Modeling the Summertime Arctic Cloudy Boundary Layer

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Introduction

Global climate models have particular difficulty in simulating the low-level clouds during the Arctic summer. Model problems are exacerbated in the polar regions by the complicated vertical structure of the Arctic boundary layer. The presence of multiple cloud layers, a humidity inversion above cloud top, and vertical fluxes in the cloud that are decoupled from the surface fluxes, identified in Curry et al. (1988), suggest that models containing sophisticated physical parameterizations would be required to accurately model this region. Accurate modeling of the vertical structure of multiple cloud layers in climate models is important for determination of the surface radiative fluxes.

This study focuses on the problem of modeling the layered structure of the Arctic summertime boundary-layer clouds and in particular, the representation of the more complex boundary layer type consisting of a stable foggy surface layer surmounted by a cloud-topped mixed layer. A hierarchical modeling/diagnosis approach is used. A case study from the summertime Arctic Stratus Experiment is examined. A high-resolution, one-dimensional model of turbulence and radiation is tested against the observations and is then used in sensitivity studies to infer the optimal conditions for maintaining two separate layers in the Arctic summertime boundary layer. A three-dimensional mesoscale atmospheric model is then used to simulate the interaction of this cloud deck with the large-scale atmospheric dynamics. An assessment of the improvements needed to the parameterizations of the boundary layer, cloud microphysics, and radiation in the 3-D model is made.

Case Study

The case chosen occurred at 0 Z June 29, 1980, in the Beaufort Sea during the Arctic Stratus Experiment. Measurements of the mean and turbulence structure of the boundary layer along with cloud microphysical and radiative properties were obtained from the National Center for Atmospheric Research (NCAR) Electra; details of these measurements may be found in Tsay and Jayaweera (1983), Herman and Curry (1984), Curry and Herman (1995), Curry (1986), and Curry et al. (1988).

The synoptic situation on June 28, 1980, consisted of a mature anticyclone centered over the Beaufort Sea. A large region of low-level cloudiness was present in the north-west region of the anticyclone. This cloud deck was approximately 300 km^2 in horizontal extent, with the surrounding region clear except for altostratus to the north. Weak rising motion of about 0.2 cm s^{-1} was measured. Figure 1 shows mean vertical profiles of temperature, water vapor, cloud water mixing ratio, and horizontal wind components obtained with the NCAR Electra. The vertical structure of this cloud system, typical of many "multilayered" systems in the Arctic, consisted of a stable surface fog layer about 250-m deep surmounted by an upper cloud deck with a base at 700 m. Mean budgets of heat and moisture demonstrated that the horizontal advection terms were an order of magnitude smaller than the largest terms in the budgets.

1-D Model Results

The complete model equations have been reported in McInnes and Curry (1995a). Only a brief summary is provided here. The basic mean prognostic variables are the horizontal momentum (U,V), the liquid water potential

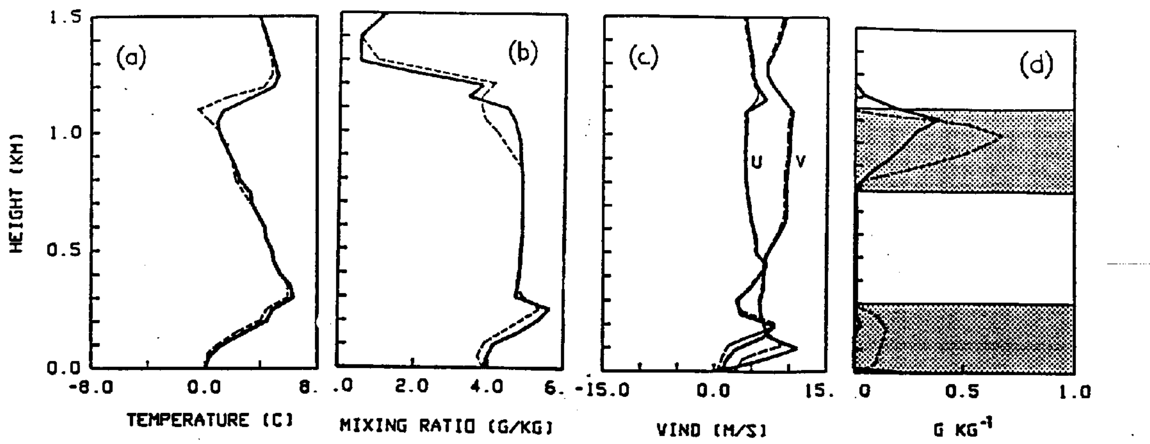

Figure 1. Comparison of observed (solid) and modeled (dashed) mean profiles of a) temperature, b) water vapor mixing ratio, c) winds, and d) liquid water content valid at 0Z June 29, 1980.

