Formation of Arctic Stratus Clouds: Comparison of Model Predictions with Observed Cloud Structure

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Introduction

The importance of the Arctic region to global climate has been highlighted by the climate modeling results in recent years (e.g., Manabe et al. 1991). Arctic stratus clouds (ASC) are not only one of the most significant regional climate features in the Arctic region, but also have an important influence on global climate. They play an important role in the vertical transfer of heat, moisture and momentum in the Arctic boundary layer.

Due to lack of observation, the mechanism for the formation of ASC, especially the formation of multiple layer clouds, is still uncertain. In this research, a one-dimensional simple model is developed and is used to study the formation of multiple cloud layers. The roles of radiation and microphysics are investigated. This model includes the radiative effect, vertical mixing, and detailed cloud microphysics. A well-tested radiative model (Tsay et al. 1989) is used for calculating the solar and infrared radiative effect. A convective scheme is used for vertical mixing. For more detail about this model, please refer to the Lie-Svendsen et al. paper in these proceedings.

Initial Data and Simulation Design

Our simulation starts with a clear atmosphere. Figure 1 shows the initial data of the simulation. The initial data is based on the observations of June 28, 1980, over the Beaufort Sea during the Arctic Stratus Clouds Experiment. The dotted lines on the plots show the observational data. Detailed descriptions of the experiment and analyses of physical properties of the boundary layer were given by Tsay and Jayaweera (1984), and Curry et al. (1988). Two nearly parallel layers of stratus clouds were observed. The upper layer of clouds, with its top at 1200 m and base at 800 m, was capped with a strong temperature inversion and significant moisture decrease. Its average thickness is about 376 m, and it has a maximum liquid water content (LWC) of about 0.5 g/kg. The lower layer of clouds, with its top at about 110 m and thickness of 80 m, formed within a very stable layer near the earth surface. It has maximum liquid water of about 0.13 g/kg.

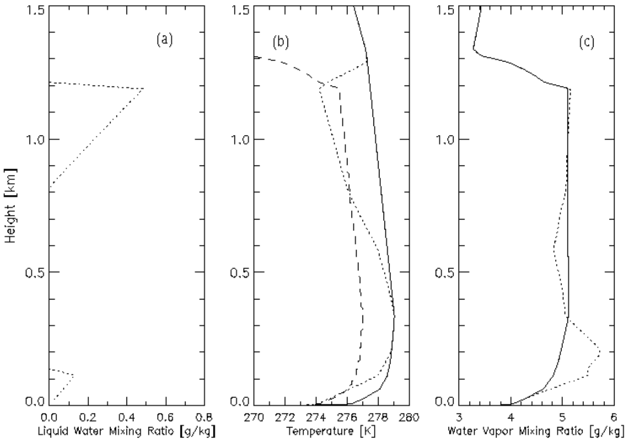

Figure 1. Observational and initial data. (a) Observed clouds; (b) temperature (dashed line is the dew point temperature); (c) water vapor mixing ratio. Solid: initial data; dotted: observation.

For the initial data, we increase the temperatures around the cloud layers so that we can start the simulation with a presumed clear atmosphere, and then study the formation of cloud. The dashed line is the dew point temperature. It is the temperature to which moist air must be cooled, with pressure and humidity held constant, for it to reach saturation with respect to water. The difference between the initial temperature and the dew point temperature is almost the same among the layers from 0.1 km to 1.2 km.

A uniform relative humidity of 86% from the surface to 1.2 km is given for the initial humidity. The initial humidities above 1.2 km are the same as the observation. With this relative humidity profile, the initial humidities (Figure 1c) are uniform from 0.3 km to 1.2 km, and decease rapidly at the height from 1.2 km to 1.3 km. They are basically the same as the observation between 0.8 km and 1.2 km, are larger than the observation between 0.3 km to 0.8 km, and are smaller below 0.3 km. The sum of the humidity over the whole layer is approximately equal to that of observation.

The initial cloud condensation nuclei (CCN) spectrum is based on a spectrum measured over the Arctic Ocean in April 1992 during the Arctic Leads Dynamics Experiment (LEADEX) (Hegg et al. 1995).

Simulation Results

A simulation of 45 hours is conducted, and two cloud layers form (Figure 2). Temperatures continually decrease during the simulation, and finally lead to the condensation of water vapor and the formation of clouds.

