Cloud-Resolving Simulations of Arctic Stratus

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Introduction

Modeling studies of the global climate suggest that the Arctic climate tends to be sensitive to perturbations such as doubling CO_2 concentrations (Walsh and Crane 1992). These modeling studies show a so-called "polar-amplification" effect in the Arctic with simulated warmings of 8-16° C compared with 1.5-4° C at lower latitudes (Houghton et al. 1992). Unfortunately, the skill in modeling high-latitude climates lags behind that of other regions, with at least a part of the uncertainty being due to inadequate representation of Arctic stratus clouds (ASC) and the subsequent cloud/surface radiative interactions (Walsh and Crane 1992). These ASC tend to be persistent and widespread with cloud fractions ranging between 0.7 and 0.9 during the summer, warm-season months (Herman and Goody 1976), with a significant reduction of cloud fraction and persistence during the transition (fall and spring) and cold season (winter).

Since the accurate representation of ASC is important for more accurate simulations of the Arctic climate and the interactions of radiation, microphysics and cloud dynamics are not well understood (Curry et al. 1988), we embark on a set of exploratory cloud-resolving simulations of ASC. We concentrate our efforts on model sensitivity simulations using the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS); warm-season cloud simulations with differing cloud condensation nucleus (CCN) concentrations are performed to examine the radiative and microphysical impact on cloud dynamics, while transition-season cloudiness is examined with a cooled representative sounding.

Model Description and Components

The model used for this study is the RAMS developed at Colorado State University, which Pielke et al. (1992) have described. The model is used in a two-dimensional version of a large-eddy simulation (LES), termed a cloud-resolving model (CRM). The simulation domain has a 3600-m horizontal extent and a height of 2880 m. The horizontal grid-point spacing is fixed at 60 m, while the vertical grid-point spacing varies from 30 m near the surface to 45 m at the top of the model domain.

The microphysical schemes employed for these simulations are bin-resolving. Both the warm microphysical model (drops only) and the ice microphysical model (ice) employ 25 hydrometeor bins covering the diameter range from 3.125 to 1000 mm (Feingold et al. 1996). The ice microphysical model uses three ice species that are defined based upon their physical growth characteristics (Reisin et al. 1995). Pristine ice is ice particles that grow by vapor deposition and small amounts of riming. Aggregates are ice particles formed by the collection of pristine ice or other aggregates. Graupel are formed by significant riming growth of pristine ice or aggregates. All growth methods are based on moment-conserving methods. Activation of CCN is a function of supersaturation and uses a fixed log-normal with a constant background CCN concentration. Activation of ice nuclei (IN) follows Walko et al. (1995) and also assumes a constant background concentration of IN.

A two-stream radiative transfer model is used for these simulations. The spectral band structure is similar to that of Ritter and Geleyn (1992) and uses their methods for the computations of gaseous absorption. Cloud optical properties are parameterized following Slingo and Schrecker (1982) and use a gamma distribution function for the water drops with a shape n=6 chosen in light of observed dispersions (Curry et al. 1988). The transition-season clouds use a more sophisticated method of computing the optical properties for each bin and appropriately summing weighted results. Tests of this method with exact gamma functions show that small errors result (between 0 and 5%).

Results

The sounding used in this study is derived from aircraft data taken on 28 June 1980 over the Beaufort Sea. A complete description of the case and relevant microphysical and radiative data can be found in Herman and Curry (1984) and Curry et al. (1988).

For the warm-season cloud, the model is initialized with the representative sounding and an initial inhomogeneity through a random perturbation of the potential temperature. The model spin-up was conducted with a no-microphysical version of RAMS that simply condenses all water vapor above 100% relative humidity (RH); a droplet concentration of 100 cm^{-3} was used for interaction with the radiation model. This spin-up was done over a 4-hour period to produce an initial cloud field. From this point, the model was run for 2 more hours using the bin-resolving microphysics with two different CCN concentrations: 100 cm^{-3} (termed the 100A experiment) and 500 cm^{-3} (termed the 500A experiment).

The transition-season simulation is a sensitivity study that uses a change to the representative sounding. In this case, the 18 June 1980 sounding is cooled 7° C throughout the vertical, while the relative humidity is held constant. This is done simply to examine how this particular boundary layer responds to the ice phase. In the radiation model, SW effects are turned off to simulate perpetual night conditions of the winter-time Arctic. A cloud field is spun-up, in this case by using a microphysical model that allows not only the production of water but also ice crystals (Walko et al. 1995). Only water drops and vapor grown ice crystals are allowed in this 4-hour spin-up. The bin-resolving microphysics is initiated at the 4-hour point and allowed to run for 15 minutes longer in order to illustrate the ice microphysical effects.

