RESPONSE TO REVIEWER 2:

The manuscript studies the sensitivity of ice particle number concentration on different assumptions about secondary ice production in Arctic mixed phase clouds. … role of secondary ice production and gives directions for further studies. Thus I recommend publication after corrections and additional discussion.

We thank the reviewer for the thoughtful comments that have clearly improved the manuscript. Our responses (black) to each point raised (red) is provided below.

What is the role of measurement conditions? It is said that the wind is from the West and measurements are performed both over the open water and ice. Droplet concentration seems similar in both, but there is no discussion how ice particle concentration differs and where the presented values are measured.
An overview of the observed conditions with respect to ice-covered or open-water surface was provided in Jones et al (2018). However since this manuscript remained in the discussion phase, a brief recap on the influence of the surface state on cloud microphysical properties is now added (lines 331-335 in the revised version). In the initial submission, in lines 271-273 we state that we use cloud measurements collected at latitudes higher than 81.7°N and within a 9×33 km^2 ice-covered area to evaluate the simulated cloud properties, as ice-covered surface conditions are also prescribed in the LES. Thus all cloud observations shown in Figures 5-7-9 in the initial document are collected over ice.

Is there any potential for the surface to be the source if ice hydrometeors?
Blowing snow is associated with strong winds over flat terrain (e.g. Vali et al. 2012; Gossart et al. 2017) or close to mountainous slopes in the vicinity of orographic clouds (e.g. Lloyd et al. 2015; Geerts et al 2015). A general threshold in 2-m wind speed for such events in freshly fallen snow is 7–10 m s^{-1}, with a weak trend toward lower threshold speeds at lower air temperatures (Dery and Yau 1999). Gossart et al. (2017) showed that the height of the blowing snow layer is usually << 500 m, except for stormy cases of heavy mixed events, precipitation and blowing snow ,when it can go up to 1.3 km. In our case, the winds are much weaker, on average ~ 5.8 m $s^{-1}$and the cloud base height is >500 m AGL, while the largest concentrations were observed at ~800 m AGL. A maximum height of 500 m for such phenomena is also recorded in Geerts et al (2017), but required much higher winds than in our case. Thus we believe there is no possibility for blowing snow to impact the examined clouds (this is also mentioned at the end of section 2.2 in the revised text) .

2) LPM: I have some problems in understanding what the LPM model employed is actually simulating. Does it solve the hydrometeor condensational growth assuming three size classes both for liquid and ice, or is it somehow parameterized how particles grow from some size range to another based on characteristic time parcel is spending in a single updraft. I'm actually surprised that there is no spectral size resolving model employed. Such models should be available and numerically efficient enough to be used in the presented application. In line 139 it is stated "The LPM allows a detailed description of the formation, growth and evolution of cloud droplets and ice particles as they interact with each other". I disagree with this, I would not call three bins detailed what comes to representation of cloud and ice particle size distributions. Thus also coagulation rate and secondary ice production are only approximate, although probably accurate enough to provide first estimates and to be used in this paper.
The LPM allows all bins to evolve dynamically by predicting their size as a function of

temperature and supersaturation. However the transition from one bin to another is controlled by the timescales. This is based on Yano and Phillips (2011) and is a simple but still convenient framework to parameterize SIP. While more advanced spectral size resolving models would likely offer more accurate predictions of SIP effects, these are computationally expensive and do not allow SIP investigations over a very large parameter space. Here we demonstrate the possibility of using a simplified framework to develop parcel-model based parameterizations for larger scale models. However, we agree that this is not a very detailed model, and we have replaced the word 'detailed' with 'adequate' in the revised text.

3) MIMICA: Line 145 or later in section 3.1: Maybe you should state explicitly the reason why SIP processes are not directly implemented into MIMICA.

The original submission had this extensively discussed in the last section. In the revised text, we have moved this discussion to the beginning of section 3.

4) How does the SIP enhancement work in a case when the ice particle concentration at cloud base in MIMICA is higher than prescribed IN concentration? Does it still enhance the concentration? I assume such conditions to occur frequently in modeled boundary layer cloud.

