1.2 SIMPLE, LARGE-EDDY, BUOYANCY FLUX MODEL FOR CLOUDY BOUNDARY LAYERS

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1. INTRODUCTION

The dynamics of cloudy boundary layers generally cannot be resolved by the grids used in mesoscale meteorological models, so some subgrid parameterization of the cloud dynamics is required. The circulation structure, buoyancy flux profile, and cloud-top entrainment rate are strongly interdependent, which complicates attempts at formulating unified single-column models that will be valid for quite different layer dynamics (e.g., stratocumulus versus shallow cumulus). In recent work, Lewellen and Lewellen (2004) (LL04 hereafter) presented a simple formulation for representing the buoyancy flux in partly cloudy boundary layers, and used that result, together with previous work on cloud-top entrainment, to formulate predictions for quasi-steady cumulus-coupled layers. We summarize those results in the first two sections below before outlining ongoing work extending those results into a fully-coupled single-column model. Details and more complete references may be found in LL04.

2. BUOYANCY FLUX REPRESENTATION

In a partly cloudy atmospheric boundary layer we can formally write the horizontal mean buoyancy flux as,

$$\overline{w'\theta_v'} = (1-\hat{R})D + \hat{R}W \quad , \tag{1}$$

where $D(z)$ and $W(z)$ represent the "dry" and "wet" buoyancy fluxes that would result if the layer were all clear or all cloudy, respectively, at height z, and $\hat{R}(z)$ represents the ratio of the actual liquid water flux to the liquid water flux that would arise for completely cloudy conditions. To good approximation D and W can be expressed as linear combinations of the fluxes of two conserved quantities, liquid potential temperature (θ_l) and total water (q_t). If the vertical velocity and cloud water were completely uncorrelated then (1) would hold with $\hat{R}(z)$ equal to the mean partial cloud fraction. This is generally not the case, however, particularly for shallow cumulus, where the actual $\hat{R}$ can exceed the existing cloud fraction by a large factor.

Motivated by LES results and simplified mass flux models of cumulus plumes, an approximation to $\hat{R}$ can be written in the form,

$$\hat{R} \approx \frac{q_l^{sc} - q_l^b}{s^{sc} - s^b} \quad , \tag{2}$$

where $q_l^{sc}(z)$ is the liquid water of a parcel at height z that has near-surface values of θ_l and q_t, s^{sc} is the difference between the total water and saturation mixing ratios of such parcels, and $q_l^b(z)$ and $s^b(z)$ are the analogous quantities for parcels possessing the mean values of θ_l and q_t at height z. Details of the formulation can be found in LL04, including a modification of q_l^{sc} and q_l^b to approximately take into account the effects of fluctuations in parcel properties.

The only information needed to evaluate (2) are the mean θ_l and q_t profiles. It does not require knowledge of less accessible quantities such as the mean liquid water, cloud fraction, saturation variance, or vertical velocity skewness, as in related formulations (e.g., Bechtold and Siebesma (1998); Cuijpers and Bechtold (1995); Lewellen and Yoh (1993)), nor does it invoke any assumptions about lateral entrainment/detrainment into updraft plumes.

Comparison with a broad range of LES results has shown that the formulation does a good job representing the buoyancy flux, bridging between the limits of layers that are well characterized by joint-Gaussian pdfs (such as stratocumulus) and cumulus-coupled layers with strongly correlated clouds and updrafts and very low cloud fractions. Samples of the comparisons to LES results are given in figures 1 and 2. The four cases of fig. 1 are from idealized quasi-steady simulations of shallow cumulus for different conditions. The two in fig. 2 represent more realistic cases used in recent GCSS-WG1 LES model intercomparisons: a diurnal cycle of shallow cumulus over land (Brown et al., 2002) based on data taken at the Atmospheric Radiation Measurement (ARM) site, and, as part of the European Project on Cloud Systems in Climate Models (EUROCS), a diurnal cycle of marine stratocumulus (Duynkerke et al., 2003).

