3B.12 NUMERICAL SIMULATIONS OF THE SENSITIVITY OF MIXED-PHASE ARCTIC STRATUS TO ICE FORMING NUCLEI

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1 INTRODUCTION

Large eddy simulation (LES) modeling studies of Arctic stratus clouds have revealed that these cloud systems are quite sensitive to rather modest changes in cloud condensation nuclei (CCN) and ice-forming nuclei (IFN) concentrations (Olsson et al. 1998; Harrington et al. 1999; Jiang et al. 2000). Harrington et al. (1999) and Jiang et al. (2000) have shown that an increase by only a factor of three in IFN concentrations, which may occur during episodes of increased pollution, can transform a very dynamically-stable supercooled stratus cloud layer into a broken optically-thin cloud layer.

During the recent SHEBA-FIRE spring field campaign, the airmass was found to be highly polluted in terms of CCN and IFN concentrations above the boundary layer and extremely clean below on several occasions. Jiang et al. (2001) performed large eddy simulations (LES) for one of these cases and showed that substantial entrainment of the CCN into boundary layer clouds can occur with the result that drizzle processes and cloud optical properties were altered. They also showed that IFN concentrations exhibited similar behavior with greatly increased values above the boundary layer. Unfortunately the case was too warm to demonstrate the impact of entrained IFN on the cloudy boundary layer.

In this paper, we describe large-eddy simulations of one of the mixed-phase cases observed on 4 May 1998, and examine the influence of variable IFN concentrations on cloud microphysics, boundary layer structure, and the surface energy budget.

2 MODEL DESCRIPTION AND EXPERIMENTAL SET-UP

The model used in this study is the latest version of the Regional Atmospheric Modeling System (RAMS) originally developed at Colorado State University (CSU), with the single-moment bulk microphysical parameterization of Walko et al. (1995) and a two-stream radiative transfer model (Harrington et al. 1999). The predicted variables include the three velocity components, the Exner function, the ice-liquid water potential temperature, and total water mixing ratio. In the single-moment bulk microphysical framework it is assumed that the hydrometeor size-spectra have a gamma distribution function, and only the mass mixing ratio of the hydrometeor species is predicted. Mixing ratio is predicted for the microphysical categories of rain, pristine ice, snow, aggregates, graupel and hail, and is diagnosed for cloud liquid water. The number concentration of pristine ice crystals is also predicted.

In the latest version of RAMS, prediction of pristine ice number concentration can optionally be influenced by an IFN concentration field. The IFN concentration can be held constant in time or prognosed. Nucleation by deposition condensation freezing with deposition nuclei is given by the conditional, fractional activation of the IFN:

$$N_t = fracifn \times N_{ifn}. \tag{1}$$

This nucleation occurs when the ambient water vapor mixing ratio exceeds saturation over ice and the temperature is below -5 ^{o}C. The fractional activation factor is given by $fracifn = exp(12.96(ss_i - ss_{i0})$, where ss_i is the supersaturation with respect to ice and ss_{i0} is an upper limit of ss_i. This formulation was derived from available measurements with continuous-flow diffusion chambers (Meyers et

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al. 1992). N_t is the total number of nucleated crystals per m^3.

The lateral boundary conditions are cyclic. The model top is a rigid lid. In order to minimize spurious reflection of upward propagating gravity waves, a Rayleigh friction absorbing layer is applied to the momentum equations and thermodynamic equation over the top five levels of the model with a damping timescale $\tau = 200$ s. The bottom boundary is specified to be consistent with surface conditions observed during SHEBA/FIRE, with a specified surface temperature of 257.0 K and surface roughness of 0.05 m.

Simulations are done in a two-dimensional (2-D) framework. The 2-D domain has 72×72 grid points with 50 m grid spacing in the horizontal, and 25 m grid spacing in the vertical from the surface up to 1400 m, thereafter stretched to 100 m near the domain top (2200 m). A time step of 2 s is used in all integrations.

We simulate one of the arctic mixed-phase boundary layer clouds observed on 4 May 1998 during SHEBA/FIRE field experiment. The case is characterized by a well-mixed layer in the lower 1 km with a sharp temperature and humidity inversion above the mixed layer.

