It has been changed to " Some raindrops were transferred to graupel particles via direct freezing, but there were few raindrops remaining near cloud top."

Line 367: panel d in Fig. 12 does not exist

Reply: It has been corrected.

Line 367-377: there are no ice particles shown in Fig. 13

Reply: The right panel shows images of ice particles, such as columns and small non-spherical particles.

Fig 4.: labels of isotherms are barely visible, but important for interpreting the plot. Purple is misspelled in the plot label.

Reply: Please note it is Fig. 5 in the revised version since a new figure is added. It has been changed with thick lines of temperature. Purpple has been changed to purple. Figure 12 in the revised version has been changed in the same way.

Fig. 5: color bar should be changed so that the colors below the dark blue are more continuous. Also a logarithmic plot would be good since ice crystal concentrations below 1 /L are hidden, but important in how ice in the top of the cloud and the HM zone connect.

Reply: Please note it is Fig. 6 in the revised version since a new figure is added. It has been changed. Two more intervals, 0.5 L^{-1} and 0.1 L^{-1} have been added so that it shows how ice in the top of the cloud and the HM zone connect.

Fig. 7: RLX10 is called RLXTEN in the text

Reply: Please note it is Fig. 8 in the revised version since a new figure is added. It has been changed. Another reviewer suggested rename the control and the sensitivity simulations to increase the readability. We agree with the reviewer and have changed the names throughout the text, the table, and the figures. Please see the table for new names.

Fig. 8: the color bar is very hard to read. A continuous color bar should be used instead. Also the plot label misses the information that maximum ice crystals concentrations are shown. RLX10 is called RLXTEN in the text

Reply: Please note it is Fig. 9 in the revised version since a new figure is added. The colour bar has been changed. The figure shows the DIFFERENCE between in number concentration. The x-axis and y-axis are time and altitude, respectively, as shown in the replotted figure. RLX10 and RLXTEN have been changed to a new name. Please see the above reply.

Fig. 9: color bar should be changed so that the colors below the dark blue are more continuous.

Reply: Please note it is Fig. 10 in the revised version since a new figure is added. It has been changed.

References

Korolev, A. and Leisner, T.: Review of experimental studies of secondary ice production, Atmos. Chem. Phys., 20, 11767–11797, https://doi.org/10.5194/acp-20-11767-2020, 2020.