At each model time-step and level the LES estimates the number of new nucleated particles = INP (using DeMott in the revised version) - existing N_{ice}. If this is negative, nucleation of new particles is assumed to not occur. This treatment can be found in widely used microphysics schemes (e.g. Morrison et al. 2005 in WRF). In the case that SIP is activated, the only difference is that: new nucleated particles = INP × SIP_{factor} - existing N_{ice} (thus if the outcome is negative, SIP does not enhance concentrations anymore). This methodology is better explained now in section 3.1 of the revised manuscript to avoid confusion.

5) Line 283: "The mean observed INP concentration is 0.006 L-1 and never exceeds 0.05 L-1". From where does these numbers come from? The conditions are really warm for heterogeneous ice nucleation, with modelled values at minimum -6.5 degrees and measured even warmer. What aerosol particles are active in such a warm temperature.

These statistics are based on all the flight data collected on 23 July 2013, between 10-11 UTC, at various latitudes, longtitudes and altitudes. They aim to provide a more general overview and also allow for comparison with other ACCACIA cases (e.g. Lloyd et al. 2015), in which INP conditions are estimated and presented in a similar way. However, we acknowledge that this vague discussion is confusing to the readers as no reference to the thermodynamic conditions is made. This is now corrected in the revised manuscript. 0.006 L^{-1} is the mean concentration is for the whole flight, which sampled at temperatures between ~ -10 °C – 0 °C and specific humidity ~ 2.5–5 g m^{-3}. The maximum INP concentration is observed at ~ T= -10 °C and Qv=2.5 g m^{-3}. However the maximum ICNC occurs at T~-5°C, much warmer conditions than those that maximum INPs are measured. Hence, measurements strongly indicate the occurrence of SIP.

Demott aerosol-aware parameterization predicts INP=0.03 L^{-1} around -6.5°C (the coldest simulated temperatures), which interestingly is in very good agreement with the upper limit of INPs measured in the Arctic (Figure 7 in Wex et al. 2019). We don't know the chemical composition of ice nuclei at these temperatures, however Wex et al. measured all types of aerosols, including bioaerosols.

6) Within MIMICA it would be possible to track temperature dependent IN concentration. How would this more realistic approach change the simulations? In comparison to observations it would have been interesting to see if the spread in modelled data is as wide as in observations. When I look at modelled data, I am really surprised how small standard deviation there is in the output. Enhancement should depend quite strongly on the updraft at the cloud base based on Figures 4, 6 and 8.

The DeMott aerosol-aware temperature-dependent parameterization is now implemented in the LES, with mean observed aerosol concentrations as input. However, the original scheme predicts INP=0.03 L^{-1} around -6.5°C: even if this very low INP concentration is likely realistic (Figure 7 in Wex et al. 2019), when prescribed in the LES simulations, it does not produce any ice. For this reason we have to consider the uncertainty in DeMott parameterization which is a factor of 10. Multiplying DeMott×10 yields very large INP concentrations (~0.3 L^{-1}) near cloud top (minimum -6.5°C), which is unrealistic for warm subzero temperatures (Figure 7 in Wex et al. 2019). For this reason, in our CNTRL simulation we apply DeMott×5. The original DeMott scheme, DeMott×10 and DeMott×100 are presented as sensitivity tests.

Below we show the mean profiles produced by the LES after spin-up period (no SIP is activated): DeMott×5 predicts concentrations (N_{ice}) varying from 0.007 L^{-1} at cloud base (~ -3°C) to 0.11 L^{-1} near cloud top. An interesting finding is that N_{ice} profile does not match the vertical distribution of INPs predicted by the ice nucleation scheme (Figure 1). This is likely due to the effect of cloud mixing of ice crystals, as this more homogeneous profile develops within the first hour of simulation. If SIP was directly implemented in the LES, N_{ice} profiles would be used to calculate ice-ice collisions. Hence we use the N_{ice} profiles as input to the LPM: a mean INP concentration of 0.007 L^{-1} is prescribed at cloud base, while as the parcel ascends the new nucleated crystals estimated with a nucleation rate based on DeMott×5 (the product of updraft velocity, an assumed lapse rate of 6 K km^{-1}, and the temperature derivative of the INP estimates) until a maximum value of 1.1 L^{-1} INPs is reached; this is the maximum N_{ice}/INP concentration produced by the LES near cloud top (Figure 1). This discussion and the Figure below have been as added to the revised Supporting Information.

