# Difficulties in simulating ice initiation in Arctic stratus

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## Case Study Description

The System for Atmospheric Modeling (SAM v 6.8.2) is used to model a **low-level, mixed-phase cloud** encountered over the North Slope of Alaska on 8 April 2008 during Flight 16 of the Indirect and Semi-Direct Aerosol Campaign (ISDAC). A particular focus of this work is examining the impact of available ice nucleating particles on cloud phase and lifetime.

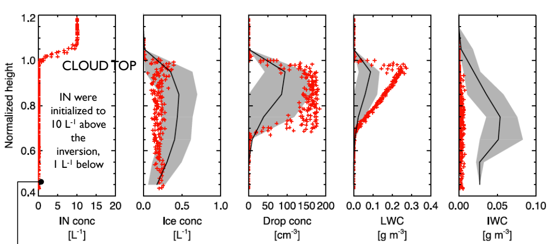
We present results from two approaches for representing ice nuclei:

(1) A **diagnostic** treatment of cloud particle precursors, in which we initialize CCN and IN concentrations using available observations and the aerosol-linked ice nuclei parameterization presented in DeMott et al. (2010). The CCN and IN are activated to cloud drops and ice crystals, respectively, according to local conditions, but the aerosol fields remain fixed throughout the duration of the simulation.

(2) A new **prognostic** treatment of IN, in which we implement losses of IN through activation to ice crystals, and allow for regeneration of IN from the sublimation of hydrometeors (pristine ice, snow, and graupel). The CCN population is held fixed, as in approach (1).

For computational efficiency required to embed SAM+aerosol in a global model, we run SAM in its two-dimensional mode, and use a two-moment (mass and number concentration) bulk microphysics model (Morrison et al., 2008).

The same ISDAC case was simulated in three dimensions by Avramov et al. (2012), using the DHARMA model coupled to a size-resolved bin microphysics model. The IN were depleted via nucleation scavenging, but not regenerated upon hydrometeor evaporation. We initialized SAM with the identical vertical profiles, surface fluxes, and large-scale forcing used by Avramov et al., and show below a portion of their Figure 10, in which their model results (red symbols, last 3 hours of the 6-hour simulation) are compared with observations (solid line is horizontal average, shading represents 15th – 85th percentile range).




IN depleted rapidly within modeled boundary layer; entrainment from above is main (slow) replenishment

Liquid cloud depth ~300 m (top of cloud)

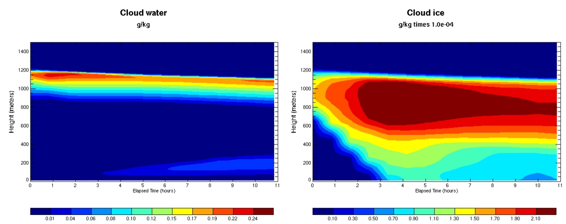
Ice concentrations ~0.4 $L^{-1}$ from near top through ~200 m below liquid cloud

IWC depends on assumed densities; impacts explored in Avramov et al.

## Approach 1: Constant Aerosol

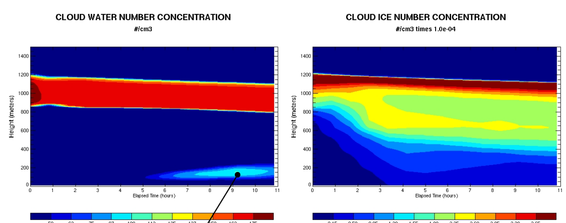
In this simulation with SAM, the IN are computed from observed aerosol size distributions. We apply constant aerosol number concentrations with height, in contrast to the assumed profile used in Avramov et al. (see figure in left panel). When implemented in the DeMott et al. equation at typical cloud top temperatures, IN concentrations of ~ 0.58 $L^{-1}$ are predicted, in good agreement with observations; concentrations of active IN are lower at warmer temperatures in the domain.

In SAM, the cloud initialized in this manner forms very rapidly (as also observed by Avramov et al.), with a ~300 m deep, persistent liquid layer. After ~3 hours spin-up time, LWC are slightly higher than the observations of ~0.1 g $m^{-3}$. The ice phase exists through cloud depth and extends several hundred meters below the liquid phase, similar to the observations, with some ice apparently precipitating to the surface. Peak IWCs of ~ 0.2 g $m^{-3}$, located ~300 m below cloud top, are much larger than observed but occur at similar altitudes.




