Responses to the comments of Referee #2

Referee #2 (Dr. Emma Järvinen): In this study, simulations of tropical deep convective clouds performed with the Weather Research and Forecasting (WRF) model are evaluated against observations from the High Altitude Ice Crystals (HAIC)-HIWC experiment. As a companion paper to Huang et al., 2021, a closer look on the role of secondary ice production (SIP) to generate observed HIWC regions is taken. Three SIP mechanisms are investigated: the Hallett–Mossop (H-M) process, ice–ice collision fragmentation (IICB) and raindrop freezing breakup (RFZB). It is found that simulations including all three SIP processes successfully produces HIWC regions in all three temperature levels that were investigated. The results highlight the importance of SIP processes in controlling the ice water content in the studied tropical convective clouds. The paper is well written and the model experiments are easy to follow. There are only minor shortcomings that should be addressed before publication. First, the ice crystal observations would have deserved more discussion and ideally, the authors could have included their best estimation of the magnitude of the uncertainties related to these observations. Furthermore, the uncertainties related to the existing SIP parameterisations should be highlighted more. After these minor revisions the manuscript is recommended for publication.

Response: We would like to express our acknowledgement for your efforts and constructive comments. Our point-by-point responses are given below. For convenience, the reviewer's comments are in **black** fonts, and our point-by-point responses are in **blue**. The line numbers in the response are based on the track-change manuscript.

General comments

1. For evaluation of the role of SIP it is crucial to have reliable observations of ice crystal number concentrations (Ni). However, the authors do not discuss the Ni observations during the HAIC-HIWC field campaign or, more importantly, their uncertainties. Although Huang et al., 2021 contains information of cloud microphysical observations, the relevant measurement methods should be summarised also in this manuscript. For example, Huang et al. (2021) states that the Ni measurements were derived from the Two Dimensional Stereo Imaging Probe (2D-S) and the Precipitation Imaging Probe (PIP) for the size range for Dmax>50 μm but in this manuscript use a higher lower size limit of 100 μm. This choice should be discussed.

   Response: We have summarized the relevant measurement methods and uncertainties in the revised manuscript. There are some studies that suggest that particles less than 200 μm may be overestimated by some processing algorithms (McFarquhar et al. 2017). To examine the dependence of our results on the lower size threshold used to calculate Ni, we have conducted sensitivity tests where different lower size limits (i.e., 50, 100, and 200 μm) were used to calculate Ni. The conclusions are consistent among these sensitivity tests, so only the results using the lower limit of 100 μm are discussed in the manuscript. We have mentioned these points in our revised manuscript and added the related figures as supplement.

Lines 228-237 in the track-change manuscript:

"Composite particle size distributions were derived from the Two Dimensional Stereo Imaging Probe (2D-S) and the Precipitation Imaging Probe (PIP) for the particles with D_{max} between 0.01 and 12.845 mm. The observed Ni only considers contributions from ice crystals with $D_{max} > 0.05$ mm due to the potential of shattered artifacts and small and poorly defined depth of field for small particles (Huang et al., 2021; Hu et al., 2021). There is considerable uncertainty in estimating concentrations of ice crystals with $D_{max} < 0.2$ mm from current probes and processing algorithms (McFarquhar et al., 2017; O'shea et al., 2021). To examine the sensitivity of findings to ice crystal concentrations in small sizes, sensitivity tests using different lower limits of D_{max} (i.e., 0.05, 0.1, and 0.2 mm) were conducted. The qualitative findings are consistent among these sensitivity tests (Figs. S1–S6), so only results using the lower limit of $D_{max} = 0.1$ mm are discussed here. More details on the processing and uncertainty of observations can be found in Huang et al. (2021) and Hu et al. (2021)."

Reference:

McFarquhar, G. M., and Coauthors, 2017: Processing of ice cloud in situ data collected by bulk water, scattering, and imaging probes: Fundamentals, uncertainties, and efforts towards consistency. Ice Formation and Evolution in Clouds and Precipitation: Measurement and Modeling Challenges, Meteor. Monogr., No. 58, Amer. Meteor. Soc., 11.1–11.33, https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0007.1.

2. How is the model sampled in order to get Ni and IWC values in the size range of 0.1-12.845 mm? How is the ice particle size defined in the model? What is the possible error in Ni if the model and observations have a different definition for size?

Response: We attained the ice number distribution function from the model and re-calculated the related variables for the same range and same bin size of D_{max} as the observed.

This procedure has been applied in the companion paper (Huang et al., 2021). Therefore, the comparison between simulations and observations is consistent.

