Factors Controlling the Properties of Multi-Phase Arctic Stratocumulus Clouds

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Introduction

The October 2004 Multi-Phase Arctic Cloud Experiment (M-PACE) Intensive Operational Period (IOP) at the Atmospheric Radiation Measurement (ARM) Climate Research Facility's (ACRF's) North Slope of Alaska (NSA) locale focused on measuring the properties of autumn transition-season arctic stratus and the environmental conditions controlling them, including concentrations of heterogeneous ice nuclei. Our work aims to use a large-eddy simulation (LES) code with embedded size-resolved cloud microphysics to identify factors controlling cloud glaciation. Our preliminary simulations of autumn transition-season stratus observed during the 1994 Beaufort and Arctic Seas Experiment (BASE) indicate that even low concentrations of ice nuclei (which were not measured during that campaign) may have significantly lowered liquid water content, indicating an active Bergeron process with little effect of collection on drop number concentration. The sensitivity of cloud properties to uncertainty in other factors, such as large-scale forcings and aerosol profiles, during both BASE and M-PACE will be investigated. Based on the LES simulations with M-PACE data, preliminary results from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) single-column model (SCM) will be used to examine the sensitivity of predicted cloud properties to changing cloud drop number concentrations for multi-phase arctic clouds. Current parameterizations assumed fixed cloud droplet number concentrations and these will be modified using M-PACE data. Here, we summarize preliminary results from the first phase of this work: large-eddy simulations of multi-phase arctic boundary layer clouds during the M-PACE IOP, as well as the BASE, for comparison.

Model Description

The dynamics for all simulations are treated with a three-dimensional (3D) LES fluid dynamics code (Stevens and Bretherton 1996), using periodic boundary conditions, a stretched vertical grid (minimum dz = 5-10 m, maximum dz = 40-50 m), uniform horizontal grid (dx = 65-130 m), and a dynamic Smagorinsky subgrid-scale model. Surface fluxes are estimated from surface conditions using similarity theory. Embedded within the LES, our microphysics code (Ackerman et al. 1995; Jensen et al. 1998; Fridlind et al. 2004) includes 20 size bins for liquid and ice. Processes include drop activation, homogeneous aerosol and drop freezing, condensation and deposition, evaporation and sublimation, particle sedimentation and gravitational collection, diagnostic aerosol, and two-stream radiative transfer in 44 wavelength bands (Toon et al. 1989). Additions for this work include prognostic ice nuclei (10 bins), decoupled from the aerosol and cloud particle size distributions by assuming that immersion and deposition/condensation ice nuclei are uniformly distributed among the aerosols and cloud particles in each size bin. Contact nuclei have been neglected in these initial simulations.

Case Studies

Before to attending the M-PACE IOP, we studied a case chosen from the only previous aircraft-based experiment during the Arctic fall season, October 25, 1994, during the BASE) (Pinto 1998; Jiang et al. 2000). We plan to consider future runs with springtime data from other experiments (for which ice nuclei have sometimes been measured), but we initially chose a BASE case study for comparison with M-PACE since autumn Arctic aerosol concentrations are at seasonally low values compared with springtime peak values. From the M-PACE IOP data, we initially chose a case study from October 9.

Aircraft observations (Figure 1) reflect the significantly different meteorological conditions dominating the two cases. Whereas the BASE cloud layer formed over pack ice under a strong inversion, the M-PACE cloud layer formed over open ocean under a weak inversion (the layer was deepening rapidly with downwind location during the flight legs, perhaps affected by factors such as geographical coastline features). Whereas the BASE case was driven by cloud top cooling and relatively weak advection, the M-PACE case was driven by surface heat and moisture fluxes and advection so strong that roll features formed in the cloud layer. Liquid water content and drop concentration reflect these factors, as well as perhaps cloud-top temperature (colder during BASE) and degree of glaciation (higher during BASE). Whereas ice nuclei were not measured during BASE, deposition/condensation ice nuclei numbers during M-PACE appear to have exceeded ice crystal numbers significantly. It is possible that ice nuclei acting in other modes accounted for the observed ice, that other freezing or multiplication mechanisms were active, or that experimental uncertainties in the ice crystal number concentrations could account for the discrepancy. We plan to investigate each of these possibilities.