The large-scale advective tendencies of potential temperature ($d\theta/dt$) and water vapor (dq/dt) are estimated from ECMWF re-analysis at 31 pressure levels, then vertically-interpolated to the model's grid and imposed throughout the simulation.

3 SIMULATION RESULTS

Special focus in the sensitivity experiments is on the concentration of ice crystals and the ability to deplete liquid water content. The IFN sounding exhibits concentrations ranging from 5 per liter below cloud base to a peak of 100 per liter at the inversion. In the control run, the initial IFN concentration is set to 5 per liter throughout the depth of the boundary layer (hereafter referred to as N5). In the sensitivity run, we initialize the IFN profile with observed data measured with the Colorado State University continuous flow diffusion Ice Nucleus Counter, and then prognose the IFN changes from its initial value due to entrainment and mixing at the cloud top (hereafter referred to as N100). Selective results will be shown in the following due to the space limitation. More results will be shown at the conference and in an upcoming article.

Figure 1 shows the layer averages of IFN concentration (N_{ifn}) at different simulation times for the N100 run. N_{ifn} increases quickly from the initial value (solid line) in the cloud layer, while it stays low below cloud at 60 min (dashed line). Higher values brought in by entrainment and turbulent mixing at the cloud top are continuously mixed throughout the entire boundary layer over the rest of the simulation (dotted line at 180 min).

The time variability of vertically-integrated and horizontally-averaged cloud liquid water path (LWP) and ice water path (IWP; the ice category is defined as pristine ice only) is plotted to examine the microphysical response of the simulated stratus cloud to IFN changes (Figure 2). The LWP (Fig. 2a) in both runs evolves with time in a similar manner: liquid water develops in 10 min and retains a nearly steady LWP value through 120 min, with slightly less LWP in the N100 run. In the N100 run, the LWP decreases rapidly from 120 min and completely disappears by 210 min. In the N5 run, the high LWP is sustained longer, and although it also reduces significantly, it retains a small value to the end of the simulation. In the N5 run, fewer ice crystals compete for the available water vapor, therefore, more water vapor available is converted to liquid water by condensation, resulting in more liquid water in the cloud.

The response of the IWP (Fig. 2b) to the differences in IFN concentration occurs during the rapid decreasing in LWP. In the N100 run, the IWP increases very quickly to its maximum value of 1.3 g m^{-2} at the expense of liquid water, then decreases to 70% of its maximum value by the end of the simulation. The maximum values of IWP in the N100 run are about twice those in the N5 run.

The impact of increased N_{ifn} on ice concentration N_i is shown in Figure 3. Domain-averaged vertical profiles of ice concentration (N_i) at the 120 min of the simulation is plotted for both runs. The maximum concentrations of ice crystals (N_i) in the N100 run is about 30 L^{-1} below the liquid cloud layer, and a much smaller value is present in the liquid cloud layer. The liquid cloud layer is located between 788 m and 938 m, and is not shown for because the difference in liquid water mixing ratio is small. The maximum value of N_i in the N5 run is only about half that in the N100 run. The increase in IFN concentration through entrainment and turbulent mixing results in larger N_i. It should be noted that the total number of ice crystals includes the contribution from other ice nucleation processes.

4 SUMMARY

We have examined how variations in IFN concentration alter the stability and structure of low-level arctic stratus in a two-dimensional cloud-resolving simulation. Data collected on 4 May 1998 during SHEBA/FIRE are used to initialize the model, and subsequently used to test the model results against observations.

Similar as to what we have found for the fall season (Jiang et al. 2000), we have found that during the spring transition season the simulated mixed-phase cloud is very sensitive to the availability of IFN concentration.

Additional simulations of this case with both 2D and 3D LES are being performed, including the prognostic cloud drop number concentration using a predicted CCN concentration. Results will be presented at the conference.