3. The sensitivity of the model to horizontal resolution and aerosol profile is discussed in Sec. 3.2. The results are discussed in terms of Ni/IWC values but it is not well justified why the 250m-resolution model was chosen for the sensitivity studies including SIP processes.

Response: As discussed in Section 3.2, we see that the simulated results using different horizontal resolution are similar. Thus, the simulation bias in Ni/IWC does not mainly result from the model resolution. As discussed in Section 2.2.2, "Lebo and Morrison (2015) found overall storm characteristics had limited sensitivity when horizontal grid spacing was decreased below 250 m in their simulated squall lines." A simulation using 125-m grid spacing consumes much more computing resources than a simulation using 250-m grid spacing. Therefore, we chose 250-m grid spacing for the sensitivity studies including SIP processes. We have indicated this point in the revised manuscript.

Lines 212-215 in the track-change manuscript:

"A horizontal grid spacing of 250 m and the more realistic vertical profile of aerosol number mixing ratio are chosen for the sensitivity experiments including SIP processes, because results reveal the model resolution and aerosol profile are not the main source of model biases in simulating HIWCs (discussed in detail in Section 3.2), and because a simulation using 125-m grid spacing consumes much more computing resources than a simulation using 250-m grid spacing."

Reference:

Lebo, Z. and Morrison, H.: Effects of horizontal and vertical grid spacing on mixing in simulated squall lines and implications for convective strength and structure, Monthly Weather Review, 143, 4355–4375, https://doi.org/10.1175/MWR-D-15-0154.1, 2015.

4. Fragmentation of ice in ice-ice collisions is shown to dominate the ice particle production rates outside the updraft core region even at temperatures warmer than -15°C. Do the authors consider this as a realistic outcome or a result of the way ice-ice collisions were implemented in the model?

Laboratory studies suggest that the number of ice ejected in collisions has a strong dependence of temperature with a maximum around -18°C (Takahashi, Nagao & Kushiyama, 1995). The break-up of ice crystals in ice-ice collisions is explained by the different ice crystal surface properties (brittle surface with plate-like growth or dendrites colliding with compact graupel). Plate-like and dendritic growth contributing to fragmentation is taking place in the temperature region between -15°C and -20°C, which explains the observed maximum in ice production rate in the laboratory studies. Ice crystals around -5 and -10°C have more compact columnar shapes. Is this difference in shapes taken into account in the parameterisation?

Response: In this study, we adopted a physically-based parameterization of ice multiplication by breakup during ice–ice collision proposed by Phillips et al. (2017). This parameterization scheme is based on an energy conservation principle, in which the number of new fragments per collision is dependent on cloud species (i.e., hail, graupel, snow or crystals whether dendritic or spatial planar), collision kinetic energy, temperature, and colliding particles' size and rimed fraction. Parameters in the scheme are estimated based on previous laboratory experiment by Takahashi et al. (1995) and field observations by Vardiman (1978). Therefore, this parameterization scheme is more reasonable than other schemes that are only temperature-dependent and just simply fit the ice particle production rate to the results attained during graupel–graupel collisions in the laboratory experiment by Takahashi et al. (1995). Moreover, fragmentation during ice–ice collision is not only dependent on ice number ejected in the collision of colliding pair but also dependent on the ice particle number concentration. It means that higher fragmentation rate of colliding pair does not mean higher total fragmentation of ice in ice-ice collisions, and vice versa. We agree that there might exist an overproduction of ice due to ice–ice collisional breakup parameterization, which was also mentioned in previous studies. In this study, we used current commonly accepted microphysical parameterizations but acknowledge that there are inevitably uncertainties in the representation of actual physical processes. The community has a general consensus that some parameterizations including fragmentation during ice–ice collision have to be revisited, and they require feedback from more theoretical studies, field campaigns including remote-sensing and in-situ observations and laboratory studies. The most important outcome of this paper is that one of the necessary conditions for HIWC formation in MCSs is enhanced production of secondary ice. The question about the actual mechanisms of SIP and the associated rates of ice production is beyond the scope of this study. These points have been discussed in the revised manuscript. Lines 152-156 in the track-change manuscript:

"In this study, current commonly accepted microphysical parameterizations are used. However, there are uncertainties in the parameterization of both primary ice production and SIP mechanisms (Korolev and Leisner, 2020). In fact, uncertainties in the parameterization of primary ice production also transfer to uncertainties in SIP processes. Therefore, more theoretical studies, field campaigns including remote-sensing and in-situ observations, and laboratory studies should be conducted to constrain parameterizations of both primary ice production and SIP mechanisms in the future (Morrison et al., 2020)."