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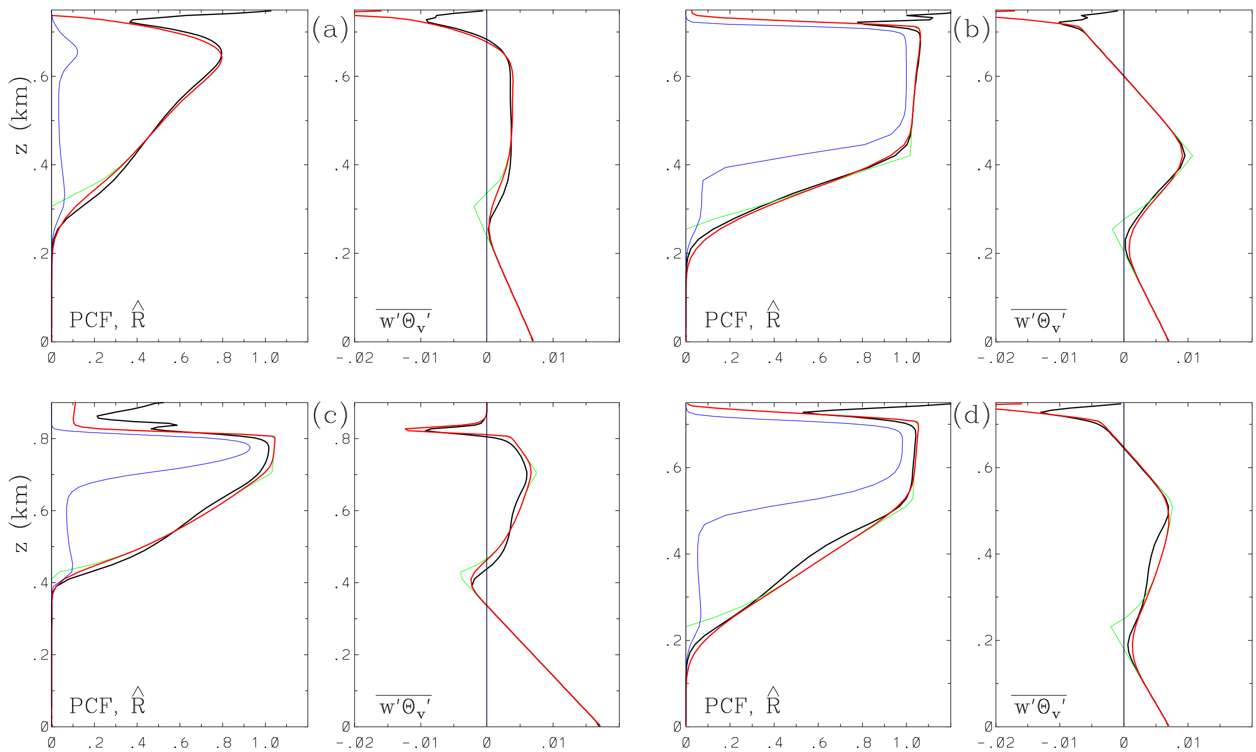

Figure 1: Mean vertical profiles of cases R1 (a), T0 (b), NHb (c) and M1 (d) from LL04. Lines represent partial cloud fraction (blue), $\hat{R}$ (black, in left panel of each pair), and $\overline{w'\theta'_v}$ (black, right panel) from LES results, and corresponding modeled $\hat{R}$ and $\overline{w'\theta'_v}$ without (green) and with (red) inclusion of fluctuation effects.

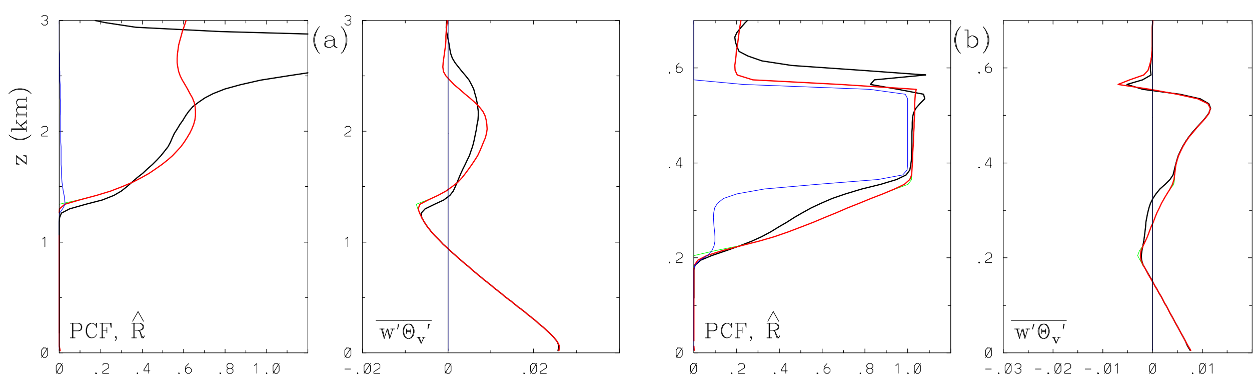

Figure 2: Mean vertical profiles from sample GCSS-WG1 cases: (a) ARM case at simulation hour 12 (1730 local time (LT)) (b) EUROCS case at simulation hour 14 (1400 LT). Lines and variables as in fig. 1.