temperature (Θ_l), and the total water mixing ratio (Q_w). Turbulent fluxes of heat, momentum and moisture are obtained from a second-order, level-3 turbulence closure scheme. The turbulence scheme is coupled to a non-precipitating statistically based cloud model. A parameterization is included for the gravitational settling of liquid water droplets. The model used to compute the radiative fluxes was developed by Morcrette (1991) for use by the European Centre for Medium Range Weather Forecasting (ECMWF) model. The radiative contributions of clouds are modeled following Curry and Ebert (1992) to be a function of the cloud liquid water content and particle effective radius. The cloud water content is determined by the model, while the particle effective radius is specified as an external parameter.

Comparison of the model results with the observations (Figure 1; see also McInnes and Curry 1995a) show that the one-dimensional model described can capture the complex boundary-layer structure which is observed in the Arctic during the summer months. The main deficiency in the model was a slight over-estimation of liquid water content in the cloud layers and under-estimation of the predicted turbulence variables. The following results were obtained by McInnes and Curry (1995a) from sensitivity studies using the 1-D model:

- Radiative effects in the model are responsible for the generation of turbulence in the upper cloud deck and for the condensation of liquid water.

- A uniform large-scale ascent imposed on the profile leads to an elevation and thickening in vertical extent of the two cloud layers. Large-scale descent produces strong turbulent kinetic energy, which eventually mixes out the vertical gradients in the mean profiles, and evaporation eventually destroys the cloud.

- The optimum vertical resolution required by the model to most accurately model the observed features of the boundary layer for the case studied here is found to be 25 m over the lowest 2 km of the atmosphere. However, when the vertical resolution is degraded to 200 m, the model still captures the broad qualitative features of the observed boundary layer.

The 1-D model is also used to examine the formation mechanism for the cloud layering. Two hypotheses have been proposed to explain the layering. Using a simple one-dimensional radiative-diffusive model, Herman and Goody (1976) proposed a hypothesis for the cloud layering in which cloud absorption of solar radiation warms the intermediate depths of the cloud layer, causing evaporation in the interior of the cloud. Using observations from the Arctic Stratus Experiment, Tsay and Jayaweera (1984) proposed that the upper cloud layer is an advective fog, the low layer forming due to surface convection. Using the 1-D model, McInnes and Curry (1995b) propose that the upper cloud layer forms initially by radiative and diffusive cooling of warm, moist air that is advected into the Arctic basin, with the subsequent evolution of a cloud-topped mixed layer generated by the cloud-topped radiative cooling. The cloud-topped mixing does not produce sufficient turbulence kinetic energy to overcome the surface stable layer and penetrate down to the surface. The air in the surface inversion layer is warmer than both the surface and cloud overhead and thus cools radiatively, eventually forming a radiation fog. An example of the modeled evolution of a two-layer cloud deck is shown in Figure 2.

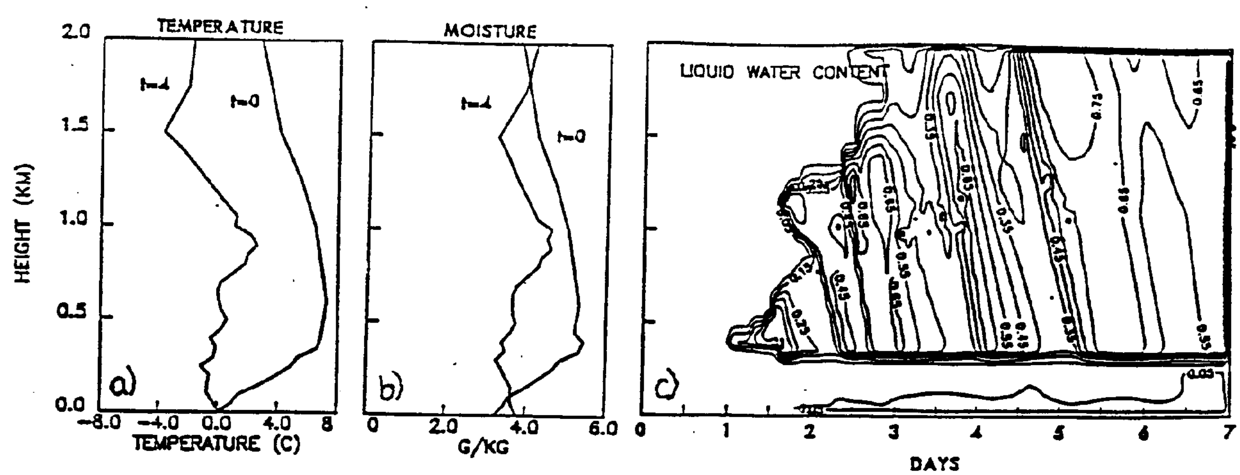

Figure 2. Modeled evolution of layered cloud system: a) temperature profiles at t = 0 and at t = 4 hours; b) humidity profile at t = 0 and t = 4 hours; and c) time evolution of cloud liquid water content.

