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Ice multiplication from ice–ice collisions in the high Arctic: sensitivity to ice habit, rimed fraction, ice type and uncertainties in the numerical description of the process

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Section S1: Constraining Primary Ice Nucleation in MIMICA

In the empirical ice nucleation active site density parameterization for immersion freezing, implemented in MIMICA by Ickes et al. (2020), it is assumed that a specified fraction of the CCN population contains microline, an efficient ice-nucleating feldspar type (see Section 3.2.1 in the main text for a discussion). The sensitivity of the calculated INP to the number of CCN and the percentage of microline is investigated in Ickes et al. (2020) using the same ASCOS case study. Here we use 50% microline, 10% microline (also tested in their study) and further test an even lower value by assuming that only 5% of N_{CCN} act as INPs (Fig. S1); this simulation is referred as 5% microline in this text.

The 50% microline results in improved representation of the available liquid (LWP) and ice (IWP) water path during the first 12 hours compared to the observations, but eventually the cloud glaciates at the end of the simulation (Fig. S1a,b). LWP and IWP are more similar between 5% and 10% microline, with the latter producing somewhat larger (smaller) IWP (LWP). Droplet concentrations are also more similar in these two simulations (Figure S1c), while distinct differences are found in ICNCs (Fig. S1d). Maximum ICNC increases as minimum mean in-cloud temperature decreases from -10.4^{o}C, after spin-up, to -12.4^{o}C at the end of the simulation (not shown), owing to cloud-top radiative cooling. Within this period, the corresponding maximum total ICNC increases from 0.8 to 2.7 L^{-1} in 10% microline and from 0.3 to 1 L^{-1} in 5% microline. In 50% microline total ICNCs increase from 4 L^{-1} to 12 L^{-1} at hour 19, after which the cloud begins gradually dissipating(Fig. S1d). This behavior is in agreement with Lowe et al. (2018), whom also showed that ICNCs exceeding 10 L^{-1} result in cloud glaciation. Total ICNCs in all simulations consist mainly of graupel, along with low concentrations of cloud ice; snow is produced only in 50% microline towards the end of the simulatied period, once cloud dissipation begins.

Wex et al. (2019) recently presented a synthesis of long-term INP measurements from several Arctic sites and published literature; all these measurements indicate that INPs do not exceed 0.2-0.7 L^{-1} at temperatures between -10^{o}C and -12.5^{o}C (see Figure 7 in Wex et al 2019). These results indicate that assuming 10% and especially 50% microline overpredict INP concentrations (Fig. 4a,b). For this reason, we adapt the 5% microline freezing parameterization, which underestimates (overestimates) IWP (LWP), but produces more realistic primary ICNCs (Fig. S1d). While primary ice nucleation is still likely overestimated in our simulations, this approach ensures that underestimates in cloud ice content are not due to underprediction of the INPs.

Section S2: Ice particle concentrations in control and sensitivity simulations

The MIMICA microphysics scheme allows for snow formation only through aggregation of cloud ice particles. However, these are particularly few in the CNTRLDEN and CNTRPLA simulations and thus collisions between them are negligible (Fig. S2a, b). Cloud ice enhancement through ice multiplication promotes cloud-ice aggregation and thus snow formation in all simulations with active break-up Fig. S2e, f). Graupel formation is also enhanced due to more frequent collisions of cloud ice/snow particles with liquid drops; this enhancement is larger in simulations with dendrites (Fig. S2c). Finally, excessive cloud ice production in BRPLA0.4 is followed by excessive graupel and snow formation (Fig S2b,d,f), with total ICNCs reaching a maximum value of 11.8 L^{-1} and glaciating the cloud.

Figures:

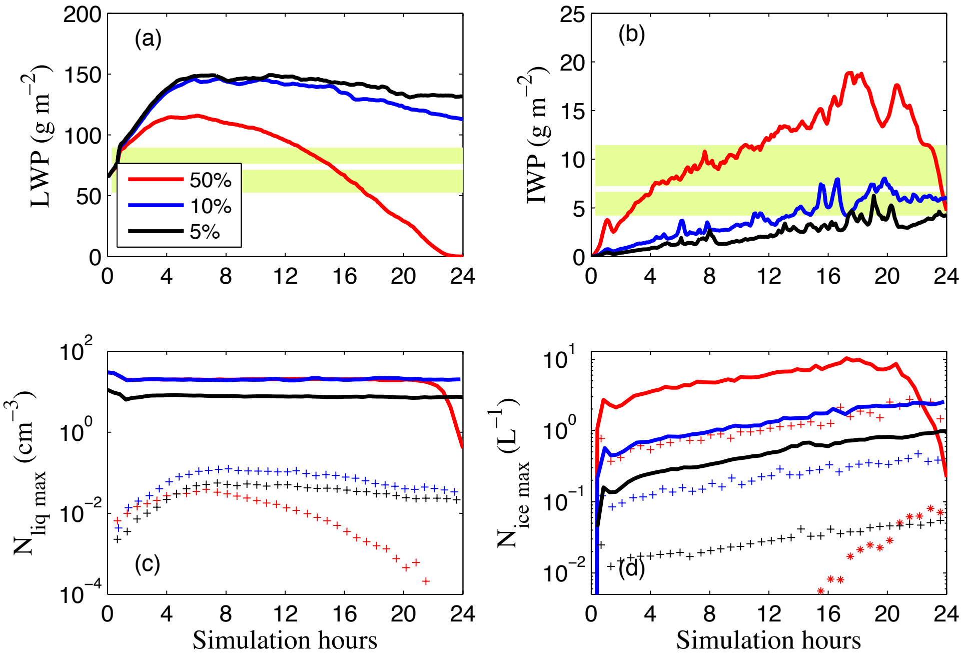

Figure S1: Timeseries of domain-averaged (a) liquid water path (LWP), (b) ice water path (IWP), maximum domain-averaged (c) liquid and (d) ice number concentration for three different immersion freezing settings (see section 3.2.1). Light green shaded area in panels (a) and (b) indicate the interquartile range of observations, while the horizontal white line shows median observed values. Solid lines in panel (c) indicate cloud droplets, while crosses represent raindrops (size > 25 μm). Solid lines in panel (d) indicate graupels, crosses represent cloud ice and dots snow. Secondary ice production is inactive in these simulations. A dendritic ice habit is assumed, which is reasonable for the examined temperature range (Pruppacher and Klett, 1997).

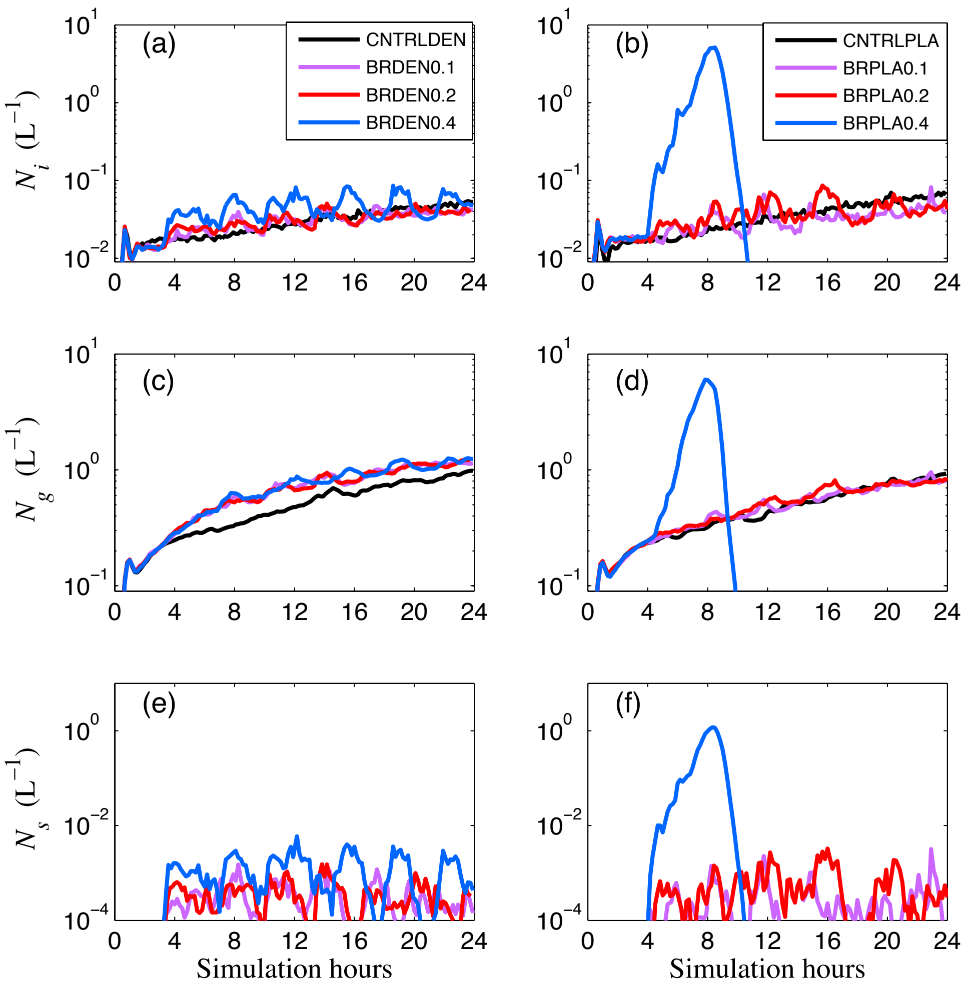

Figure S2: Timeseries of domain-averaged (a, b) cloud ice (*Ni*), (c, d) graupel (N_g) and (e, f) snow (N_s) number concentrations for simulations with dendrites (left column) and plates (right column). Black lines represent simulations that account only for PIP. Purple, red and blue lines represent simulations with active break-up and a prescribed rimed fraction of 0.1, 0.2 and 0.4, respectively, for the cloud ice/snowflakes that undergo break-up. Note the logarithmic y-scale