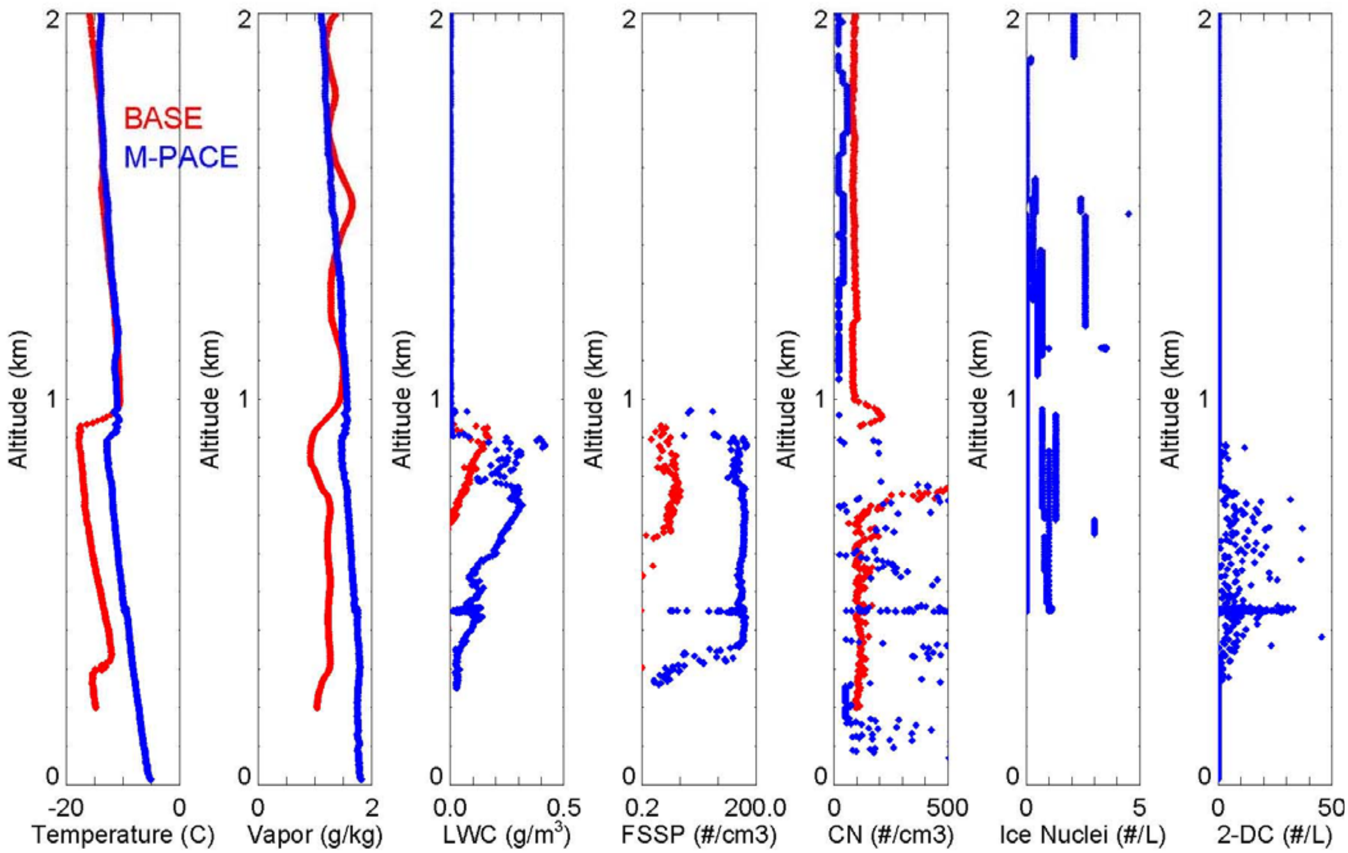

Figure 1. Observed profiles of temperature, water vapor, liquid water content, droplet number concentration (as measured by a forward-scattering spectrometer probe), ice nuclei (immersion/condensation mode, as measured by the counter-flow diffusion chamber instrument), and ice crystal number concentration (as measured by a two-dimensional cloud [2DC] probe). Ice nuclei were not available from the descent chosen during M-PACE, so all values from the flight are shown.