The lower layer cloud initially forms at 29.5 model hours at about 0.065 km. The liquid water of the lower layer cloud increases rapidly during the first several hours after the cloud initially forms (not shown).

The upper layer clouds initially form at 35 model hours at about 1.155-km altitude. A small temperature inversion has already existed before the formation of the upper cloud layer. This temperature inversion significantly increases after the cloud forms. At 5 hours after the formation of this cloud layer, the temperature inversion increases to about 2.5 K. A small water vapor inversion can also be seen.

During the first several hours after cloud formation, and especially after the first 2 hours, cloud liquid water increases very fast due to rapidly decreasing temperatures. The speed of cloud development gradually decreases after 2 hours. Five hours after cloud formation, the LWC near cloud top is about 0.8 g/kg and the cloud top is at 1200 m. A small water vapor inversion forms at the top of cloud layer.

The lower cloud layer forms 5 hours before the upper cloud layer forms. It develops significantly during this period. After the formation of the upper cloud layer, temperatures within the lower cloud layer don't change much. The cloud liquid water doesn't change much, either.

The temperature decrease is mainly due to the net radiative cooling (Figure 3). The maximum of both solar and infrared radiation occurs around the cloud top. Before the formation of the upper cloud layer, the maximum appears around the top of the lower layer cloud. After the formation of the upper cloud layer, the radiation around the lower cloud layer decreases significantly, and that around the upper cloud layer increases significantly. At 40 hours model time, both strong solar and infrared radiation appears near the cloud top at around 1.2 km. The maximum infrared cooling is much stronger than the solar heating effect. Strong net cooling with a maximum of -17 K/hour appears around the

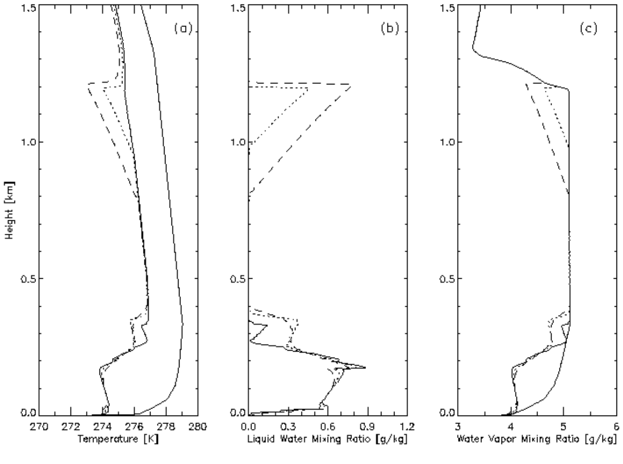

Figure 2. Simulation results. The upper cloud layer forms at 35 hours. (a) temperature [K]; (b) liquid water mixing ratio [g/kg]; (c) water vapor mixing ratio [g/kg]. Solid: clouds form (35 hours); dotted: 2 hours after clouds form (37 hours); dashed: 5 hours after (40 hours); heavy: initial data.

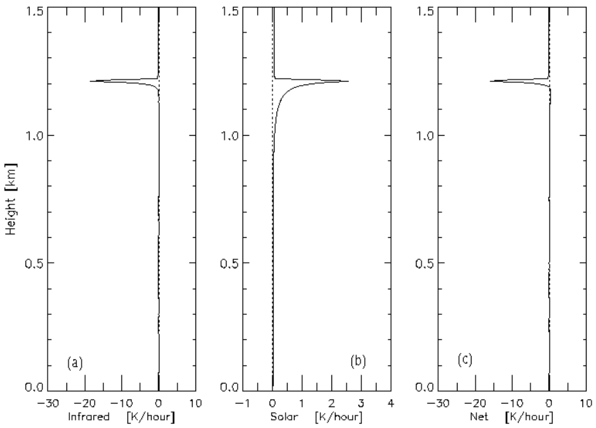

Figure 3. Simulation results. (a) Infrared cooling; (b) solar heating; (c) net radiative heating. 5 hours after the formation of the upper layer clouds (40 hours).

cloud top. Strong radiative cooling only occurs on a very thin layer near cloud top.

