Buffering of Ice Crystal Number Concentration to Ice Nucleus Abundance Above Arctic Stratus

Research Highlight

Observations of long-lived mixed-phase Arctic boundary-layer clouds on 7 May 1998 during the FIRE-ACE/SHEBA campaign provide a unique opportunity to test understanding of cloud ice formation. Under the microphysically simple conditions observed (apparently negligible ice aggregation, sublimation, and multiplication) at cloud-top temperatures of -20°C, well above the homogeneous freezing temperature (where cloud droplets freeze spontaneously), the only expected source of new ice crystals is activation of heterogeneous ice nuclei (IN, which are rare aerosol particles that can induce droplet freezing), and the only sink of ice crystals is sedimentation onto the surface.

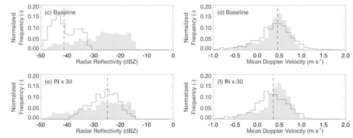
Detailed three-dimensional computer simulations with size-resolved cloud particle distributions are initialized with IN number concentration measured above cloud top, but details of ice formation from observed IN are unknown. If IN form ice crystals rapidly (in so-called deposition, condensation, or immersion modes), as commonly assumed, IN are depleted by turning into ice crystals within minutes. Subsequently, pseudo-equilibrium ice number concentration is then limited to a small fraction of the overlying IN concentration. However, in order to reproduce observed ice crystal size distributions and cloud-radar reflectivities (see Figure 1) with rapidly consumed IN in this case, the IN concentration measured above-cloud must be multiplied by ~30, indicating a gap in understanding the source of ice crystals in this case, as in most past cases.

Based on a combination of observed conditions and detailed process simulations, we develop a simple mixed-layer model to describe the evolution of ice number concentration within the boundary layer (which is found in observations and simulations to be roughly constant with height). The steady-state solution to the simple model reveals that the ratio between the number concentration of ice crystals to that of the overlying IN is given by the cloud-top entrainment rate (w) divided by the number-weighted ice fall speed at the surface (v). This ratio (w/v) is much smaller than unity, since $w < 1$ cm/s and $v > 10$ cm/s. Such conditions are expected to be common for this cloud type, since stratus clouds cannot persist with much greater entrainment rates, and ice crystals do not fall much more slowly. This result has implications for modeling IN diagnostically (a typical treatment in models, where the sources and sinks of IN are ignored), interpreting measurements, and quantifying sensitivity to increasing IN concentrations. A ratio of w/v less than unity implies that entrainment rate limitations serve to buffer the response of such clouds to increases in IN concentrations. For this case, it takes an increase of nearly 200 IN per liter aloft to increase the ice number concentration by 1 per liter.

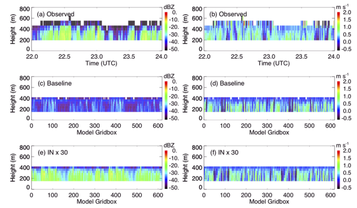
The characteristic time scale of ice number concentrations, which is the e-folding time to approach equilibrium, is found from the simple model to correspond to the time it takes an ice crystal to fall through the boundary layer at the number-weighted fall-speed. This time scale is about 20 minutes for this case.

However, it must be noted that results are sensitive to the assumed properties of the individual ice crystals such as mass and shape, which are not constrained by the available measurements. We argue that single-particle measurements of ice crystal masses and fall speeds are needed to better constrain such studies. In addition, we note that our detailed simulations do not reproduce the pronounced mesoscale heterogeneity in radar reflectivity that is observed (see Figure 2), a discrepancy we leave for future work.

Reference(s)



Observed and simulated histograms of MMCR radar reflectivity (left) and mean Doppler velocity (right) below cloud base. Shaded areas are observations from 2200–2400 UTC, 7 May 1998. Top panels are from simulations with observed IN concentrations above the cloud layer; bottom panels are from simulations with ~30 times the observed IN concentration aloft.



MMCR radar reflectivities and Doppler velocities from observations obtained 2200–2400 UTC, 7 May 1998 (top), from simulations with observed IN concentrations above the cloud layer (middle), and from simulations with ~30 times the observed IN concentration aloft.

Fridlind AM, B van Diedenhoven, AS Ackerman, A Avramov, A Mrowiec, H Morrison, P Zuidema, and MD Shupe. 2012. "A FIRE-ACE/SHEBA case study of mixed-phase Arctic boundary-layer clouds: Entrainment rate limitations on rapid primary ice nucleation processes." Journal of the Atmospheric Sciences, 69(1), doi:10.1175/JAS-D-11-052.1.

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Cloud-Aerosol-Precipitation Interactions