Parameterization of Stratus- and Cumulus-topped Boundary Layers in the Eastern Pacific

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1. Introduction

Boundary layer clouds play an important role in the heat and moisture budgets of the atmosphere over the subtropical oceans. In particular, their impact on planetary albedo and boundary layer entrainment makes their accurate representation critical for climate simulations.

Available boundary layer parameterizations in the MM5 have in the past produced a positive bias in albedo over the northeastern Pacific Ocean, while underestimating the diurnal cycle of liquid water path. Because of the difficulties in accurately representing the internal structure of the marine boundary layer, as well as the lack of representation of boundary layer cumulus clouds, there has been a tendency to establish and maintain a persistent stratocumulus deck at all times over much of the region.

To address these issues, a new planetary boundary layer (PBL) scheme for the MM5 is introduced which utilizes a 1.5 order turbulence closure model based on variables conserved under condensation. Representation of entrainment processes at the top of the turbulent PBL is expressed through an entrainment parameterization.

In conjunction with the PBL scheme, a parameterization for moist shallow convection is under development. This scheme is an entraining plume model, using a mass-flux closure influenced by convective inhibition (CIN) and boundary layer turbulent kinetic energy (TKE).

Results from simulations of the month of June, 1987 are presented. Comparisons are made between MM5 runs using the Blackadar high resolution PBL scheme (HIRPBL) and the new scheme (UWPBL), and between simulated and observed shortwave radiation for the period.

2. Model Description

The UWPBL scheme follows the work of Grenier and Bretherton (2000), which describes the development of a PBL parameterization for large-scale models. Within the boundary layer, this parameterization predicts the time evolution of TKE using a 1.5 order turbulence closure model (TCM). The turbulent fluxes of thermodynamic quantities and of momentum are also predicted. Surface fluxes are diagnosed from similarity theory, and the depth of the boundary layer evolves based on an entrainment closure described below.

In order to minimize errors in the turbulent fluxes of moisture and latent heat, thermodynamic variables are introduced which are conserved for the condensation and evaporation of water. The prognostic variables are then the components u and v of the horizontal wind, total water q_t defined by

$$q_t = q_v + q_l \tag{1}$$

and liquid potential temperature θ_l defined by

$$\theta_l = \frac{L}{C_p \Pi} - q_l \tag{2}$$

where q_v is the water vapor mixing ratio and q_l is the liquid water mixing ratio. Π represents the Exner function.

Turbulent mixing within the boundary layer is expressed in terms of K-theory, with diffusivities dependent on both local stability and TKE, as well as a length scale representing the structure of the turbulent layer.

At the top of turbulent layers, which may incorporate one or more model layers, an entrainment closure is utilized to diagnose entrainment fluxes of momentum and thermodynamic variables into the layer. The entrainment rate at the flux level defining the top of the layer is expressed as

$$w_e = A\frac{E^{3/2}}{l\Delta b} \qquad (3)$$

where E and l are the TKE and master length scale from the TCM, Δb is the buoyancy jump across the level, and A is a moisture-dependent entrainment efficiency parameter of the form proposed by Turton and Nicholls (1987).

Shallow convection originating in the boundary layer is represented through a population of entraining/detraining plumes. Following Kain and Fritsch (1990), plume air is mixed with environmental air at each model layer, and mixtures which are negatively and positively buoyant are respectively detrained and entrained.

Air entering the base of a plume is specified to have the properties of a source layer comprising one or more model layers.This air is given an initial velocity based on the square root of the local TKE, and if it is able to reach its level of free convection, convection ensues. The mass flux at the cloud base, M_{cb}, is then determined by the equation

$$M_{cb} = r_1 \rho e^{-r_2 C / E_{bl}} \sqrt{E_{bl}} \qquad (4)$$

where ρ is density, is C is the CIN, E_{bl} is the boundary layer average TKE, and r_1 and r_2 are nondimensional coefficients.