3-D Model Results

The model used for the 3-D simulations is Version 5.1 of the Pennsylvania State University (PSU)/NCAR Mesoscale Model (MM5). For a complete description of the model, see Grell et al. (1994). In this study we use a horizontal resolution of 40 km and a vertical resolution which varies with height from about 70 m just above the surface to 1 km near the top of the troposphere. The model is run using the hydrostatic option. For moist physics, the Dudhia (1989) simple ice phase and Hsie (1984) stratiform warm-phase precipitation formulations are used. Moist vertical diffusion is allowed and an upper radiative boundary condition is employed to allow energy to pass through the atmosphere unreflected while the lateral boundaries are relaxed toward the large-scale analysis. The two-stream radiation scheme of Dudhia (1989) is used for radiative transfer computations, and Blackadar's high-resolution planetary boundary layer scheme (Zhang and Anthes 1982) is used to vertically mix momentum, moisture variables, and temperature in the boundary layer. The surface temperature and albedo were specified at 271.4 K and 0.55, respectively, in accordance with the observations described by Herman and Curry (1984) for this case and remain constant over the integration period. The model is initialized using ECMWF analyses for June 27, 1980, at 12 Z and is run for a period of 60 hours.

Model results are examined after 36 hours integration, corresponding to the time of the observations shown in Figure 1. The modeled surface pressure field and liquid water content at 960 mb are shown in Figure 3. The spatial coverage of cloud predicted by the model is much larger than that observed in the satellite visible image.

Comparison of the modeled liquid water content (Figure 4a) with the observations (Figure 1) indicates that the cloud modeled by the 3-D model consists of a single-layered cloud with base at the surface. The cloud microphysics scheme produces unrealistically large amounts of cloud water. This overestimation of cloud water has a large impact on the net radiative fluxes at the surface (Figure 5). The shortwave flux is greatly attenuated by these optically thick clouds with incident shortwave radiation at the surface of less than 10% of the top-of-the-atmosphere values.

It appears that the conversion of cloud water to rain occurs much too slowly allowing for the buildup of cloud water in the atmospheric boundary layer for the baseline run (Figure 3b; Figure 4b). In the baseline simulation, we used an autoconversion threshold of 0.5 g kg^{-1}. Observations described by Curry (1986) suggest that drizzle begins at much lower values of liquid water content in the Arctic stratus clouds. Therefore, in Figure 4b we show the time evolution of cloud water content for an autoconversion threshold of 0.25 g kg^{-1}. This effectively reduced the total amount of cloud water by allowing for rain at much lower cloud water mixing ratios. The autoconversion threshold is certainly not a universal constant. For example, one would expect different rates of autoconversion depending on the drop size distribution and the size of the largest drops. These parameters are dependent on the concentration, type, and size of available condensation nuclei which vastly differ over climatic regimes (e.g., continental versus maritime).

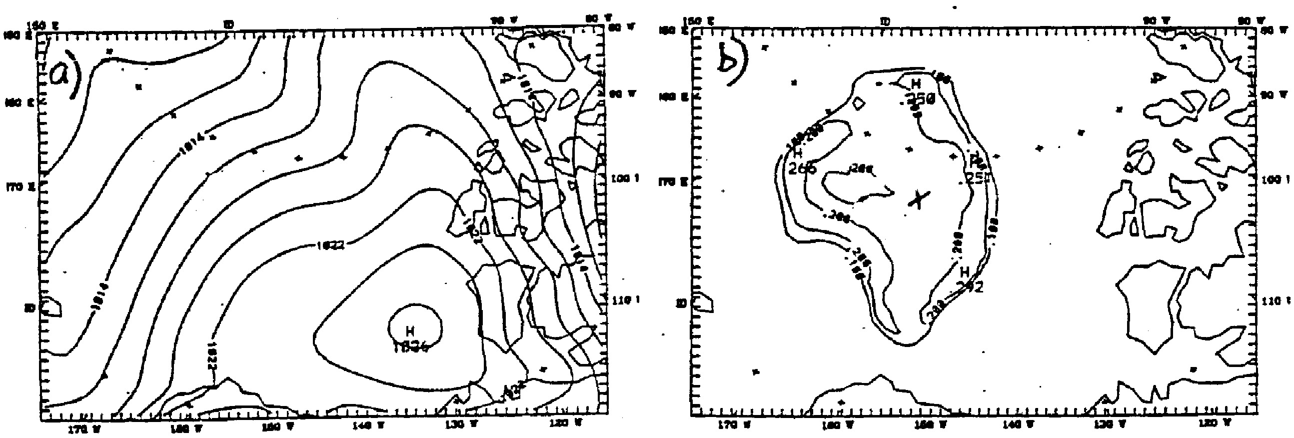

Figure 3. Model simulation of a) surface pressure field and b) cloud liquid water mixing ratio at 960 mb for the same time as the observations in Figure 1 "X" denotes the location of the aircraft measurements described in Figure 1.