Reference:

Phillips, V. T., Yano, J.-I., and Khain, A.: Ice multiplication by breakup in ice–ice collisions. Part I: Theoretical formulation, Journal of the Atmospheric Sciences, 74, 1705–1719, https://doi.org/10.1175/JAS-D-16-0224.1, 2017.

Takahashi, T., Y. Nagao, and Y. Kushiyama, 1995: Possible high ice particle production during graupel–graupel collisions. J. Atmos. Sci., 52, 4523–4527, https://doi.org/10.1175/1520-0469(1995)052,4523:PHIPPD.2.0.CO;2.

Vardiman, L., 1978: The generation of secondary ice particles in clouds by crystal–crystal collision. J. Atmos. Sci., 35, 2168–2180, https://10.1175/1520-0469(1978)035,2168:TGOSIP.2.0.CO;2.

5. It is important to state that there are severe uncertainties in the parameterisations of SIP mechanisms. Although there is a statement about this in Summary and Conclusions, this could be also stated earlier in the manuscript (e.g. in Sec. 2.1). Ideally, some additional sensitivity tests by tuning the different SIP parameterisations could have been performed.

Response: We have stated the uncertainties in the parameterizations of SIP mechanisms in Section 2.1. As the response to the comment #4, in this study, we used current commonly accepted microphysical parameterizations although they have uncertainties in the representation of physical processes. The community has a general consensus that some parameterizations including fragmentation during ice–ice collision have to be revisited, and they require feedback from more theoretical studies, field campaigns including remote-sensing and in-situ observations and laboratory studies. The most important outcome of this paper is that one of the necessary conditions for HIWC formation in MCSs is enhanced production of secondary ice. The question about the actual mechanisms of SIP and the associated rates of ice production is beyond the scope of this study. These points have been discussed in the revised manuscript.

Lines 152-156 in the track-change manuscript:

"In this study, current commonly accepted microphysical parameterizations are used. However, there are uncertainties in the parameterization of both primary ice production and SIP mechanisms (Korolev and Leisner, 2020). In fact, uncertainties in the parameterization of primary ice production also transfer to uncertainties in SIP processes. Therefore, more theoretical studies, field campaigns including remote-sensing and in-situ observations, and laboratory studies should be conducted to constrain parameterizations of both primary ice production and SIP mechanisms in the future (Morrison et al., 2020)."

Lines 432-437 in the track-change manuscript:

"For example, the high ice production rate due to the fragmentation during ice-ice collisions is highly uncertain, and its high production rate in anvil cloud regions between −40 °C and −50 °C (Fig. 7) is rarely seen in observations. However, these uncertainties do not influence the main conclusions due to the orders of magnitude differences in ice number concentrations between the experiments with and without SIP mechanisms. This study enhances understanding of the processes leading to formation of the numerous small crystals in HIWC regions in which enhanced production of secondary ice is one of the necessary conditions."

Minor comments

Line 203: Can the authors explain the choice to discuss the results in the form of Ni/IWC? What is the additional value in this representation?

Response: Because IWC varies among samples and there may exist bias in the simulated IWC compared to observations, using the form of Ni/IWC allows us to focus on ice number distribution. Further, because most observed and simulated IWC are between 1 and 3 g m^{-3}, and only very small instances of IWC greater than 3 g m^{-3} occur, the results using either Ni or Ni/IWC are very similar.

Figure 4: Can the observations be added to the corresponding subplots or even combine Figures 3 and 4?

Response: If the observations are added to the corresponding subplots, they will mask some simulated samples. Instead, we add a figure combining Figs. 3 and 4 to the appendix (Fig. A1) for reference.

Figure 5: Same as for Fig. 4. It would be helpful to have the observations included. In addition, please explain the acronyms HM, RFZB, IICB and SIPs in the figure caption to improve readability.

Response: Same as the response to the last comment. Figure A2 including observations and simulations is shown in the appendix for reference. The acronyms HM, RFZB, IICB and SIPs have been explained in the figure caption.

Line 256: What kind of significance test was performed? Please add this information.

Response: We used *t*-test from SciPy package (https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.linregress.html). We have indicated this in the revised manuscript.

Line 345: Some discussion of how generating more ice in the early or lower parts of the cloud though SIP will lead to HIWC regions with more small ice crystal at colder and higher part of the cloud would be helpful to visualise the dynamics of these systems.

Response: We have added the related discussion in the revised manuscript.

Lines 388-389 in the track-change manuscript:

"More small ice particles generated in the early or lower level cloud through SIP processes also can increase the small ice crystals at upper cloud through vertical advection."