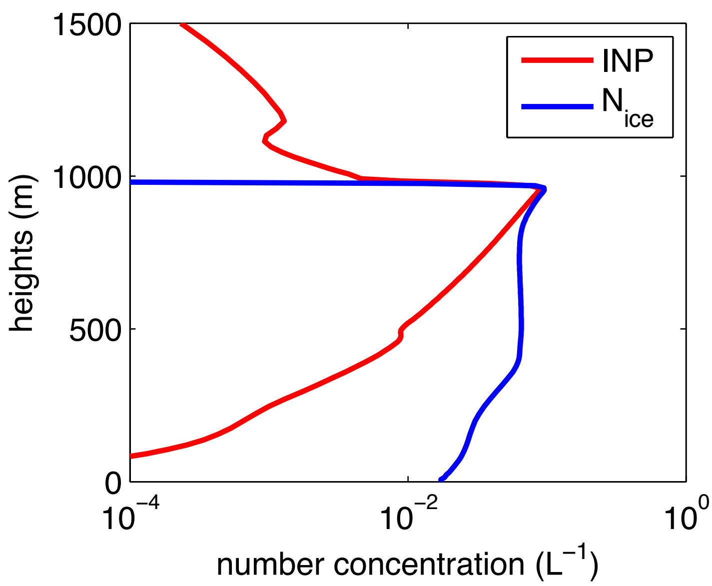

Figure 1*:* Mean LES profiles of INP and N_{ice} concentrations after spin-up period.

Furthermore, we would like to clarify that the small standard deviation in the LES simulations is not due to the prescribed INP conditions. The LES reaches a quasi-steady state after a few hours and the presented statistics are derived from that period of equilibrium. LPM is run over a relatively large parameter space, but the LES conditions are not that variable, especially in the quasi-steady state. In Figure 2a below it is obvious that only the low updraft conditions are representative of the simulated cloud (stronger updrafts are basically outliers with relative frequency < 0.2%). Also we cover in-cloud temperature conditions with the LPM; however, the parameterization in the LES is eventually a function of cloud base temperature, whose range is much narrower (Figure 2b). Since running the LPM is computational cheap, testing a larger parameter space was no problem for us: it ensures that all possible conditions are accounted for. However, now we understand that the wider thermodynamic conditions presented in Figures 4,6,8 in the previous manuscript might confuse the reader. For this reason we have moved the LPM look-up tables to the Supporting Information, while only the dominant conditions are discussed in the main text.

