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Another Piece of Evidence for Important but Uncertain Ice Multiplication Processes

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The formation of ice in clouds at temperatures between 0 and −38°C is not well understood, translating to large uncertainties in the effect of cloud ice on precipitation formation and for cloud radiative properties. Atlas et al. (2022) demonstrate that a particularly uncertain ice formation pathway – rime splintering, a so-called secondary ice formation or ice multiplication process during which interactions of ice particles with droplets or with each other lead to more ice – is decisive for clouds over the Southern Ocean. Their study spotlights an Achilles' heel of today's state of the art of model representation of cold cloud microphysics.

Unlike our (low) level of knowledge on secondary ice formation, enormous progress has been made in the past decades regarding the mechanistic understanding of primary ice formation (heterogeneous ice nucleation triggered by suitable aerosol particles) and its quantitative measurement in both the laboratory and the field. Results obtained via different methods have converged, and we have a reasonably good understanding of the sources of INP and their abundance in various parts of the world (Hoose & Möhler, 2012; Kanji et al., 2017). Central for this development were international instrument and method intercomparison campaigns (e.g., DeMott et al., 2018).

But evidence suggests that primary ice formation is not sufficient to explain all cloud ice. In-situ field observations find number concentrations of ice particles to exceed the concentration of ice nucleating aerosol particles by orders of magnitude in many cases, which is taken as evidence of ice multiplication in various regions and mixed-phase cloud types. A number of different mechanisms has been proposed (see the recent review by Korolev & Leisner, 2020), but the in-situ observation of the underlying processes is difficult, perhaps impossible. These include the rime splintering process (also Hallett-Mossop process, Hallett & Mossop, 1974), droplet shattering upon freezing, collisional breakup of ice particles and several more. Some indications on dominant processes in certain situation can be derived from indirect evidence, such as the temperature ranges of the observed ice enhancement or the correlation with large droplet sizes (Coopman et al., 2021; Lasher-Trapp et al., 2016; Luke et al., 2021). In contrast to primary ice formation, there are relatively few recent efforts to study ice multiplication in the laboratory. Some of the key experiments are decades old and have not been re-examined with modern instruments capable of a more precise characterization of the conditions and a better quantification of the newly produced ice particles. Thus, the parameterizations derived from them bear very large uncertainties.

Despite the shaky empirical foundation of secondary ice parameterizations, cloud resolving and parcel model studies have succeeded in constraining ice multiplication and eliminating candidate processes for individual case studies. It has to be noted that results always depend on the case characteristics: cloud top temperature and temperature in the layer of interest, amount and size distribution of liquid and ice hydrometeors, habit of ice hydrometeors, concentration of ice nucleating aerosol particles, updraft velocities, supersaturation with respect to liquid water, and possibly other dynamical, thermodynamical and microphysical properties all have an impact on the strength of simulated ice multiplication. Cloud resolving models represent some but not all of these characteristics quite accurately, while still requiring a simplified representation of particle-to-particle variability (which is a common weakness of bulk schemes). The rime splintering process was found to have an impact on convective clouds, both marine and continental, as the presence of graupel is a prerequisite (e.g., Connolly et al., 2006; Huang et al., 2017). In general, the reported impact is stronger in shallow cumulus than in deep convective clouds which reach homogeneous freezing levels. In combination with collisional breakup, rime splintering also was found to contribute significantly to ice number concentrations in Arctic and coastal Antarctic stratocumulus clouds (Sotiropoulou et al., 2020, 2021; Young et al., 2019). Collisional breakup was also proposed for orographic clouds in combination with seeding from above (Georgakaki et al., 2022). Droplet shattering has been suggested to contribute to glaciation of tropical marine shallow cumulus with relatively warm cloud top temperatures (Lawson et al., 2015).

