Simulation of Cloud/Radiation Interaction Using a Second-Order Turbulence Radiative-Convective Model

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Introduction

Extended sheets of low-level stratus and stratocumulus clouds are a persistent feature over the eastern parts of the major ocean basins associated with the quasi-permanent subtropical high-pressure systems. These clouds exert a strong influence on climate through their high albedo, compared with the underlying surface, and their low altitude. The former leads to a reduction of the net shortwave flux entering the atmosphere, and the latter leads to an infrared loss in a way essentially the same as the cloud-free conditions. Randall et al. (1984) estimated that an increase of a few percent of global low-level stratiform clouds may offset the warming caused by a doubling of the atmospheric CO_2.

The Atmospheric Radiation Measurement (ARM) Program, sponsored by the U.S. Department of Energy, envisions a locale in the Eastern North Pacific for extensive measurements of stratiform boundary-layer clouds and their interaction with atmospheric radiation. Thus, a physically-based parameterization scheme for marine low-level stratiform clouds can be developed for general circulation models (GCMs).

This paper is a modeling study with the current understanding of the important physical processes associated with a cloud-capped boundary layer. The numerical model is a high-resolution one-dimensional version of the second-order turbulence convective/radiative model developed at the Los Alamos National Laboratory (Kao and Yamada 1989; Yamada and Kao 1986). The data collected during the intensive field observations of the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) (Albrecht et al. 1988) are used to validate the model.

One important finding of the FIRE data is the diurnal variation of cloud behavior (e.g., Blaskovic and Davies 1991; Betts 1990) in terms of cloud liquid water content and cloud depth. To simulate the observed cloud diurnal variability, we incorporated a parameterization of shortwave absorption due to clouds (Slingo and Schrecker 1982) into our model. In this paper, we will focus on the physical mechanisms in modulating the diurnal variation of clouds.

The FIRE Data

FIRE is a comprehensive field experiment which provides measurements to test theories on the formation, maintenance, and dissipation of marine stratiform clouds. The measurements were obtained off the coast of California, from 29 June to 19 July, 1987, with aircraft, satellite, and surface-based instruments. The field site of FIRE was located on San Nicolas Island (33.1°N, 119.31°W). Albrecht et al. (1988) have summarized the overall aspects of the FIRE experiment. Among many observational studies of the FIRE data, Hignett (1991) presented the turbulent structure of a cloud-capped boundary layer during FIRE. Blaskovic and Davies (1991) analyzed the average diurnal variation of cloud properties and related surface variables.

The Model

The complete model equations have been reported in Yamada and Kao (1986) and Kao and Yamada (1989). Only a brief review is provided here. The basic mean prognostic variables are the horizontal momentum (U,V), the liquid water potential temperature (θ_l), and the total water mixing ratio (Q_w). Turbulent fluxes in terms of momentum, heat, and water substance are obtained from simplified turbulence-closure equations (Yamada 1983). The model also prognostically calculates turbulent kinetic energy (q^2) and turbulence length scale (l). This is an important feature in simulating the transient nature of turbulent mixing within the cloud layer.

The longwave radiation flux is computed according to the method developed by Sasamori (1968), which is based on a chart approach using two-stream numerical approximations to the transfer equations. To reduce computing time, the absorption functions are expressed as analytic functions. It also allows up to three absorbing gases: water vapor, carbon dioxide, and ozone. The fluxes depend on the path length of each absorbing gas. This method is further modified to include cloud effects. Since clouds provide an additional radiation source and their area coverage can be fractional, this method first computes the total flux at each layer by summing the fluxes resulting from each source, which is then attenuated by partial cloudiness.

The shortwave parameterization is designed for the calculation of absorption, reflection, and transmission by stratiform clouds based upon a two-stream approximation for multiple scattering of cloud droplets. In the model, we divide the solar spectrum into six absorption bands and six windows between these bands, according to the water vapor absorption spectrum. Each absorption band is further divided into five sub-bands in which the transmission functions are represented by the exponential function with effective absorption coefficients. The scattering of solar radiation by cloud droplets is represented by a single mean size of cloud droplets according to Slingo and Schrecker (1982).

