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Secondary ice production in mixed-phase clouds

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Disparities exist between measured ice-nucleating particle (INP) and ice crystal number concentrations (ICNC) at warmer subzero temperatures, even after correction with shatter-minimizing probe inlets. These discrepancies suggest that mechanisms other than primary nucleation can generate ice within mixed-phase clouds. Here, we take the first steps toward a more comprehensive parameterization of ice formation in mixed-phase clouds by modeling three secondary ice production processes – rime splintering, frozen droplet shattering, and collisional breakup – with a six-hydrometeor-class parcel model. A first round of simulations indicates the importance of representing ice hydrometeor non-sphericity for collision-based secondary production processes. Collision-based non-linearity, along with the 'phasedness' of a process (i.e. whether it involves ice hydrometeors, liquid ones, or both), also manifests in the temporal evolution of ICNC. In a second round of simulations, estimates are made for the INP number that must exist prior to initiation of secondary production. We find an INP threshold up to 0.07 L-1 for collisional breakup, but that a 'thermodynamic sweet spot' with moderate updraft and warm enough cloud base temperature is more influential for frozen droplet shattering and rime splintering. We conclude with an organizational schematic to guide parameterization development, future observational and modeling studies toward a more complete understanding of atmospheric ice formation and cloud glaciation at warm subzero temperatures.