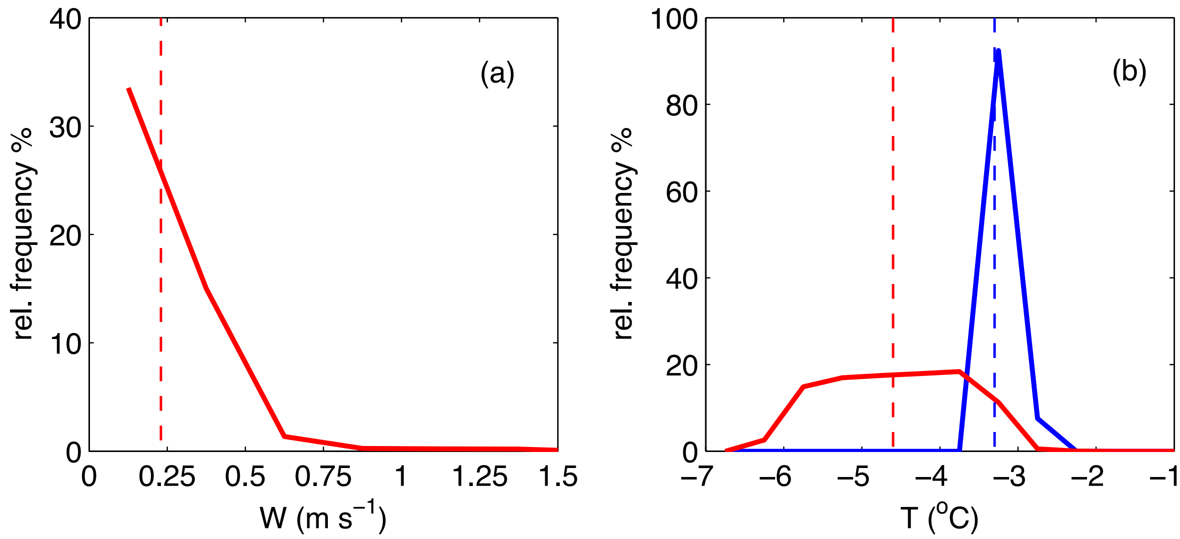

Figure 3: Relative frequency distribution for hourly outputs of 3D LES fields of (a) incloud updraft velocities (u_z>0.05 m s^{-1}) and (b) in-cloud (red) and cloud-base (blue) temperatures. Dashed lines represent mean values.

7) Line 463: "A main challenge in parameterizing BR is that a correct spectral representation of the ice crystals is required, which is more feasible in bin microphysics schemes". This is true, and the same limitations holds for all cases when temperature dependent ice nucleation or secondary ice production is included. If the number concentration is tuned to be correct, the size distribution and total mass is probably wrong due to given shape for size distribution.

This is a common problem in bulk microphysics schemes. The very detailed bin microphysics schemes however are computationally expensive and that's why they are not widely used in weather prediction and climate models. For this reason we suggest that LPMs can serve as a efficient way to parameterize SIP in large-scale models: although several simplifications are still employed, they likely can offer a reasonable estimate of the order of magnitude of SIP multiplication in different cloud states.

8) Jones et al., 2018 is not accepted for publication, so it should not be cited.

We have removed this citation in the revised manuscript

9) Schwarzenboeck et al., 2009 title is "Indications for stellar-crystal fragmentation in Arctic clouds"
Thank you, corrected

References:

Déry, S. J. and Yau, M. K.,1999: 'A Climatology of Adverse Winter-Type Weather Events', J. Geophys. Res. 104(D14), 16,657–16,672.

Morrison, H., Curry, J.A., & Khvorostyanov, V.I. (2005). A New Double-Moment Microphysics Parameterization for Application in Cloud and Climate Models. Part I: Description, . *Atmos. Sci.,* 62*,* 3683-3704 62

Vali, G. , Leon, D. and Snider, J. R. (2012), Ground‐layer snow clouds. Q.J.R. Meteorol. Soc., 138: 1507-1525. doi:10.1002/qj.1882

Geerts, B., B. Pokharel, and D.A. Kristovich, 2015: Blowing Snow as a Natural Glaciogenic Cloud Seeding Mechanism. *Mon. Wea. Rev.,* 143, 5017–5033,https://doi.org/10.1175/MWR-D-15-0241.1

Lloyd, G., Choularton, T. W., Bower, K. N., Gallagher, M. W., Connolly, P. J., Flynn, M., Farrington, R., Crosier, J., Schlenczek, O., Fugal, J., and Henneberger, J.: The origins of ice crystals measured in mixed-phase clouds at the high-alpine site Jungfraujoch, Atmos. Chem. Phys., 15, 12953–12969, https://doi.org/10.5194/acp-15-12953-2015, 2015.

Lloyd, G., Choularton, T. W., Bower, K. N., Crosier, J., Jones, H., Dorsey, J. R., Gallagher, M. W., Connolly, P., Kirchgaessner, A. C. R., and Lachlan-Cope, T.: Observations and comparisons of cloud microphysical properties in spring and summertime Arctic stratocumulus clouds during the ACCACIA campaign, Atmos. Chem. Phys., 15, 3719-3737, https://doi.org/10.5194/acp-15-3719-2015, 2015.

Gossart, A., Souverijns, N., Gorodetskaya, I. V., Lhermitte, S., Lenaerts, J. T. M., Schween, J. H., Mangold, A., Laffineur, Q., and van Lipzig, N. P. M.: Blowing snow detection from ground-based ceilometers: application to East Antarctica, The Cryosphere, 11, 2755–2772, https://doi.org/10.5194/tc-11-2755-2017, 2017.