Review for:

Conditions favorable for secondary ice production in Arctic mixed-phase clouds

by Julie T. Pasquier

Summary:

Pasquier et al. investigate the conditions that favor secondary ice production (SIP) in Arctic clouds, observed during NASCENT campaign, and examine the possible underlying mechanisms. For their investigations they use in-situ cloud microphysical measurements derived by a holographic cloud imager on a tethered balloon system and ground-based remote-sensing and ice nucleating particle (INP) measurements. Their analysis focuses on a six-day period which revealed the occurrence of SIP for about 40% of the time, while very high SIP events (with ICNCs > 10 L^{-1}) were identified in 3.5% of the analyzed data. The highest SIP efficiency was found at temperatures between -3°C and -5°C; interestingly, this was attributed to the drop-shattering mechanism rather than to the Hallett-Mossop process, which has been thought to be the dominant SIP mechanism at these temperatures. Ice-ice collisions is also identified as the second most important SIP mechanism, especially at colder temperatures down to -24°C.

This is a very well-written paper and a very interesting study. Models fail to reproduce the micro- and macro- physical structure of Arctic clouds and the description of ice microphysical processes has long been known to be a main contributor to these errors. Also while SIP has been hypothesized to be responsible for the enhanced cloud ice number concentrations often observed in the pristine Arctic environment, where INP availability is limited, the exact SIP mechanisms remain unknown. In general, there are very few in-cloud ICNC datasets from the Arctic and also most of them are not combined with INP measurements, which makes it difficult to quantify the influence of primary ice production versus SIP. This highlights the importance of the present study and the analyzed datasets for understanding ice production in Arctic clouds. For this reason, I recommend this paper for publication after the comments below have been addressed.

Comments:

Line 63-64: maybe discuss a bit how ice shape is expected to influence SIP (with references)

Line 105: since measurements were collected during four months in total, why only such a small sample of six days is presented here? Please explain

Line 111-114: are particles below 25 micro re-examined manually or are they treated as droplets in the analysis? In the case they are treated as droplets, can you estimate the magnitude of SIP underestimation? Fragments generated by drop-shattering can about 10 micro (Phillips et al. 2018), while these can be even smaller for the other two SIP processes. The same question concerns misclassified ice crystals with circular shape.

Line 114-115: could you provide more details on the criteria (characteristics) used to classify to ice particles as recirculated or aged? How do you separate these two categories?

Lines 125-126: what do you mean 'minimized'? Could you provide an estimate for how frequently shattering occurs? You should use the inter-arrival time algorithm (Korolev and Field 2015) to identify shattering artifacts and exclude them from the analysis.

Lines 153-154: There is something I don't understand about this method. Why pristine ice crystals with size < 106 micro cannot be newly-formed primary ice crystals? Why these should solely be associated with SIP? Please explain.

Lines 180-181: provide reference

Lines 193-195: I am not convinced that the profiles derived on 8/11 and 11/11 are well-mixed. A Θ-gradient of 0.5°C is often used as criterion for decoupling (Sotiropoulou et al. 2014, Gierens et al. 2020). Please use one of the proposed methods in the literature to ensure cloud-surface coupling.

Lines 238-239: you do not provide any information on updraft velocity for November 10 to support this statement. I suggest to provide a time-height cross-section for this parameter (at least in the appendix or as supplementary material).

Section 3.2: While this section focuses on the investigation of the high SIP event in the afternoon of 11/11, it is worth including a short discussion for the possible drivers of the weaker SIP before 18:00.

Lines 332-333: However, peaks in the columnar ice concentrations before 13:00, which are of similar magnitude as the one observed round 13:00-13:155, are not associated with CDNCs increases. What is the reason behind their formation?

Line 333: There seems to be an almost constant white shading at sizes between 7-8 micro in both Figures 6 and 8. Is this some kind of artifact?

Line 342: It worths discussing here a bit more about the ice-ice collision process. Is it the same mechanism here as proposed by Geogakaki et al. (2022) for seeder-feeder events? They suggest that ice particles falling from the upper cloud collide with ice particles within the lower mixed-phase layer, resulting in mechanical break-up. And if this the case, why the process does not take place earlier, since the seeding-feeding system is observed from approximately 12:00 to 14:00?

Line 344: please provide the reference of Georgakaki et al. (2022) here, who reached the same conclusion about seeder-feeder cases.

Line 344: do you exclude the possible contribution of sublimation break-up? Deshmukh et al. (2022) suggest that as precipitation particles falling from the seeder cloud into a sub-saturated environment may experience sublimation break-up. Then, as the new fragments enter the saturated conditions of the feeder cloud, they can further grow through vapor deposition and enhance ICNCs (see their schematic in Fig. 14).

Line 361: Could the correlation between ice-snow concentrations be due to the fact that SIP particles will eventually grow to snowflakes? This means that increases in snow concentration would follow the increases in the number smaller ice particle.

Line 367-368: Again, the contribution of sublimation break-up should be investigated here (see comment above)

Line 385: How sensitive are the results to the choice of this CDNC threshold?

Lines 386-387: This comment concerns the small OEF for cloud droplets. The presence of cloud drops is expected to be important for SIP within the Hallet-Mossop temperature zone, but not outside of it. If you calculate the OEF only for the H-M zone, does the factor changes significantly?

Lines 400: updraft speeds are hardly discussed in this manuscript. I suggest to add a figure for this variable and discuss this more thoroughly in relevance to SIP occurrence and drizzle formation

Line 433: Please add the reference of Luke et al (2021) here. They were the first to show that high SIP events are associated with the presence of large drops in Arctic clouds. It is worth trying to relate your analysis to their findings, derived with remote-sensing methods.

Line 450: Could you infer a minimum INPC that is necessary to initiate SIP from your measurements? Or at least an INPC level below SIP is never expected to occur.

Line 461: This is a statement that is not clearly supported by the analyzed data. The connection of updraft velocities, CCN and drizzle concentrations should be shown explicitly in the figures.

Lines 465-466: if the contribution of sublimation break-up cannot be excluded with the existing data, maybe the possibility of having more mechanisms activated should be addressed here.

REFERENCES:

Deshmukh, A., Phillips, V. T. J., Bansemer, A., Patade, S., & Waman, D. (2022). New Empirical Formulation for the Sublimational Breakup of Graupel and Dendritic Snow, *Journal of the Atmospheric Sciences*, *79*(1), 317-336.

Gierens, R., Kneifel, S., Shupe, M. D., Ebell, K., Maturilli, M., and Löhnert, U.: Low-level mixed-phase clouds in a complex Arctic environment, Atmos. Chem. Phys., 20, 3459–3481, https://doi.org/10.5194/acp-20-3459-2020, 2020.

Korolev, A. and Field, P. R.: Assessment of the performance of the inter-arrival time algorithm to identify ice shattering artifacts in cloud particle probe measurements, Atmos. Meas. Tech., 8, 761–777, https://doi.org/10.5194/amt-8-761-2015, 2015.

Luke, E.P., F. Yang, P. Kollias, A.M. Vogelmann, and M.,Maahn, 2021: New insights into ice multiplication using remote-sensing observations of slightly supercooled mixed-phase clouds in the Arctic. *Proceedings of the National Academy of Sciences,* **118**. doi: 10.1073/pnas.2021387118

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Sotiropoulou, G., Sedlar, J., Tjernström, M., Shupe, M. D., Brooks, I. M., and Persson, P. O. G.: The thermodynamic structure of summer Arctic stratocumulus and the dynamic coupling to the surface, Atmos. Chem. Phys., 14, 12573–12592, https://doi.org/10.5194/acp-14-12573-2014, 2014.