Figure 1a-1d shows statistical fields from the warm-season simulations for the 100A and 500A cases. These fields are averaged over the horizontal domain and the last hour of the simulation time. We concentrate our discussion on the upper cloud deck and not on the lower fog layer. The model-produced liquid water content (LWC) and vertical velocity variance (W'W') fields for both simulations compare favorably with those reported in Curry et al. (1988). Note that the W'W' fields for 100A indicate the production of more energetic eddies than 500A. The LWC fields for these two cases show the presence of more drizzle in 100A as the cloud top LWC is reduced, while the lower cloud LWC is enhanced over 500A. The production of stronger eddies in 100A is due to a subtle interaction of radiation and microphysics. Figure 1c shows that in 100A, more cooling is occurring throughout the downdraft structures of the model than in 500A. The 500A case shows the effects of larger cloud top cooling in Figure 1c; however, less negative buoyancy is produced below cloud top than in 100A. This stronger cooling within the downdrafts of 100A appears to be due to larger evaporative cooling rates that occur there (not shown). This effect, coupled with the larger LWC below cloud top, enhances the buoyancy production (Figure 1d) of 100A over 500A and leads to stronger eddies.

The transition-season simulations are shown in Figure 1e-1h; all fields are averaged over the horizontal domain and over 3-minute intervals to capture the rapidly evolving field. Averages are for 4.06, 4.16, and 4.25 hours. Figure 1e shows the evolution of the ice water content (IWC) fields over the 15-minute period; the removal of water species from the upper cloud is readily evident. During this period, the LWC (not shown) of the cloud continually decreases from a profile similar to Figure 1a to a sharp spike at cloud top with a maximum of 0.15 g m^{-3} at 4.25 hours. During this time, the cloud top radiative cooling continually decreases from -7 K h^{-1} at 4 hours to -3.5 K h^{-1} at 4.25 hours (not shown). This loss of water mass and reduction in cloud-top radiative cooling causes model downdrafts to switch from a structure in which the cloud top and cloud interior are continually cooled to one in which the cloud downdrafts are warming (Figure 1f). This seems to have the effect of reducing the buoyancy production (Figure 1g) and, therefore, reducing the energetics of the model eddies (Figure 1h).

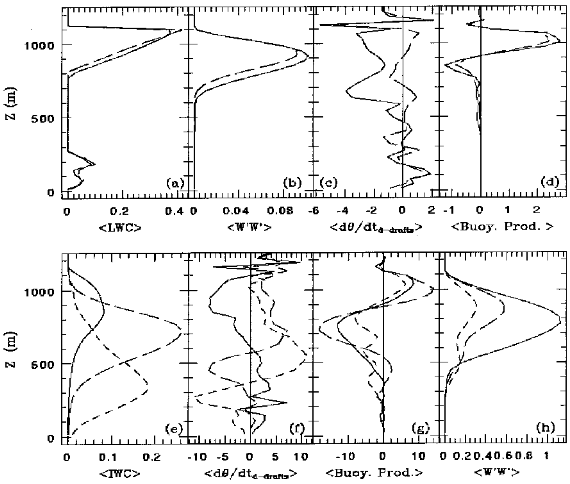

Figure 1. (A) LWC (g m^{-3}) (b) W'W' (m^2 s^{-2}), (c) q-tendency (K h^{-1}), (d) Buoyancy Production (10^{-4} m^2 s^{-3}) for 100A (solid line) and 500A (dashed-line), (e) IWC (g m^{-3}), (f) q-tendency (K h^{-1}), (g) Buoyancy Production (10^{-4} m^2 s^{-3}), (h) W'W' (m^2 s^{-2}) at 4.06 hours (solid line), 4.16 hours (long dashed line) and 4.25 hours (short dashed line).

Conclusions

Herein we have described cloud-resolving simulations of ASC from the perspective of sensitivity analysis. The modeled warm-season clouds show a sensitivity to the CCN concentration assumed and reveal that the dynamical structure can become weaker if CCN concentrations are enhanced. Sensitivities due to the cooling of the representative sounding show that the production of ice species causes an initially vigorous cloud deck to quickly begin dissipating. This effect seems to be due to the fact that the ice particles can quickly attain appreciable sizes and, thus, terminal fall speeds. The subsequent removal of ice water mass from the cloud results in a reduction of the eddy energetics through the eventual warming of the downdraft cores.

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