Using Field Measurements and Numerical Simulations to Constrain Mechanisms of Ice Formation During the Mixed-Phase Arctic Cloud Experiment Intensive Operational Period

A. Fridlind and A. Ackerman
National Aeronautics and Space Administration – Goddard Institute for Space Studies
New York, New York

Introduction

Mechanisms of ice formation in supercooled clouds that are too warm to allow the homogeneous nucleation of water remain poorly constrained by measurements (e.g., Cotton and Field 2002). Ice mass and number concentrations have long been thought to exceed what can be quantitatively explained by simultaneous measurements of ice nuclei (e.g., Koenig 1963; Beard 1992). In late 2004 at the Atmospheric Radiation Measurement program's North Slope of Alaska site, the Mixed-Phase Arctic Cloud Experiment (M-PACE) Intensive Operation Period revisited this problem with state-of-the-art instrumentation on aircraft, ground, and satellite platforms. Here we use ground and aircraft data to constrain numerical simulations of the October 9–10 single-layer mixed-phase boundary layer cloud case. The simulations are carried out with a large-eddy simulation code (Stevens and Bretherton 1996; Kirkpatrick et al. 2006) with size-resolved microphysics (aerosols, liquid, and ice) (Jensen et al. 1998; Ackerman et al. 1995) and two-stream radiative transfer at 44 wavelength bands (Toon et al. 1989). We focus specifically on understanding the phase, mass, and number size distribution measurements that were quality-controlled by the McFarquhar research group in order to evaluate various hypotheses for ice enhancement under the M-PACE conditions. We note that it is especially difficult to evaluate ice number owing to the difficulty of identifying the phase of small particles and eliminating instrumental uncertainties associated with aircraft measurements. Cloud particle images indicating small ice crystals that resemble laboratory specimens (e.g., Bacon et al. 2003), for instance, may be artifacts of large particle shattering on inlets. Mass measurements are also subject to difficult uncertainties associated with particle size distribution (e.g., Korolev et al. 2004). Our goal here is to take all available measurements provided to us this time and quantitatively evaluate consistent microphysical explanations for them.

Results

All simulations were initialized with the specifications developed by the Cloud Modeling and Parameterization Working Group (science.arm.gov/workinggroup/cpm/scm/scmic5) for "Case B." In order to more carefully evaluate ice nucleation, we added prognostic ice nuclei (IN) to the model in the following manner. In each grid box, they were initialized to the background observed value of approximately 0.2/L. They were then assigned uniformly to an array of least easily to most easily nucleated and were assumed to be equally available in all four primary modes (Table 1). When conditions were met to consume available IN of particular nucleability in a particular mode, IN were removed from the array and produced a concomitant number of ice, either from the aerosol or drop populations. Remaining IN were then advected and transported as passive tracers for availability in subsequent time steps. Multiplication via the rime-splintering and drop shattering mechanisms (Pruppacher and Klett 1997) was also included in the model, although neither made a significant contribution to ice number or mass. Drop shattering was accounted for in the following manner: whenever drops larger than 50 μm in diameter froze by either contact nucleation or coalescence with ice, a small fraction were assumed to freeze in a manner that produced a total multiplication factor of 2, which was assumed to be an upper limit estimate of the drop shattering effect.

Table 1. Ice formation mechanisms represented in all simulations (primary modes and multiplication) and in sensitivity tests (other mechanisms).

Mechanism	**T, C**	**S**	**Description**
Primary modes			
Contact	–4 to –14	—	drop + IN(aerosol) → ice
Condensation	–8 to –22	> Sw	IN(aerosol) → ice
Deposition	< –10	> Si	IN(aerosol) → ice
Immersion	–10 to –24	—	drop + IN(drop) → ice
Multiplication			
Rime-splinter	–3 to –8	—	250 collisions → ice
Drop shattering	< 0		freezing drop → ice
Other mechanisms			
Evaporation nuclei	< 0	> Sw	evaporated drop → IN(aerosol)
Evaporation freezing	< 0	> Sw	evaporating drop freezes
Ice preactivation	< 0	> Si	evaporated ice → IN(aerosol)

In the base case simulation (including the primary nucleation modes and multiplication mechanisms listed in Table 1), almost no ice was formed (Figure 1a versus 1b). However, we were able to better match observations if one in 10,000 evaporating drops produced an ice nucleus (Rosinski and Morgan 1991) (Figure 1a versus 1c), or if evaporating drops were assumed to freeze during the evaporation process (Cotton and Field 2002) (Figure 1a versus 1d), or if every ice crystal that evaporated (including secondary ice) yielded an ice nucleus that was "pre-activated" (e.g., Roberts and Hallett 1967) and they were permitted to build up in the boundary layer over a number of hours without any removal processes