A bimodal distribution of finer vertical resolution is designed (Kao and Yamada 1989) to resolve detailed variations of thermal stratification near the surface and cloud top. The minimum Δz in the simulation is 7 m.

Results

The initial profile of potential temperature is constructed with a sea surface temperature of 15.5°C and a surface pressure of 1012 mbar. A slightly stable lapse rate of 1.5 $K{\cdot}km^{-1}$ is assumed from the surface up to 550 m (Hignett 1991), followed by a strong inversion layer from 550 m to 650 m, with the lapse rate of 50 $K{\cdot}km^{-1}$. Stratification with a lapse rate of 5.0 $K{\cdot}km^{-1}$ is given for the rest of the vertical domain. The initial profile of water vapor mixing ratio is constructed by assuming the relative humidity in the slightly stable layer to be 95%, followed by a relative humidity of 20% for the rest of the vertical domain. The initial winds are also adopted from Hignett (1991). Since the FIRE observations were associated with surface high-pressure systems, we include large-scale subsidence rates linearly increasing from zero at the surface up to 0.5 $cm{\cdot}s^{-1}$ at 1000 m, and then linearly decreasing to zero at the top of the domain.

Figure 1 shows the time evolution of liquid water potential temperature versus height from day 4 to day 11 of the model simulation. The first three model days were considered as the model adjustment period, which had certain diurnal variations but not as regularly as that shown in Figure 1. The inversion layer is clearly identified with a diurnal cycle in thickness. The potential temperature in the boundary layer also undergoes a distinct diurnal cycle: well-mixed in the nighttime and early mornings versus moderately stratified in the upper part of the boundary layer in the afternoons. Figure 2 shows the time evolution of total water mixing ratio, where its diurnal cycle is in phase with potential temperature shown in Figure 1. In the nighttime and early mornings, the total water is quite well mixed, and, in the afternoons, the total water reaches a minimum in the upper half of the boundary layer. Figure 3 shows the time evolution of cloud liquid water. Again, almost the same diurnal cycle is seen.

To explain the features of diurnal variations in Figures 1 to 3, it is instructive to show the time evolution of turbulence kinetic energy (Figure 4). Turbulence kinetic energy is more significant in the nighttime and early mornings than in the afternoons, where the depressed turbulence agrees with the stratification shown in Figure 1. Because of this less turbulent mixing, the water supply from the surface is reduced, resulting in a total water minimum as shown in Figure 2, which in turn causes the liquid water minimum shown in Figure 3.

We have postponed the discussion of the reason for the temperature variations shown in Figure 1, especially the distinct stratification in the upper part of the boundary layer in the afternoons. The variation is primarily caused by the cloud radiative heating from absorption of solar radiation. Radiative heating not only heats the air and evaporates the