As a plume reaches its level of neutral buoyancy, it may penetrate the inversion above, and entrain air into the boundary layer. Following Wyant et al. (1997), the downward mass flux resulting from this process is expressed as

$$M_{cb} = \frac{AM_c}{\mathrm{Ri}} \qquad (5)$$

where M_c is the mass flux at the inversion base and A is a nondimensional constant. Ri is a bulk Richardson number defined at a flux level as

$$\mathrm{Ri} = \frac{B_c z_c}{w_c^{\ 2}} \qquad (6)$$

where B_c is the buoyancy of the plume in the layer above, z_c is the height of the plume, and w_c is the plume velocity at the flux level.

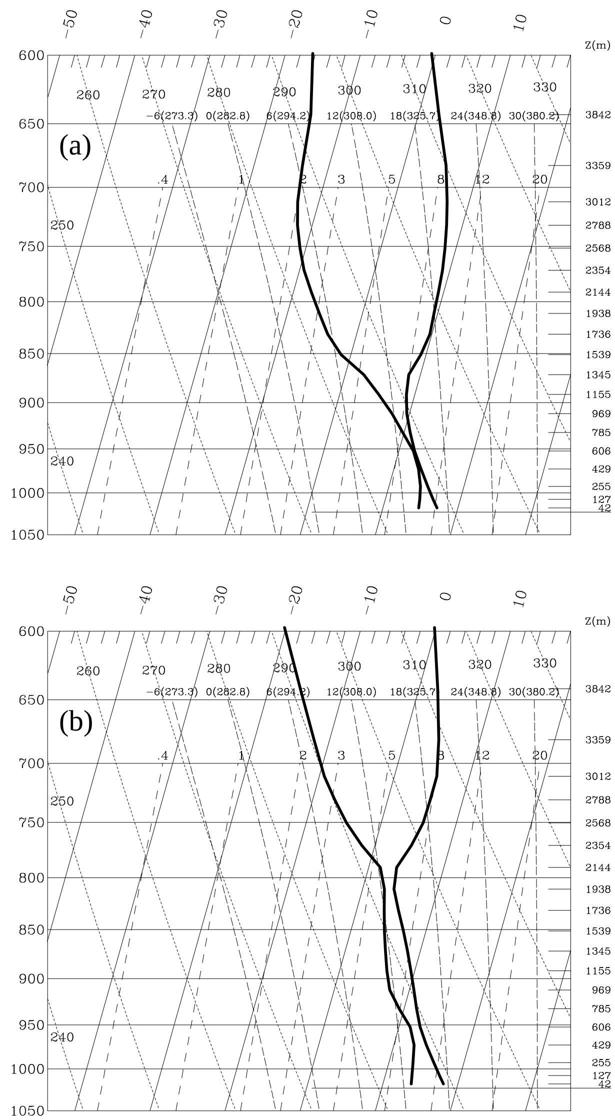

Figure 1. Mean nighttime soundings for the model grid point at 30˚ N, 140˚ W for June,1987. (a) HIRPBL, (b) UWPBL.

3. Results

After modeling a number of idealized boundary layers using a one dimensional version of MM5, the UWPBL and HIRPBL schemes were compared in a three dimensional simulation of the northeastern Pacific Ocean during the month of June, 1987. The horizontal grid spacing was 60 km, and there were 28 layers in the vertical. The area examined, extending from 15˚ N to 45˚ N and from 115˚ W to 160˚ W, is characterized by high stratocumulus cloud amount near the coast and a transition to a trade cumulus regime in the southwest.

Throughout the domain, the UWPBL parameterization produces deeper and less saturated marine boundary layers than the HIRPBL scheme. Figure 1 shows the mean nighttime soundings for a typical point near the center of the domain, located at 30˚ N, 140˚ W. While the Blackadar scheme produces a shallow, cloud-topped PBL, the UWPBL scheme develops a dry mixed layer near the surface, with a decoupled conditionally unstable convective layer above, much as observed in the sounding at that location shown in Klein et al. (1995).

Panels (a) and (b) of Figure 2 show the mean outgoing shortwave radiation at the top of the atmosphere for the domain, as simulated by the MM5 using the HIRPBL and UWPBL schemes. Panel (c) shows the ERBE monthly mean shortwave exitance for the same period. The UWPBL parameterization produces a field qualitatively similar to the observations, with a region near the coast of high albedo associated with persistent stratocumulus, and a downward gradient to the southwest.

