**Reviewer # 2**

1 Summary

This manuscript investigates the formation of columnar ice crystals in different types of (winter) clouds at temperature warmer than −10 ◦C, by analyzing two years of vertical profiles of reflectivity, Doppler velocity and LDR collected by a W-band polarimetrioc radar over the Hyytiala site in Finland. Environmental conditions (mostly temperature and relative humidity) are provided by the ICON NWP model. The identification of columnar ice crystals is based on their typical linear depolarization ratio (LDR) signature, and their occurrence can be quantified and analyzed as a function of the cloud type (single vs multi-layer cloud) as well as the temperature difference between cloud top and the altitude of columnar ice formation. Those analyses suggest that (i) columnar ice formation is relatively frequent (from 5 to 30% depending on the cloud top temperature), (ii) columnar ice formation is associated with more intense surface precipitation, (iii) the liquid water path (LWP) is larger when columnar ice crystals are produced compared to when there is no such production, and (iv) some secondary ice production (SIP) mechanisms are likely involved to explain the larger number of ice crystals than ice nucleating particles in the case of single-layer clouds.

2 Recommendation

Taking advantage of a nice set of vertical profiles of radar observations at W-band over wellknown site in Finland, this work relevantly combines radar measurements and model output to investigate the importance (in terms of occurrence and impact on surface precipitation) of columnar ice production in "warm" ice or mixed-phase clouds and to characterize those. In addition, the discrepancy found between the estimated order of magnitude of ice crystal number on the one hand and of ice nucleating particle number on the other, the latter being smaller, suggest that secondary ice production mechanisms must be active in order to complement primary ice production. The proposed approach and the obtained results are sound (although some aspects remain rather speculative), and they are relevant for the ACP readership. I do not have major concerns, so I recommend to send the manuscript back to the authors for minor revisions. A list of comments and questions is provided below.

We sincerely appreciate the reviewer for very thorough comments on our paper. We have amended the manuscript as suggested. Please see below our response to your comments.

3 Specific comments

1. P.2, l.2-3: in high latitude regions (Arctic, Antarctic, Southern Ocean), INP concentration has been estimated to be lower than at mid-latitudes (e.g. DeMott et al., 2016; Wex et al., 2019).

Thank you for the nice supplement. We have added a sentence as follows:

*In addition, it has been found that INP concentrations in high latitudes are generally lower than in mid-latitudes (e.g., Demott et al., 2016, Wex et al., 2019).*

2. P.2, l.18: other SIP processes than HM have been already implemented in different atmospheric models. For instance: Hoarau et al. (2018); Sullivan et al. (2018); Zhao and Liu (2021).

Agree. We have added these works at proper places, and have amended the previous statement as:

*This is referred as to Hallett–Mossop (H-M) process, the most studied and most frequently implemented SIP mechanism in numerical models (Field et al., 2017).*

3. P.4, l.9-13: what is the horizontal resolution of ICOM simulations above Hyytiälä?

It is 13 km. In the revised manuscript, we have added such description in Section 2.2.

4. P.6, l.24: the used statistics of relative humidity from the ICOM simulations likely depend on some of the microphysica parameterizations. This should be mentioned and those parameterizations could be listed (no need of exhaustive descriptions).

Agree. Given $RH_{ice}$ was calculated from $RH_{liquid}$, we have removed $RH_{ice}$ in the revised manuscript for avoiding misleading. We have added such sentence:

*However, the values of $RH_{liquid}$ and $RH_{ice}$ should be interpreted with caution. ICON applies a liquid saturation adjustment, limiting the liquid supersaturation to saturation. $RH_{liquid}$ values exceeding 100 % are attributed to numerical artifacts. $RH_{ice}$ was calculated based on the forecasted temperature, pressure as well as $RH_{liquid}$, therefore can be affected by numerical artifacts as well. Given the uncertainty of ICON forecasts, we regard the presented statistics in Fig.2 as a sanity check for our method.*

5. P.8, l.12-13: "the majority of columnar ice production cases took in areas of high supersaturation, which is potentially favorable for liquid water droplet formation or existence", according to Fig.2.b, most cases are below 100% of RH with respect to liquid water...

Thank you for pointing this out. This sentence has been amended as

*the majority of columnar ice production cases took in areas close to liquid supersaturation.*

6. P.8, l.17: smaller than −8 ◦C would be more correct I think.

Amended.

7. P.10, l.8: the argument that "precipitation processes are more complex" is a bit short, please elaborate.

We have amended this sentence as

*Colder clouds are prone to be consisting of the multiple cloud layers where precipitation processes are affected by multiple processes, such as riming, aggregation, sublimation, at various levels (Houze Jr and Medina, 2005, Verlinde et al., 2013, Moisseev et al., 2015).*

8. P.12, l.11-16: I would suggest to make a more explicit reference to Section 5 here, to inform the reader that this question is addressed later in Section 5.

Thank you for the constructive suggestion.

*In this study, we find that such clouds also frequently occur over Hyytiälä, and more detailed analysis will be presented in Sec. 5.*

9. P.12, l.30: "is responsible" should be "could be responsible" as this is speculative.

Amended

10. P.12, Section 4.3.2: there is no reason (even speculative) provided to explain how the supercooled liquid water could be generated in such clouds...

Due to the lack of sounding observations, it is challenging to identify the mechanism of generating supercooled liquid water. Therefore, we tend to be conservative on explain the presence of liquid. Also, we did find such clouds resemble with some previous studies, and we will do further analysis in the future. We have added the discussions below:

*Although sounding measurements were absent, this cloud type seems to be very similar with the one reported by Westbrook and Illingworth (2013), namely, a layer of supercooled liquid water with the top temperature of around -15℃ seeding low-level stratus clouds in the boundary layer.*

11. P.13, l.2-3: it was not totally clear to me where are these waves in Fig.8.b, maybe circling them would help...

We have added the zoom-in view on the waves in Fig. 8b.

12. P.13, l.2-5: more explanations about those waves (nature, origin...) should be provided. If they are related to larger scale processes, are they reproduced in ICON simulations?

We agree that these wave signatures are interesting. Our separate study (Li et al., ACP, 2021), with thorough analysis, has reported that Kelvin-Helmholtz waves with such velocity oscillations are favorable for large liquid drops formation and SIP. We are currently looking in-depth on such phenomenon, and more detailed explanations will come in our future studies.

13. P.13, l.5: "pointing to a possible connection between the two": between 06:30 and 07:30, I do not see any wave signature (I may have missed it) but the period is still identified as" columnar ice productive", so the connection is not that clear in my view...

We have added the zoom-in view on the waves in Fig. 8b. The connection should be more visible.

14. P.14, l.3: the explanation about the atmospheric waves generating SLW is too short (and speculative): the Doppler velocities (Fig.9.b) do not show significant updraft around 1 km of altitude between 06:00 and 10:00 while columnnar ice crystals are identified by their LDR signature...

We agree with the reviewer. We have added the zoom-in view on the waves in Fig. 8b. The link between waves and SLW, SIP is exactly a topic that we are investigating and we have discussed it in a separate study (Li et al., ACP, 2021). We have referred to (Li et al., ACP, 2021) in the revised manuscript.

15. P.15, l.17: detectably?

Corrected.

16. P.16, l.6-9: there are also ice only SIP mechanisms (e.g. Korolev and Leisner, 2020).

Agree. We have amended this sentence as

*In multilayered clouds, identified here as cloud types II and III, it has been found that the ice formation can be enhanced by the H-M process (e.g., Grazioli et al., 2015; Giangrande et al., 2016; Sinclair et al., 2016; Keppas et al., 2017; Sullivan et al., 2018; Gehring et al., 2020), among other mechanisms (Korolev and Leisner, 2020).*

17. P.18.l.25: a " ," is missing between 0.03 and 5.

Corrected.

18. P.19, l.27-28: "It was found that... formation of ice particles": I find this formulation rather confusing: this work focuses on the formation of columnar ice crystals at temperatures warmer than −10 ◦C, not on the formation of ice crystals in general.

We have amended the sentence as:

*It was found that columnar ice formation is relatively frequent in clouds at temperatures of -10 ℃ or warmer.*