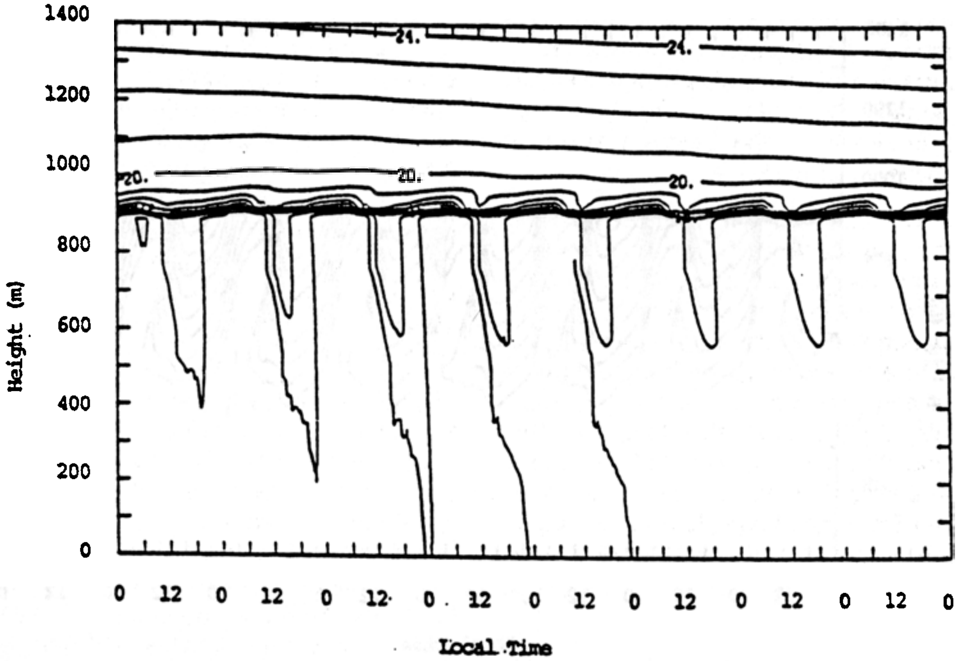

Figure 1. Time evolution of liquid water potential temperature as a function of height.

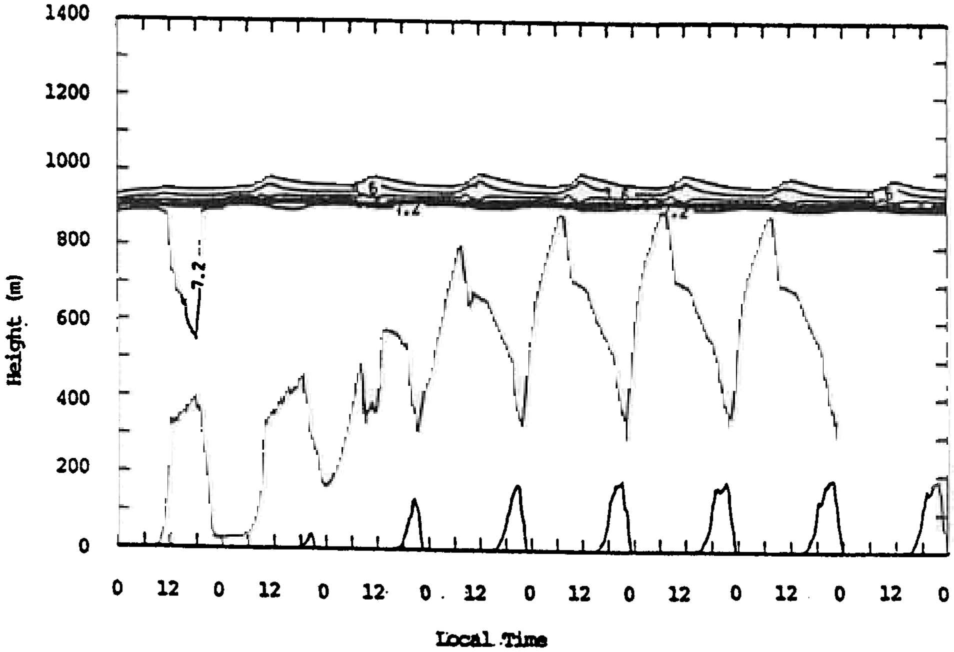

Figure 2. Time evolution of total water mixing ratio as a function of height.