The UWPBL scheme demonstrates a negative bias in upwelling shortwave in the southeastern portion of the domain. The result suggests that stratocumulus is not being properly maintained, which may in part be due the partitioning of sensible and latent heat fluxes between the TCM and the convective mass flux scheme. Interactions between the stratocumulus and cumulus parameterizations in the model will be the subject of future research.

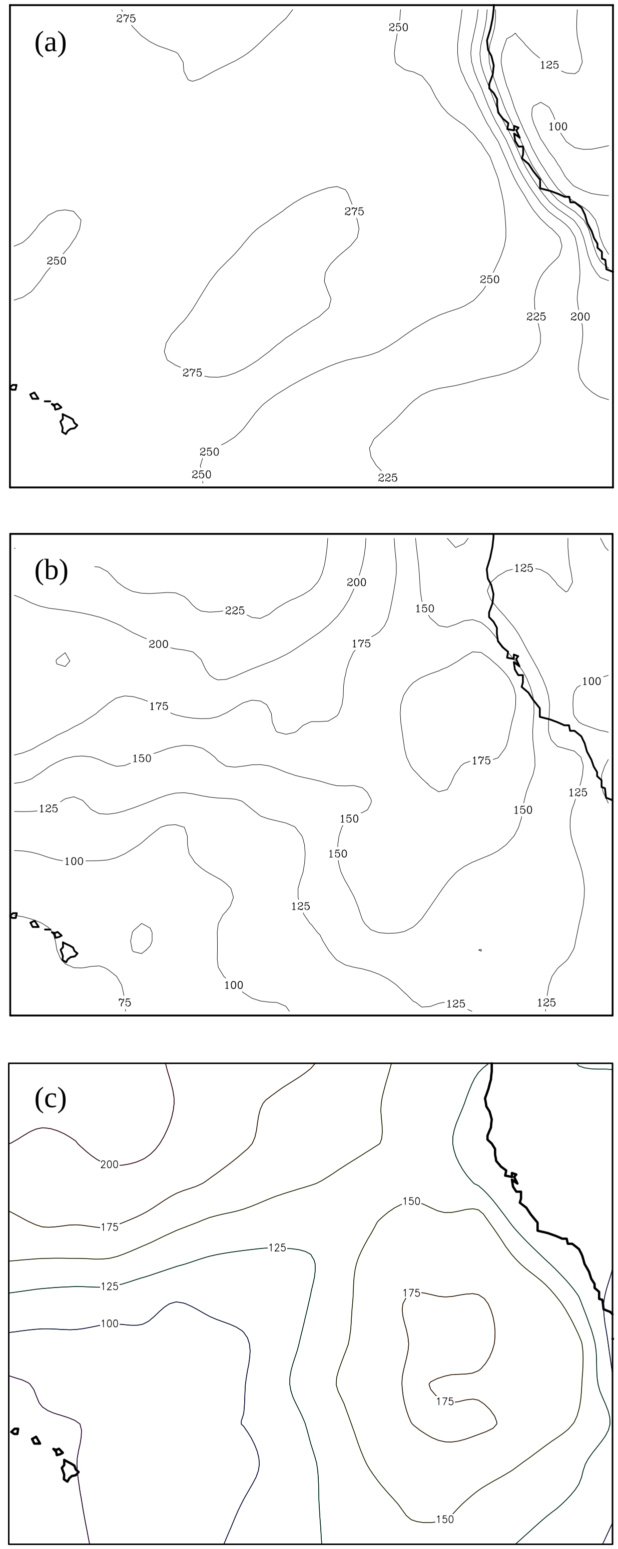

Figure 2. Mean upwelling shortwave radiation for June, 1987 from MM5 using (a) HIRPBL and (b) UWPBL, and (c) observed.

4. Summary

Preliminary evaluation of a new PBL parameterization shows an improvement in the simulated structure and radiative properties of the marine boundary layer. Under the scheme, turbulence in the boundary layer can be represented by both a TCM and a mass flux scheme, and additional work is needed to understand the interaction of these two components and their respective entrainment formulations.

5. Acknowledgments

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6. References

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