As shown on Figure 4, the droplet density is almost constant with height. The maximum of droplet density doesn't change much with time during cloud evolution. The equivalent radius increases with height and with time. That is why we see the cloud liquid water increase with height and time. These properties correspond very well with the observation (Tsay 1984; Curry 1986).

The droplet spectrum of the simulation also corresponds well with the observation. Figure 5 shows the droplet spectrum of the upper cloud layer at 5 model hours after the cloud has formed. There is only one peak around the cloud base and two peaks around the cloud top. At the cloud base, the peak appears around 5 µm. This mono modal peak is shifted to a larger radius as one moves from the cloud base toward the cloud top. Around the cloud top, two peaks appear around a diameter of 8 µm and 17 µm. These results also show that the droplet sizes increase with the height. They also continue to increase as the cloud develops. Therefore, we can see that the increase of LWC is related to the increase in droplet size increasing rather than concentration.

Different droplet spectrum appears at the lower cloud layer. Figure 6 show the droplet spectrum of the lower cloud layer at 40 hours model time, that is 10.5 hours after the lower cloud forms. Its distribution is different from that of the upper cloud layer. A single peak appears at the cloud top, and triple peaks appear at the cloud base.

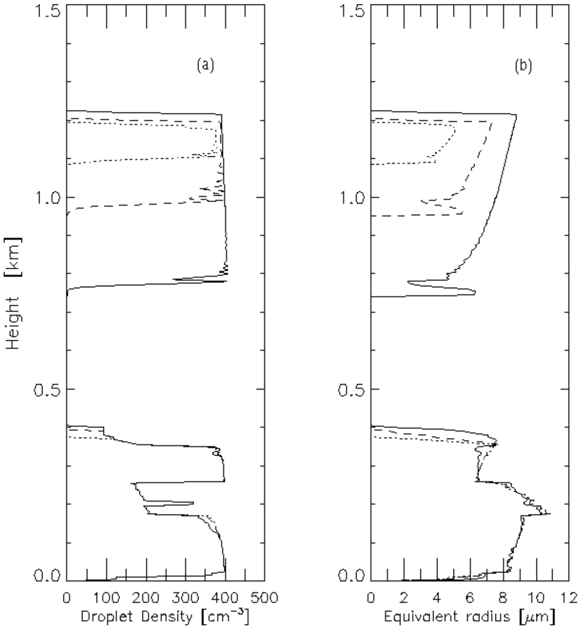

Figure 4. Simulation. (a) Droplet density [cm^{-3}]; (b) equivalent radius [µm]. Dotted: 1 hours after (36 hours); dashed: 2 hours after (37 hours); solid: 5 hours after (40 hours).

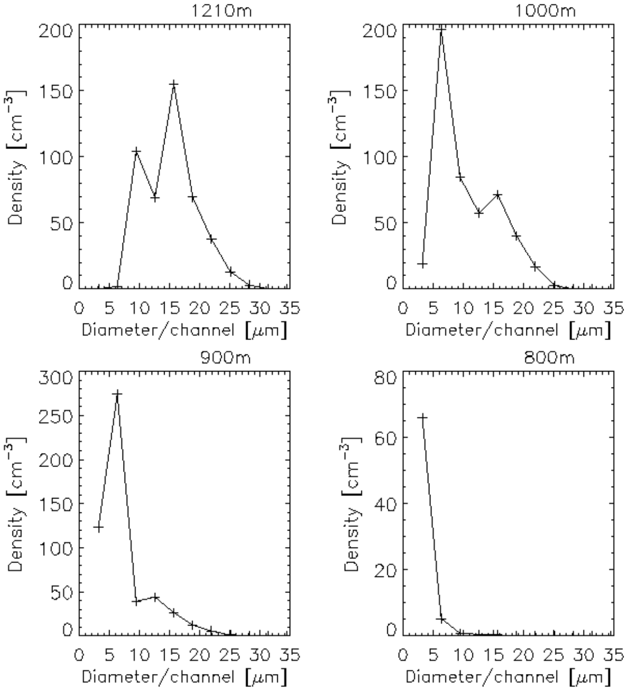

Figure 5. Droplet spectrum 5 hours after clouds form (40 hours).