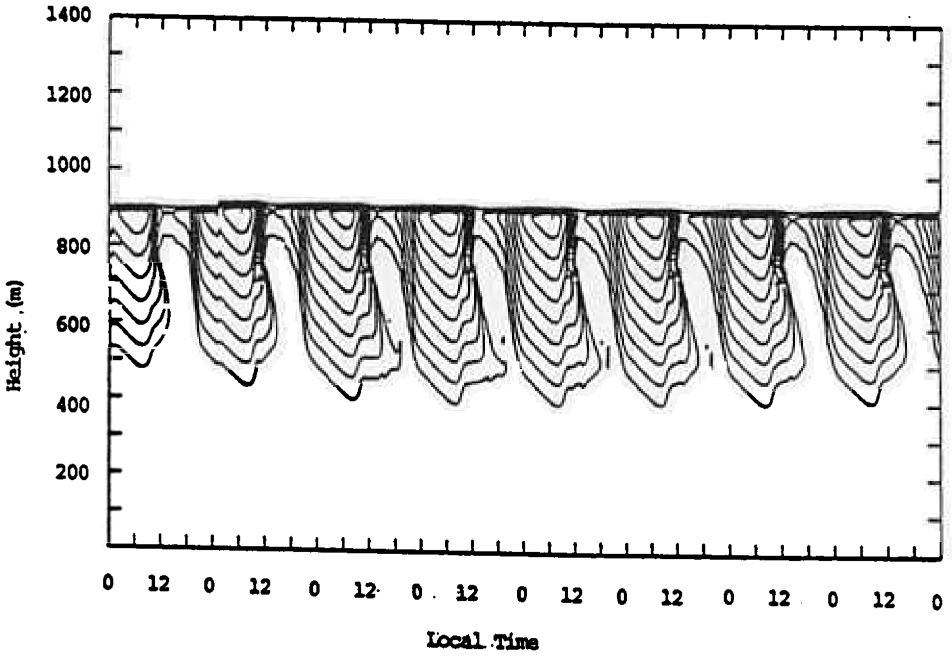

Figure 3. Time evolution of cloud liquid water as a function of height.

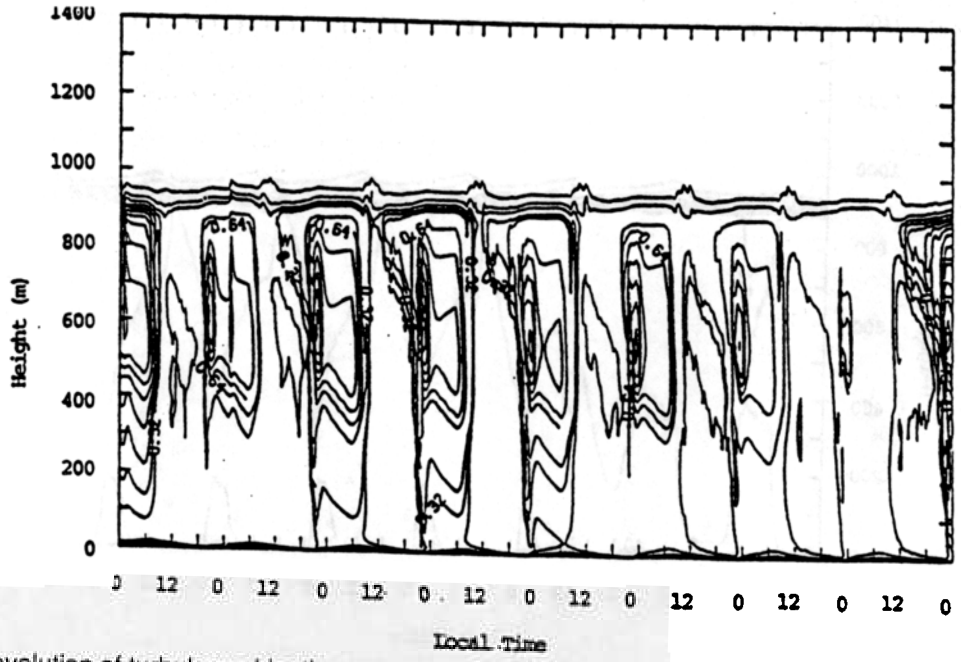

Figure 4. Time evolution of turbulence kinetic energy as a function of height.

cloud droplet, but also depresses the turbulent mixing by stabilizing the boundary layer. Overall, the physical process described above has been characterized as the "the decoupling of turbulent mixing caused by cloud radiative heating" by several theoretical and numerical approaches (e.g., Turton and Nicholls 1987; Duynkerke and Driedonks 1987) to understand the cloud-capped boundary layers. Our current study here has readdressed this issue with the FIRE data.

Future Work

Extensive sensitivity tests are required to ascertain the model validity as well as to systematically include all the possible ambient atmospheric and surface conditions. Detailed budget analyses are also useful in categorizing the cloud-capped boundary layers into a few classes. Thus, the parameterization schemes can be designed for GCM or NWP purposes.

Acknowledgments

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