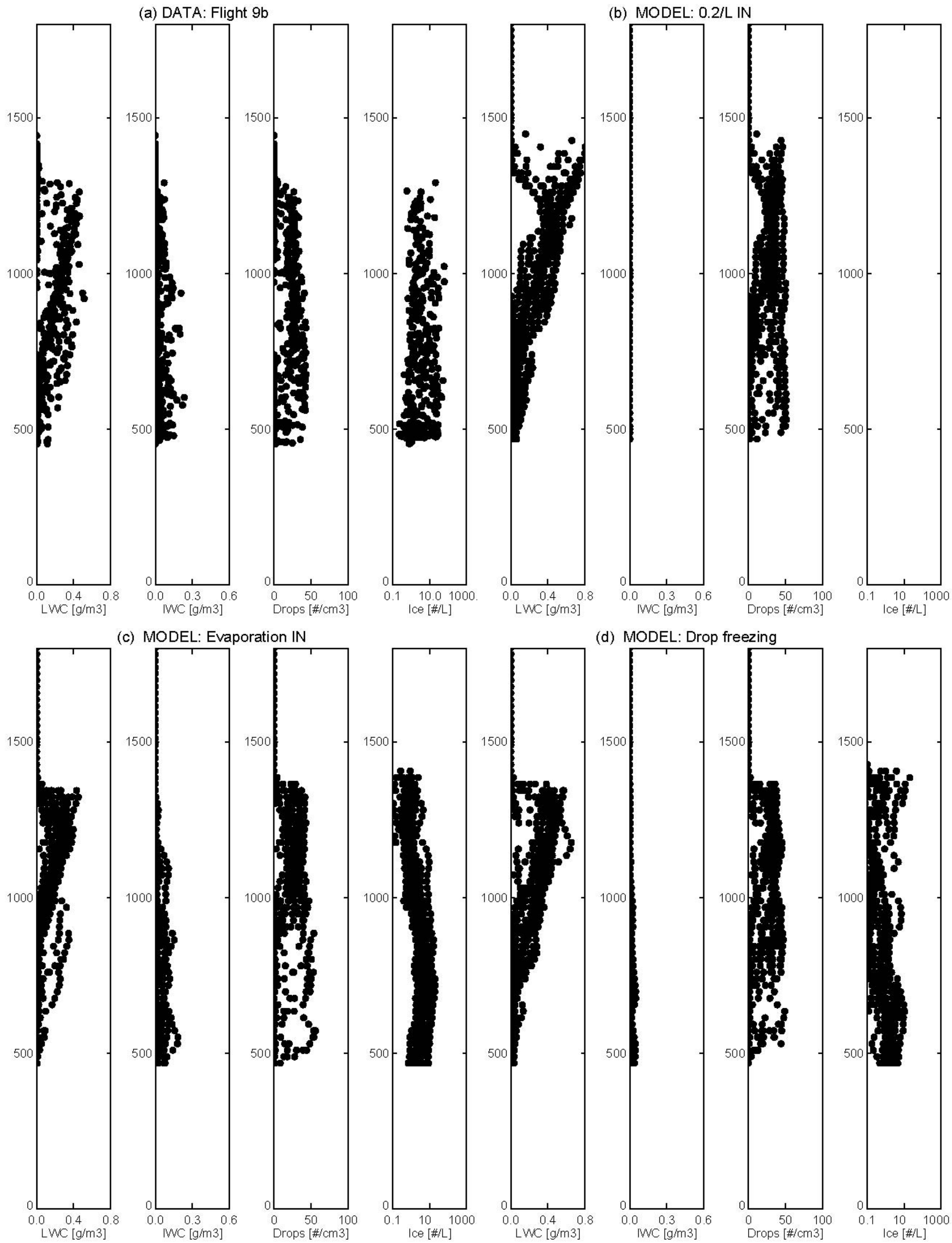

Figure 1. M-PACE data (a) compared with model results with 0.2/L IN (b), evaporation nuclei (c), and drop freezing during evaporation (d).

except activation (not shown here). We also considered the effect of charge-enhancement of evaporation nuclei (Tinsley et al. 2000) that could increase the likelihood of small drops freezing (Tripathi and Harrison 2002), but once phoretic forces were properly calculated during the simulation, these factors did not influence results significantly.

Summary and Discussion

These preliminary results establish our initial conclusions that background ice nuclei probably are not sufficient to sustain observed ice mass and number under mixed-phase conditions at low drop number concentrations, as has been noted by previous authors (Rangno and Hobbs 2001). We have identified three possible microphysical mechanisms that may operate to explain the observations, providing additional ice mass and number. Future work will be focused on evaluating differences between the simulations with these three mechanisms, in collaboration with Greg McFarquhar and Gong Zhang.

Acknowledgments

This preliminary work is based on data supplied by Hans Verlinde, Greg McFarquhar, Andrew Heymsfield, Michael Poellot, Anthony Prenni, and Paul DeMott. We also relied upon analyses supplied by Shaocheng Xie, Stephen Klein, and Hugh Morrison, as well as the satellite and flight track images supplied by Patrick Minnis. We take responsibility for any errors appearing here. Any submissions to peer-reviewed publications will offer authorship to all those who supplied M-PACE data used in our analysis.

References

Ackerman, AS, OB Toon, and PV Hobbs. 1995. “A model for particle microphysics, turbulent mixing, and radiative transfer in the stratocumulus-topped marine boundary layer and comparisons with measurements.” *Journal of Atmospheric Science* 52:1204–1236.

Bacon, NJ, MB Baker, and BD Swanson. 2003. “Initial stages in the morphological evolution of vapour-grown ice crystals: A laboratory investigation.” *Quarterly Journal of the Royal Meteorological Society* 129:1903–1927.

Beard, KV. 1992. “Ice initiation in warm-base convective clouds: An assessment of microphysical mechanisms.” *Atmospheric Research* 28:125-152.

Cotton, RJ, and PR Field. 2002. “Ice nucleation characteristics of an isolated wave cloud.” *Quarterly Journal of the Royal Meteorological Society* 128:2417–2437.

Hobbs, PV, and AL Rangno. 1985. "Ice particle concentrations in clouds." *Journal of Atmospheric Science* 42:2523-2549.

Jensen, EJ, OB Toon, A Tabazadeh, GW Sachse, BE Anderson, KR Chan, CW Twohy, B Gandrud, SM Aulenbach, A Heymsfield, J Hallett, and B Gary. 1998. "Ice nucleation processes in upper tropospheric wave-clouds observed during SUCCESS." *Geophysical Research Letters* 25:1363–1366.

Kirkpatrick, MP, AS Ackerman, DE Stephens, and NN Mansour. 2006. "On the application of the dynamic Smagorinsky model to large-eddy simulations of the cloud-topped atmospheric boundary layer." *Journal of Atmospheric Science* 63:526–546.

Koenig, LR. 1963. "The glaciating behavior of small cumulonimbus clouds." *Journal of Atmospheric Science* 20:29–47.

Korolev, AV, GA Isaac, SG Cober, JW Strapp, and J Hallett. 2003. "Microphysical characterization of mixed-phase clouds." *Quarterly Journal of the Royal Meteorological Society* 129:39–65.

Pruppacher, HR, and JD Klett. 1997. Microphysics of Clouds and Precipitation, Kluwer Academic Publishers.

Rangno, AL, and PV Hobbs. 2001. "Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations." *Journal of Geophysical Research* 106:15,065–15,075.

Rosinski, J, and G Morgan. 1991. "Cloud condensation nuclei as a source of ice-forming nuclei in clouds." *Journal of Aerosol Science* 2:123-133.

Stevens, DE, and CS Bretherton. 1996. "A forward-in-time advection scheme and adaptive multilevel flow solver for nearly incompressible atmospheric flow." *Journal of Computational Physics* 129:284–295.

Tinsley, BA, RP Rohrbaugh, M Hei, and KV Beard. 2000. "Effects of image charges on the scavenging of aerosol particles by cloud droplets and on droplet charging and possible ice nucleation processes." *Journal of Atmospheric Science* 57:2118–2134.

Toon, OB, CP McKay, TP Ackerman, and K Santhaman. 1989. "Rapid calculation of radiative heating and photodissociation rates in inhomogeneous multiple scattering atmospheres." *Journal of Geophysical Research* 94:16,287–16,301.

Tripathi, SN, and RG Harrison. 2002. "Enhancement of contact nucleation by scavenging of charged aerosol particles." *Atmospheric Research* 62:57–70.