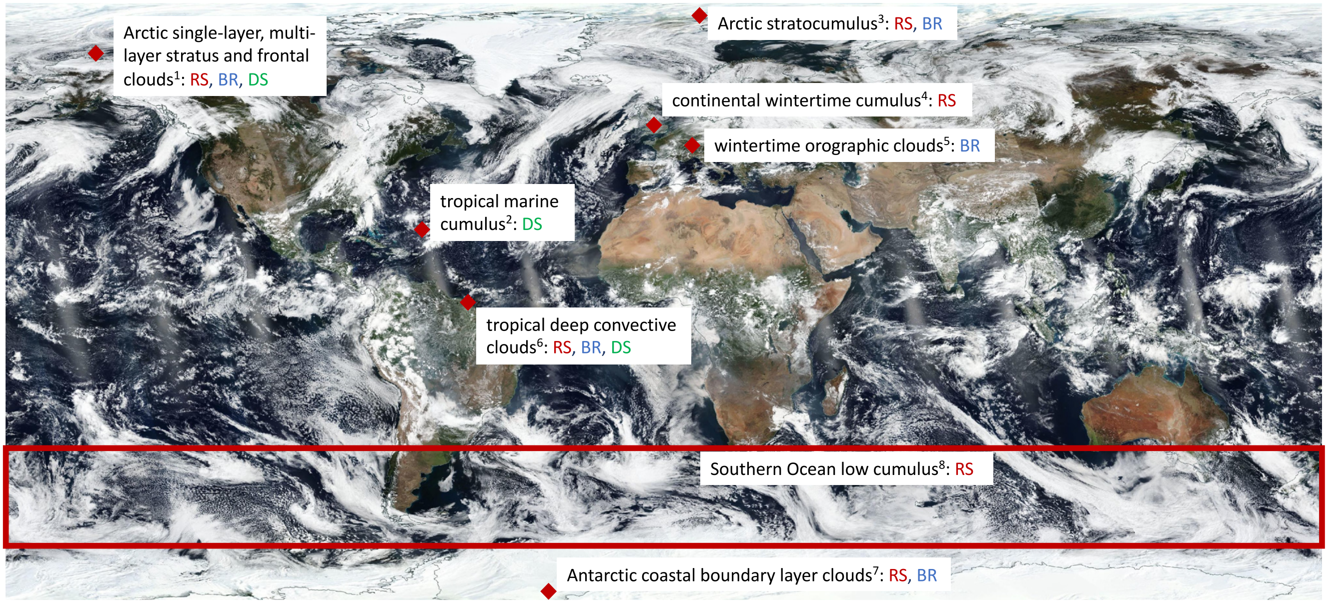

Figure 1. Locations, cloud types and dominating secondary ice mechanisms in recent cloud modeling studies. RS: Rime splintering, BR: Breakup after ice-ice collisions, DS: Droplet shattering upon freezing. Background image: SUOMI NPP/VIIRS Corrected Reflectance (True Color) composite for 21 Sept 2021 (NASA Worldview, 2022). References: Zhao et al. (2021)[1]; Lawson et al. (2015)[2]; Sotiropoulou et al. (2020)[3]; Huang et al. (2017)[4]; Georgakaki et al. (2022)[5]; Sotiropoulou et al. (2021)[6]; Atlas et al. (2022)[7]. The red box encompasses the area in which Atlas et al. (2022) found a strong effect of rime splintering on the cloud radiative effect.

However, the picture of typical ice multiplication processes associated with regions and cloud types (Figure 1) is still incomplete, and is biased toward the rime splintering process, which is the most frequently implemented ice multiplication process – often the only ice multiplication process included in standard configurations of models (Field et al., 2017). Furthermore, previous studies focusing on just one or few cloud events are difficult to extrapolate. The analysis of global storm resolving simulations by Atlas et al. (2022) provide a view of a wide variety of clouds and excellent statistics on a large number of individual clouds captured in the model. The grid scale of their model allows a direct comparison to both in-situ and satellite observations. They find that low cumulus clouds over the Southern Oceans are very sensitive to the implementation of the rime splintering process, while low stratus clouds and high clouds in the same region do not react systematically. The impact on the simulated cloud radiative effect is large, and the activation of the rime splintering processes reduces the bias compared to observations.

In addition, the study of Atlas et al. (2022) highlights the problems associated with presently used parameterizations of the rime splintering process, and why we should worry about them. Due to a lack of physical understanding, important parameters, like threshold values for the onset of the process, and the rate of splinters per mass of rime, are not well constrained. Furthermore, other ice multiplication processes are completely neglected in all standard cloud schemes, although increasing evidence points at their relevance in other cloud types or even in conjunction with the rime splintering process. Large-domain storm resolving simulations (like the work of Atlas et al., 2022) combine the advantages of consistent representations of cloud dynamics and microphysics with comparability to in-situ and remote sensing observations. However, at present the development of cloud microphysical parameterizations is ahead of fundamental experimental (and also theoretical) studies on secondary ice formation. A concerted effort of the cloud physics community, similar to the work on primary ice formation in the past two decades, is needed to reduce the associated uncertainties.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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