A ONE-DIMENSIONAL SIMULATION OF THE STRATOCUMULUS-CAPPED MIXED LAYER

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Abstract. A marine stratocumulus model has been developed which has four major sub-models: (1) a one-dimensional version of the CSU cumulus model, (2) a partially-diagnostic higher-order turbulence model, (3) an atmospheric radiation model for both short-wave and long-wave radiation, and (4) a partial condensation scheme and cloud fractional parameterization.

A set of numerical experiments have been performed to study the interactions among the turbulence, the long-wave radiation, the short-wave radiation, and the sub-grid condensation processes. The results indicate that surface sensible eddy heat flux and not radiative cooling is the major control on the rate of cloud-top entrainment. Cloud-top radiation cooling occurs principally within the upper part of the mixed layer. However, for the stratocumulus with numerous towers penetrated into the capping inversion, most of the long-wave radiation occurs within the capping inversion. It is found that cloud-top radiation cooling is balanced by turbulence transport of sensible heat from cloud-base levels.

1. Introduction

The formulation and testing of the turbulence model and the sensitivity experiments with the model using Wangara Day 33 data have been discussed by Chen and Cotton (1983). The marine stratocumulus model is an extension of that work by the inclusion of (1) an atmospheric radiation model for both short-wave and long-wave radiative transfer through a clear, fully cloudy or partly cloudy atmosphere and (2) a partial condensation scheme and cloud fractional parameterization. An eventual goal of this modeling work is to use the model or a simplified version of it as a turbulence closure scheme in a three-dimensional mesoscale model of cloud systems. In fact, using a computer package developed at NCAR, the one-dimensional (1D) model described herein is simply a 1D version of the 3D cloud mesoscale model described by Tripoli and Cotton (1982).

Lilly (1968) studied the cloud-capped mixed layer by using a mixed-layer model. As indicated by Deardorff (1980b), Lilly's mixed-layer model has the following assumptions:

(i) the boundary layer is well mixed for the semi-conservative mean variables;
(ii) the capping inversion has negligible thickness;
(iii) the cloud fractional coverage is 100%;
(iv) there is no wind shear;
(v) there is no drizzle;
(vi) the radiative divergence is entirely within the capping inversion;
(vii) a $\theta_e$ or $\theta_u$ jump must exist across the capping inversion in order to maintain the stratocumulus cloud layer;
(viii) the mixed-layer model is closed by either the maximum or the minimum entrainment rates at the top of the mixed layer.

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From the energy budget of turbulence kinetic energy of the mixed layer, neither the maximum nor the minimum entrainment rate is reasonable. Schubert et al. (1979) modified assumptions (viii) by assuming a linear interpolation of the maximum and minimum entrainment rate. Deardorff (1980b) further investigated the cloud-capped mixed layer by using his three-dimensional model. In this paper we will attack the same problem using a one-dimensional model accompanied with a detailed radiation parameterization and sub-grid condensation scheme.

According to the analysis work reported by Noonkester (1979), the evolution of marine stratocumulus is sensitive to radiative cooling and warming. In order to obtain the exact profile of the radiative flux in the atmosphere, one may solve the monochromatic radiation transfer equations separately. The total flux can be calculated by the integration over the whole spectrum. It is obvious that this integration method will put a heavy burden on a computer. Therefore, some parameterizations are adopted to represent the radiation transfer process in the atmosphere.

The radiation model consists of two parts: short-wave and long-wave radiation. The parameterization of long-wave radiation flux through a clear atmosphere follows Rodgers (1967). Because of the presence of cloud, however, Rodgers’ clear-air emissivity approach is no longer valid. Stephens (1978) solved this problem by introducing the ‘effective’ emissivity of the cloud, where the cloud-layer emissivity is parameterized from observations. For the emissivity of an air column containing a clear and cloudy atmosphere (or a partially cloudy atmosphere), Herman and Goody’s (1976) ‘mixed-emissivity’ assumption is adopted.

The short-wave radiation model includes atmospheric molecular scattering, Lacis and Hansen’s (1974) ozone absorption, and Stephens’ (1978) parameterization of reflectance, transmittance and absorptance of a cloud layer. The structure of the short-wave radiation model follows that of Stephens and Webster (1979), which is a two-stream model (upward and downward flux). Stephens’ (1977) ‘equivalent transmittance’ is employed to derive the reflectance, transmittance and absorptance of a ‘clear-cloud mixed’ atmosphere.

Because Stephens’ parameterization of short-wave radiation through a cloud layer can be ‘tuned’ to match the results from a detailed theoretical model, one can be more confident of its quantitative value. The exact profile of the radiative variables – reflectance, transmittance and absorptance of a cloud layer – is important to the diurnal evolution of a stratocumulus. This is because the ‘penetrative distance’ by the short-wave radiation is determined by the above-mentioned radiative variables. The simulation of summer-time Arctic stratus (Herman and Goody, 1976) shows that the penetration of short-wave radiation into the cloud is the source of heating which leads to the formation of two separate cloud layers. However, for a high water content cloud, the penetrative distance is very shallow.

The ‘all or nothing’ condensation scheme is replaced by a ‘partial condensation’ parameterization. We adopt a scheme which is similar to Banta and Cotton (1980). The basic assumption of this scheme is that the variable \( r - r_s \) is distributed according to a probability density function. The variables \( r \) and \( r_s \) represent the total water mixing ratio and the saturation mixing ratio. Two types of probability density function are tested: