The Influence of Radiation and Large-Scale Vertical Motion on the Persistence of Arctic Stratus Clouds

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Introduction

Arctic Stratus Clouds (ASCs) are important modulators of local climate, and perhaps even global climate. One of the most significant features of ASC is that they can persist for several days. Nevertheless, the mechanism responsible for their persistence still remains unknown. Several studies have been undertaken to understand the mechanism of the maintenance of the multiple cloud layers. With a one-dimensional (1-D) second-order turbulence closure model, McInnes and Curry (1995) and Cotton et al. (1995) pointed out that the radiative cooling is important for the maintenance of multiple cloud layers. Olsson et al. (1998) discussed the influence of cloud microphysics on the boundary structure. By using a three-dimensional (3-D) large eddy simulation (LES), Zhang et al. (1997) successfully simulated a case with multiple cloud layers, and investigated the maintenance as well as the evolution of the clouds. The results showed that the multiple cloud layers are mainly maintained by longwave radiative cooling, and vertical heat transport has an effect of compensating the radiative cooling.

In this study, we simulate an ASC case observed on June 28, 1980, during the Arctic Stratus Cloud Experiment with a LES model, to investigate the persistence of the multiple cloud layers and discuss the roles of solar radiation and large-scale motion.

The Model and Initial Data

The complete set of equations for our LES model have been described in Moeng (1984). The longwave radiation is parameterized according to Herman and Goody (1976). The shortwave radiation is calculated with a well-tested model developed by Tsay et. al (1989).

The observational data of June 28, 1980, during the Arctic Stratus Experiment are used as the initial data for the simulation. Detailed descriptions of the experiment and analyses of physical properties of the cloud boundary layer were given by Tsay and Jayaweera (1984), and Curry et al. (1988). Two nearly parallel layers of stratus clouds were observed.

The made domain is 2 km x 2 km x 2 km with horizontal and vertical grid spacing of 50 m and 25 m, respectively. The simulation is integrated forward for 3 hours. The results shown below are the simulations at 3 hours model time. Both solar and longwave radiative effects are included. We set the large-scale vertical velocity to 0 m/s in the base simulation.

Simulation Results

Figure 1 shows model results of liquid water mixing ratio. The upper layer cloud develops during the simulation. This cloud layer rises (its top rises 75 m and its base rises 25 m). The lower layer develops during the simulation. Its top also rises 50 m. The cloud water decreases at the third hour.

Corresponding to the rising of the top of the upper layer cloud, the temperature inversion layer rises about 75 m (Figure 2). Temperatures continue to decrease within the cloud layers during the simulation. They decrease most significantly around the cloud top with a rate of -2 K/hour. Temperature inversion right above the top of the upper cloud layer continues to increase. Temperatures also decrease in the lower cloud layer. The maximum is about -0.6 K/hour.

Strong infrared (IR) cooling occurs at the top of cloud layer (Figure 3) where significant temperature reduction occurs. For the upper layer, the maximum cooling is up to

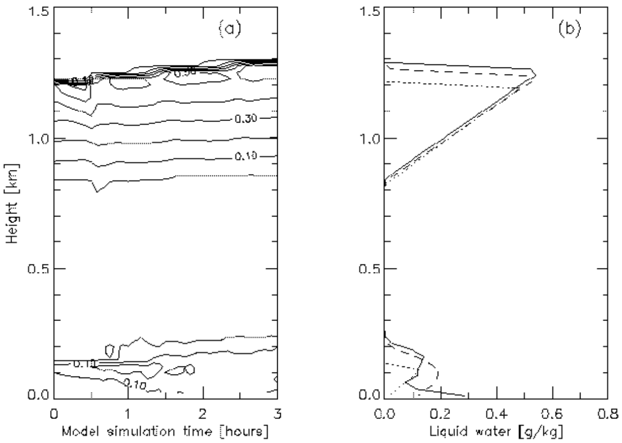

Figure 1. Liquid water mixing ratio [g/kg]. (a) Evolution over 3 hours (contour interval is 0.1 g/kg); (b) vertical profile after 2 hours (dashed) and 3 hours (solid) of model integration. Dotted line shows the initial data.

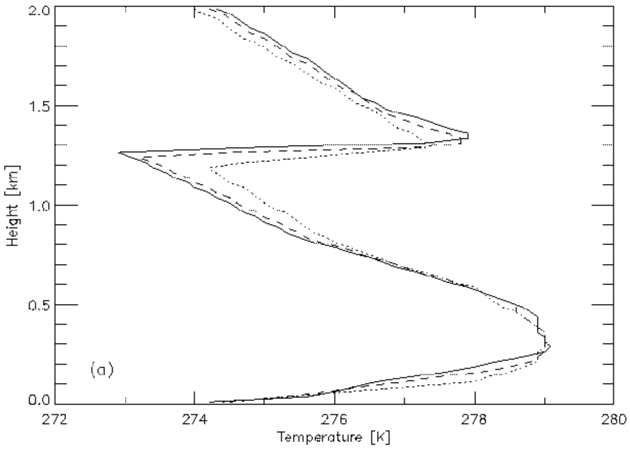

Figure 2. Vertical temperature profile after 2 hours (dashed) and 3 hours (solid) of model integration (dotted line shows the initial data).

-7.9 K/hour at 1.275 km. The maximum cooling of the lower layer is only -0.5 K/hour at 0.25 km. Strong solar heating occurs in the upper cloud layer. The maximum cooling is of 1.3 K/hour at 1.275 km. The distribution of the net radiation is similar to the infrared radiation. The maximum cooling at the top of the upper layer is of value of -6.8 K/hour. Inside the upper layer cloud, there exists small heating. The net radiation at the lower layer cloud is mainly the same as the infrared radiation.

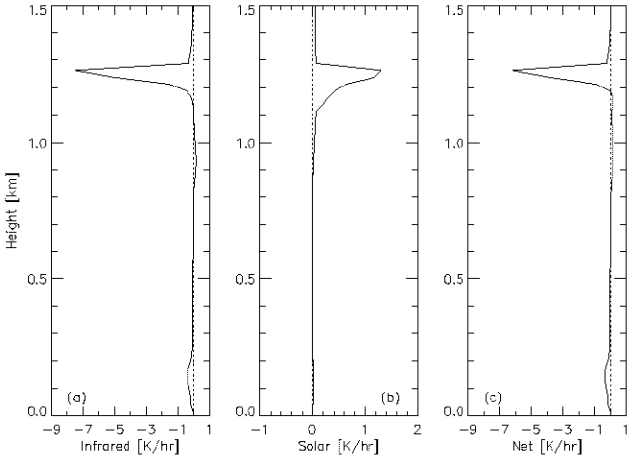

Figure 3. Vertical profile of (a) infrared radiation; (b) solar radiation; (c) total radiation. Averaged from 2 to 3 hours.

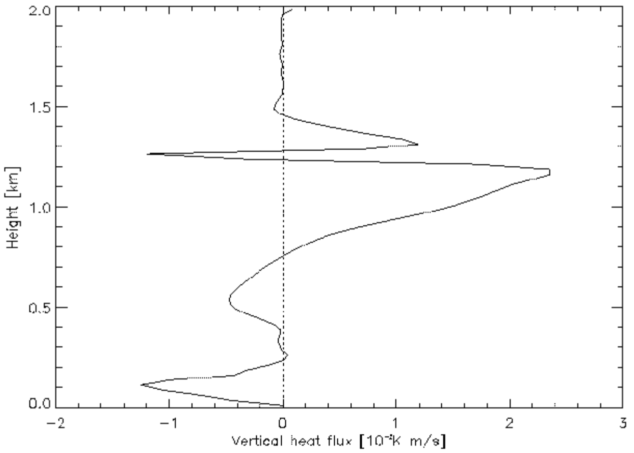

Figure 4. Vertical heat flux averaged from 2 to 3 hours. Unit is 10^{-2} K m/s.

Figure 4 shows the vertical heat flux. There is upward vertical heat flux under the cloud top and downward heat flux right above the cloud top. Both of these processes transport heat to the cloud top and compensate the cloud top cooling. There is downward heat transfer in the mixed layer between 400 m and 750 m. In the lower cloud layer, the heat is transported downwards under the cloud top, and also compensates for the cloud longwave cooling.

Sensitivity Experiments

In order to further understand the mechanism of the maintenance of multiple cloud layers, several sensitivity experiments are undertaken. The roles of radiative transfer and large-scale motion are investigated.

The Role of Radiative Transfer

Figure 5 shows vertical profile of liquid water mixing ratio at 3 hours model time. It shows three simulation results: with both solar and infrared radiation (dashed line), without solar radiation (solid line) and without solar and infrared radiation (dotted line).

Without solar radiation, cloud liquid increases the most significantly. This is different from the results that include solar radiation; the upper cloud layer develops both upward and downward. The turbulent kinetic energy of this simulation is the strongest (not shown).

Without any (solar and IR) radiation, the turbulent kinetic energy is very small (not shown). The cloud liquid water decreases, which means the cloud layer is decaying.