Cloud drop number concentrations are controlled by the (constant) available CCN, and are ~170 $cm^{-3}$, at the high end of the observed range. The simulated cloud ice number concentrations after 3 hours are ~0.37 $L^{-1}$ near cloud top, and ~0.2 $L^{-1}$ through most of the depth of the ice cloud. Agreement with observed number concentrations is very good.

**Conclusions**: Using observed aerosol number concentrations to initialize (fixed) CCN and IN concentrations produces a realistic and persistent mixed-phase cloud. However, the aerosol budget is unexplained.

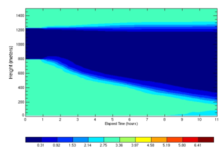



Note the presence of a modeled fog layer near the surface, which was not reported in the observations. The fog is partly a response to the initial thermodynamic profiles. In the initializations for Approach 2 runs, we dry the boundary layer completely from 0-200 m.

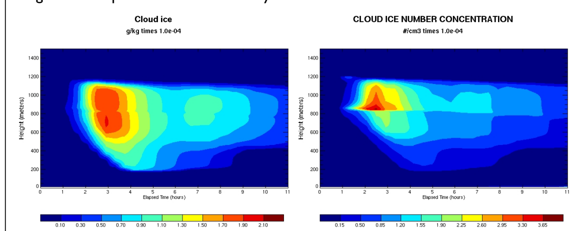
## Approach 2: Ice Nuclei Budgets

To implement a budget for IN, we compute the maximum IN concentration at cloud top (coldest temperature) using the same inputs and parameterization as in Approach 1. These concentrations are used to initialize a tracer variable, initially constant with height throughout the domain, that is depleted when ice crystals are nucleated according to the DeMott et al. relationship. We find that IN are rapidly activated and depleted early in the simulation, resulting in collapse of the cloud; slow replenishment rates due to cloud top entrainment cannot re-establish the cloud within a 12-hr run. Therefore, all subsequent runs are conducted with a constant initial IN profile above and below the cloud layer, but zeroed through the cloud depth. Freezing occurs in response to slow inputs of IN that are entrained into cloud from above and below.

Evolution of modeled IN concentrations ($L^{-1}$) as cloud develops. The model is initialized with no IN in the cloud layer (800-1200 m). Above and below this layer, maximum initial IN concentrations of 2.91 $L^{-1}$ are implemented, a 5x increase from the diagnostic runs but within observed values. As cloud motions develop, IN are mixed in from above and below cloud, as can be seen in the gradients at cloud top and base.

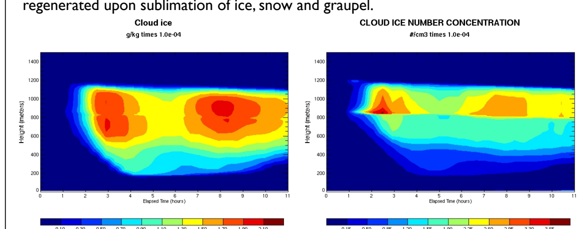


In the first simulations, IN are depleted when activated to ice crystals, but are not regenerated upon sublimation of ice hydrometeors.




Cloud ice forms later than in Approach 1, but with with similar peak IWCs. After ~6 hours of simulation, steady IWCs ~0.08 g $m^{-3}$ are predicted, similar to observations. The ice number concentration vertical profile is quite different from Approach 1: peak concentrations occur about 300 m below cloud top rather than at cloud top, in better agreement with the observations. Steady concentrations of ~0.1 $L^{-1}$ are lower than observed.

In the second simulations, IN are depleted when activated to ice crystals, and are regenerated upon sublimation of ice, snow and graupel.




**Conclusions**: Replenishment of the IN pool via sublimation of ice hydrometeors appears to be an important mechanism for extending cloud lifetime. Resulting cloud simulates observed ~3 h "pulses" in cloud depth.

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**References: Avramov et al.**, 2011, *J. Geophys. Res.*, doi:10.1029/2011JD015910; **DeMott et al.**, 2010, *Proc. Nat. Acad. Sci.* 107: 11217-11222; **Morrison et al.**, 2008, *J. Climate* 21: 3642-3659.