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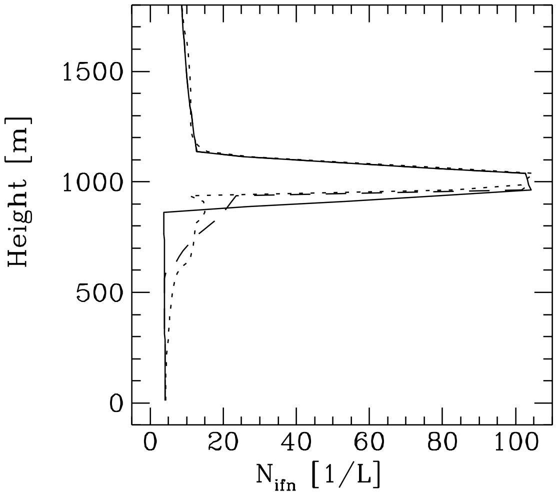

Figure 1: Layer-averaged profile of IFN concentration for the N100 run. The solid line denotes the initial profile, the dashed line denotes the profile at 60 min, and the dotted line denotes the profile at 180 min.

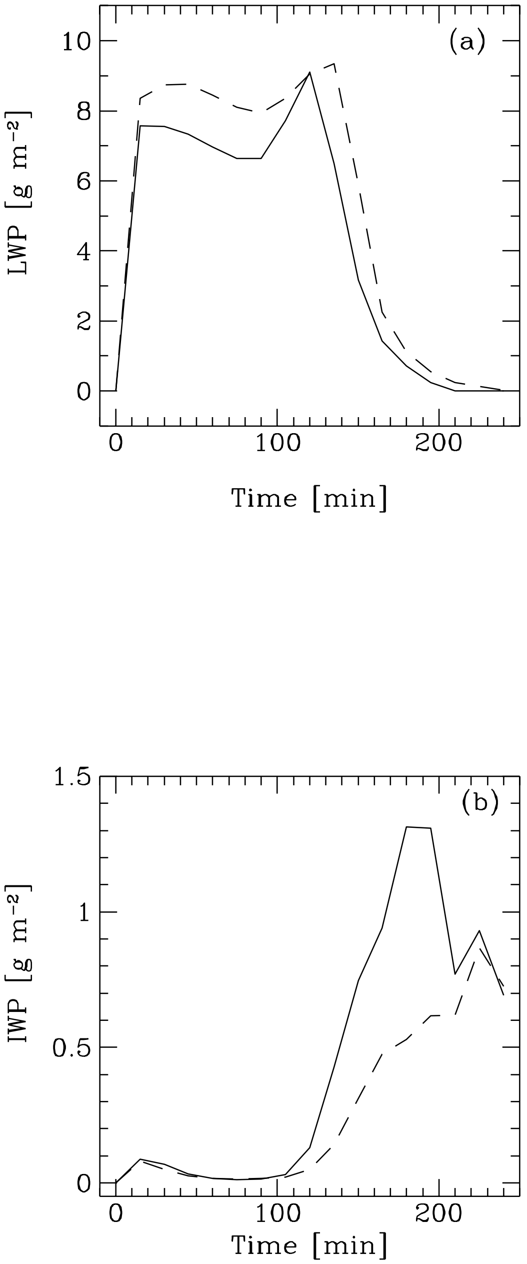

Figure 2: Time variability of (a) LWP and (b) IWP. The solid line denotes the N100 run and the dashed line denotes the N5 run.

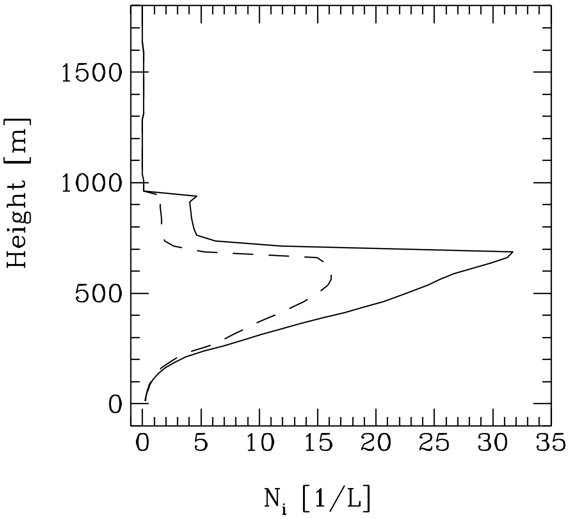

Figure 3: Layer-averaged profile of concentration of ice crystal at 120 min for both the N5 and N100 run. Line types are the same as in Fig. 2