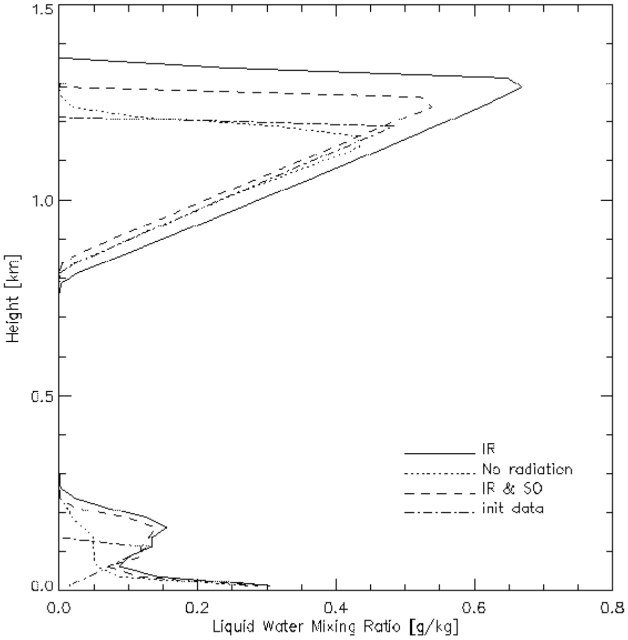

Figure 5. Vertical profile of liquid water mixing ratio at 3 hours. Solid: with only infrared radiation; dotted: no radiation; dashed: with infrared and solar radiation; dashed-dotted: initial data.

The Effect of Large-Scale Vertical Motion

Figure 6 shows four simulations at 3 hours model time with large-scale vertical motion of 3 cm/s, 10 cm/s, -3 cm/s and -10 cm/s. The results are compared with the base simulation that has zero large-scale vertical motion.

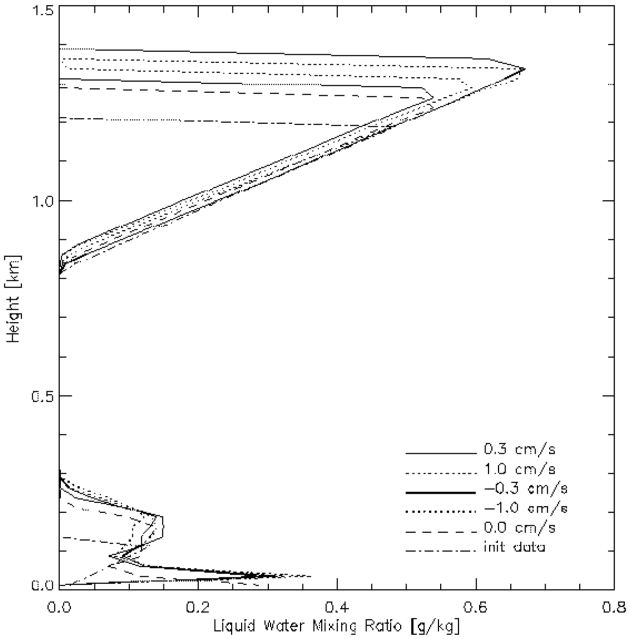

Figure 6. Liquid water mixing ratio at 3 hours. Dashed-dotted: initial data; dashed: w = 0 cm/s; solid: w = 0.3 cm/s; dotted: w = 1 cm/s; heavy solid: w = -0.3 cm/s; heavy dotted: w = -1 cm/s.

The simulations with downward large-scale vertical motion is more favorable to the cloud development. The simulation with a large-scale velocity of -3 cm/s has the largest cloud liquid water. Also, the simulations with downward large-scale vertical motion has stronger turbulent kinetic energy (not shown). The simulation with a large-scale velocity of -3 cm/s has the strongest turbulent kinetic energy.

Conclusions

With a LES model, we simulate an ASC case observed on June 28, 1980, during the Arctic Stratus Cloud Experiment, and investigate the maintenance of multiple cloud layers.

During the 3-hour simulation, clouds continue to develop due to decreasing temperature. The temperature decrease is mainly caused by longwave cooling. There existed upward vertical heat transport under the cloud top and downward heat transport right above the cloud top. The effect of such vertical heat transport compensates the cloud top cooling.

The effects of solar and terrestrial radiation are examined. The solar radiation had the effect of decreasing the longwave cooling. We find that cloud layer decays if both the solar and terrestrial radiation are not considered.

By comparing simulations with different large-scale vertical velocities, we find that weak downward vertical motion is the most favorable situation for maintaining the cloud layers.

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