Preliminary Results

Preliminary results indicate that we can obtain a stable cloud layer with realistic liquid water content during BASE. However, if we initialize ice nuclei concentrations to the low autumn values typical of M-PACE conditions, and we allow them to be consumed as precipitation removes them from the boundary layer, then we are not able to sustain ice concentrations near observed values. During M-PACE, we have more difficulty obtaining a stable cloud layer. Under the weak inversion, the cloud layer depth is sensitive to poorly-constrained forcings, such as large-scale advection and subsidence. Since we prescribed a uniform wind (with vertical dimension) and began with a small domain, we also do not capture the large-scale rolls that were present, which likely causes a more active cloud layer than was observed. Despite these inaccuracies, it seems clear that ice nuclei would be consumed quickly by the cloud field during M-PACE, as during BASE. Entrainment, because it is so high during M-PACE, is able to nonetheless sustain ice, but not at the high number concentrations observed (when all ice nuclei modes are assumed to be counted by the continuous-flow diffusion chamber instrument, which is clearly not the case, but we used here as a useful first approximation). A cross section of an M-PACE simulation with approximately a four-fold increase in ice nuclei over the observations typical of October 9 (Figure 2) shows how the ice nuclei become depleted in the cloudy boundary layer.

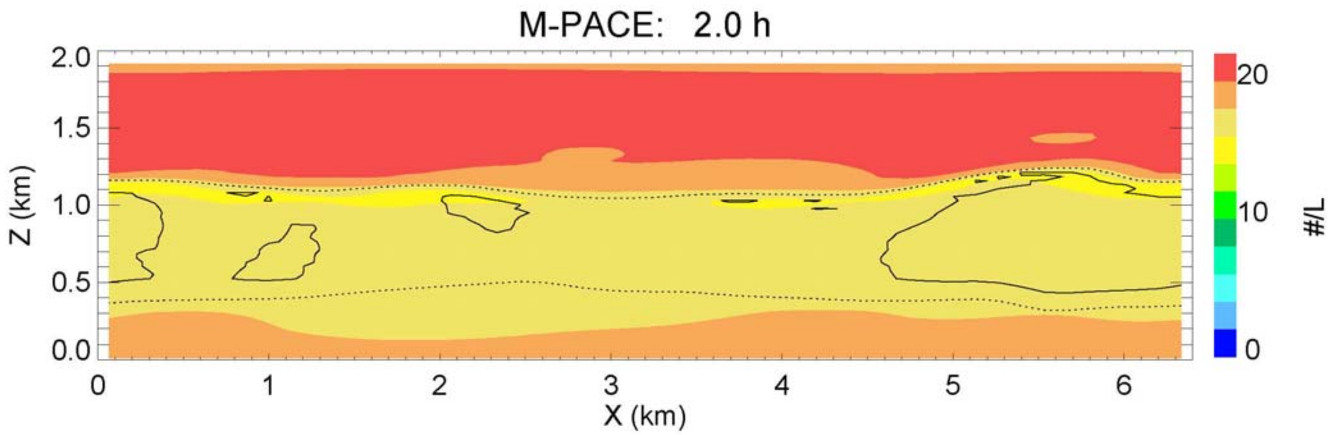

Figure 2. Horizontal cross section of modeled ice nuclei fields for an M-PACE simulation. Ice nuclei are initiated to 20/L throughout the domain (at least a factor of four above observations from October 9, see Figure 1). During the course of the simulation they are consumed in the cloudy boundary layer, as determined by the minimum temperature, peak supersaturation, and entrainment evolution. The dashed black contours indicate regions of supersaturation with respect to ice and the solid black contours indicate supersaturation with respect to liquid water.

Preliminary Results

We plan to focus next on constraining ice crystal fall velocities, which are being derived by Greg McFarquhar, and large-scale forcings. It will be important to capture the roll vortices during M-PACE cases, by adding vertical wind shear and using a larger simulation domain, to properly represent vertical velocities within cloud. Finally, we will analyze the 3D ice/liquid structure (mass, number, and morphology) for clues as to the ice formation and/or multiplication processes that control ice content in the observed cases. What we learn will finally be applied to the GISS GCM parameterizations.

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