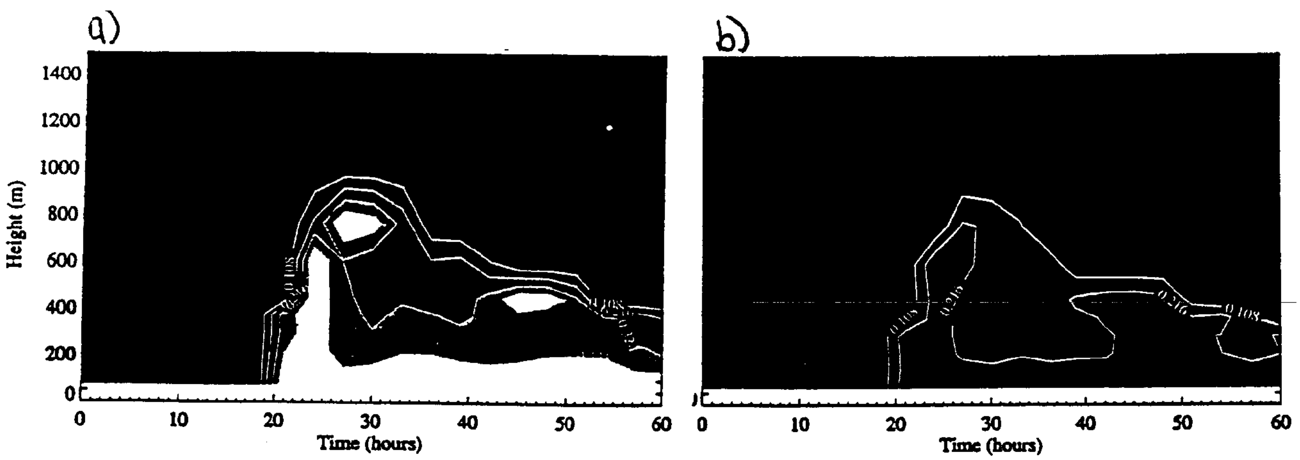

Figure 4. Modeled time evolution of cloud liquid water mixing ratio (g kg^{-1}) using the 3-D model, at the location corresponding to the observations in Figure 1: a) autoconversion threshold of 0.5 g kg^{-1}; b) autoconversion threshold of 0.25 g kg^{-1}.

The importance of an accurate depiction of cloud microphysical processes is seen in Figure 5. After the onset of cloud, the curves for the incident shortwave radiative diverge by as much as 30–40 W m^{-2}.

Conclusions

These results imply that

- The layered cloud formation requires a fairly sophisticated boundary layer parameterization such as second-order closure.
- Modeled cloud water content is very sensitive to the autoconversion threshold in bulk microphysical parameterizations, and drizzle must be included to control the modeled liquid water content.
- Surface shortwave radiation fluxes are very sensitive to the modeled cloud microphysical characteristics.

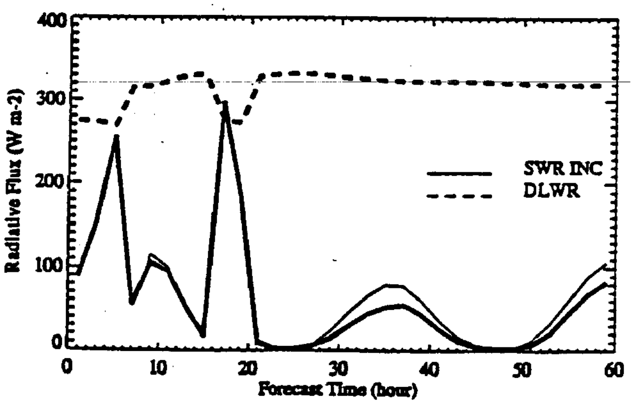

Figure 5. Time series of modeled surface radiation fluxes. DLWR: downwelling longwave radiation; SWR INC: incoming shortwave radiation. For SWR INC, the bold line corresponds to the water content in Figure 4a and the thin solid line corresponds to the water content in Figure 4b.

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