Sensitive Studies

In this simulation, solar radiation has been turned off. By comparing the results of simulation with and without solar radiation, we can discuss the role of solar radiation on the formation of the multiple cloud layers. The initial data for this simulation is the same as the base simulation, in which solar radiation is considered. Without solar radiation, two cloud layers still form approximately at the same height of observation (Figure 7). The upper cloud layer forms first at 20.5 hours model simulation time. The lower cloud layer forms half an hour later at 21 hours. Since the upper cloud layer already exists, the radiative cooling of the low cloud layer is not as strong as that of the base simulation. The lower layer is not able to develop. The droplet size distribution is similar to that for the simulation with solar radiation (not shown).

Without considering solar radiation, the cloud forms earlier and develops faster. Therefore, we may conclude the effect of solar radiative transfer is to slow down the formation and evolution of clouds.

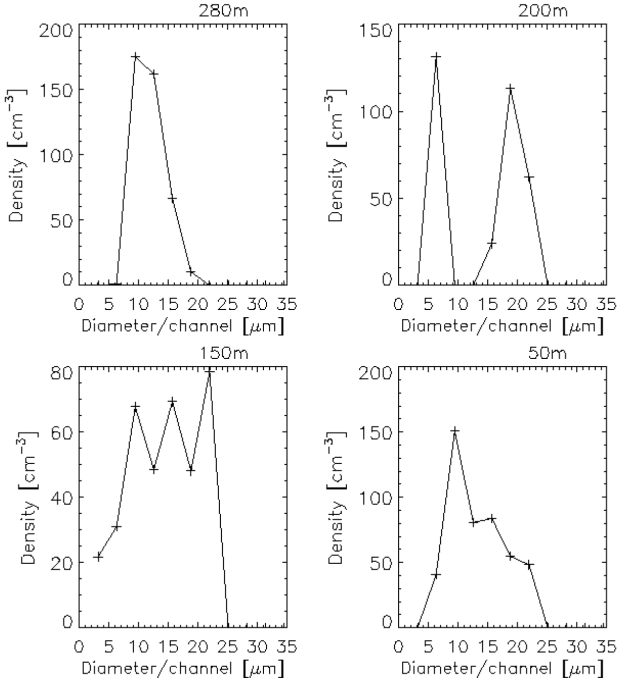

Figure 6. Droplet spectrum 10.5 hours after clouds form. (40 hours).

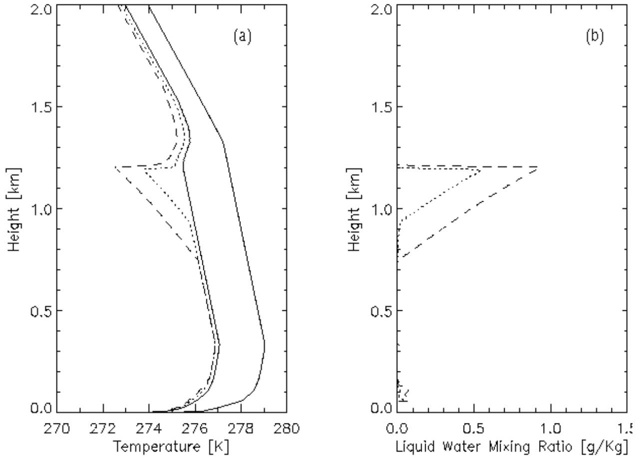

Figure 7. Simulation results without solar radiation. (a) Temperature [K]; (b) liquid water mixing ratio [g/kg]. Solid: 1.0 hours before the clouds form (18 hours); dotted: 2 hours after clouds form (21 hours); dashed: 5 hours after clouds form (24 hours). Heavy: initial data.

Conclusions

An ASC case with multiple cloud layers is simulated with a simple radiative-convective model with detailed cloud microphysics. Our simulation reproduces the two cloud layers observed with inversions of temperature and humidity occurring near the cloud top. The model output also provides detailed cloud microstructure, which compares well with the observations.

Our results suggest that radiative cooling plays a very important role during the initial stage of cloud formation. The cloud formation can be explained as the result of continual temperature decrease due to radiative cooling. The observed temperature inversion can also be explained by radiative cooling.

We use the model to explore the relative role of solar and infrared radiation. The two cloud layers form as a consequence of the initial humidity profile. Solar radiation has the effect of compensating for the longwave cooling. However, the two cloud layers form whether or not we include solar radiation.

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