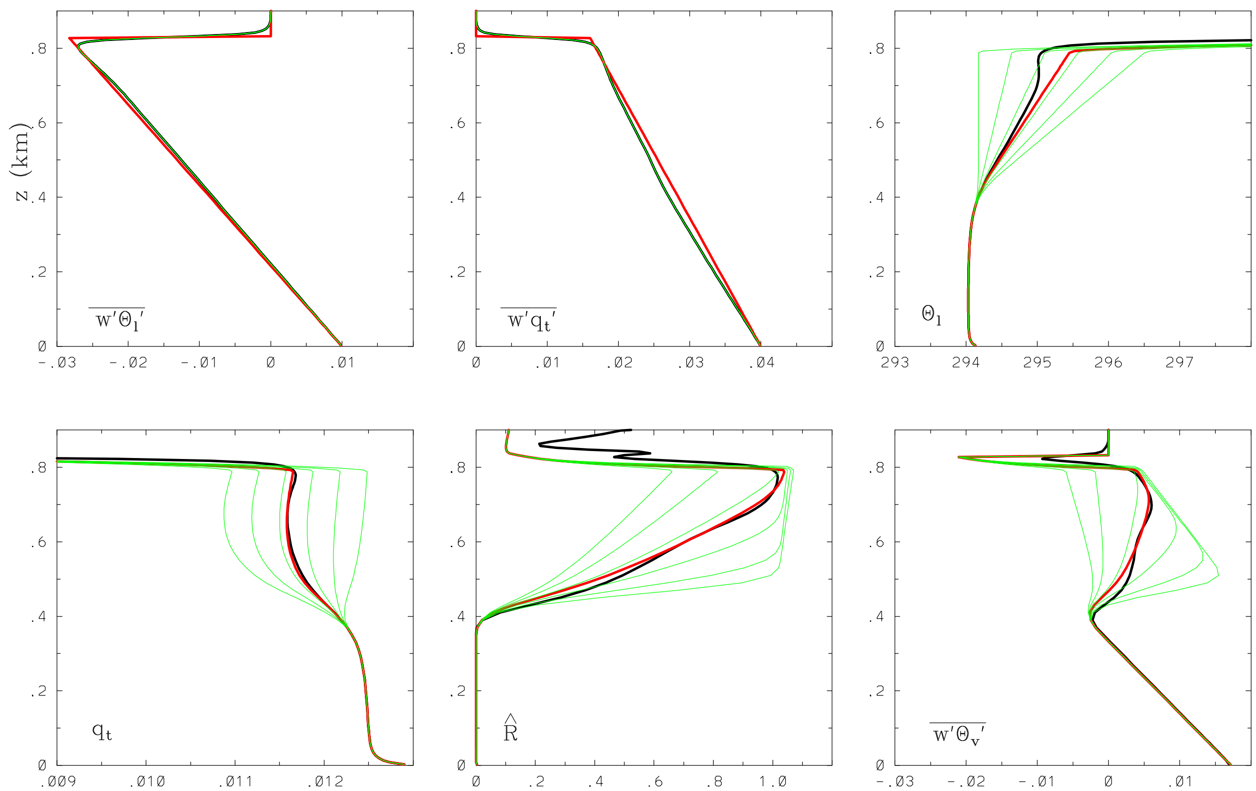

Figure 3: Sample mean vertical profiles from case NHb of LL04. Black lines are LES results; green lines are sample members of a one-parameter family of approximate solutions; red lines are the predicted members of this family satisfying the entrainment constraints.

Note that by construction $\hat{R}$ turns on at the lifting condensation level of the parcels with near-surface properties, and goes to one at heights where parcels with the local mean θ_l and q_t would be saturated. The modeled $\hat{R}$ properly follows the steep increase of the LES measured one in the column cloud region of cumulus-coupled layers, while the partial cloud fraction remains small. The model performs particularly well for transitional layers in between uniform stratocumulus and well-developed shallow cumulus. In such cases (e.g., cumulus under stratocumulus) the behavior differs from that predicted by the formulation of Bechtold and Siebesma (1998), which was empirically fit to the limits of very high or very low cloud fraction. In the present formulation there is not a one-to-one correspondence between the effective cloud fraction $\hat{R}$ and the mean cloud fraction. The underlying dynamical regime is important as well, and is reflected in the structure of the θ_l and q_t profiles. Moreover, because of the dependence on near surface values of θ_l and q_t, the formulation is non-local in z.

3. STEADY CUMULUS PREDICTIONS

The representation for the buoyancy flux described above allows us to extend previous work on cloud-top entrainment (Lewellen and Lewellen, 1998) to partly cloudy cumulus layers, with good agreement with LES results (LL04). In turn these results can be used to extend previous work on the relationship between entrainment and quasi-steady circulation structure in cloudy boundary layers (Lewellen and Lewellen, 2002), to predict the structure in quasi-steady cumulus-coupled layers. We argued in Lewellen and Lewellen (2002) that in cumulus-coupled layers the large-eddy entrainment predictions should be applied separately to the cloud and subcloud layers. The feedback between large-scale circulation structure and cloud-top entrainment is a critical ingredient in determining the quasi-steady properties a layer will equilibrate to, including the θ_l and q_t profile shapes. By postulating a one-parameter family of profiles for these conserved variables, it is possible to use the entrainment constraints to choose from among this family. The quasi-steady predictions require only a minimal set of input parameters to be given (the surface fluxes of θ_l and q_t, their mean subcloud values,

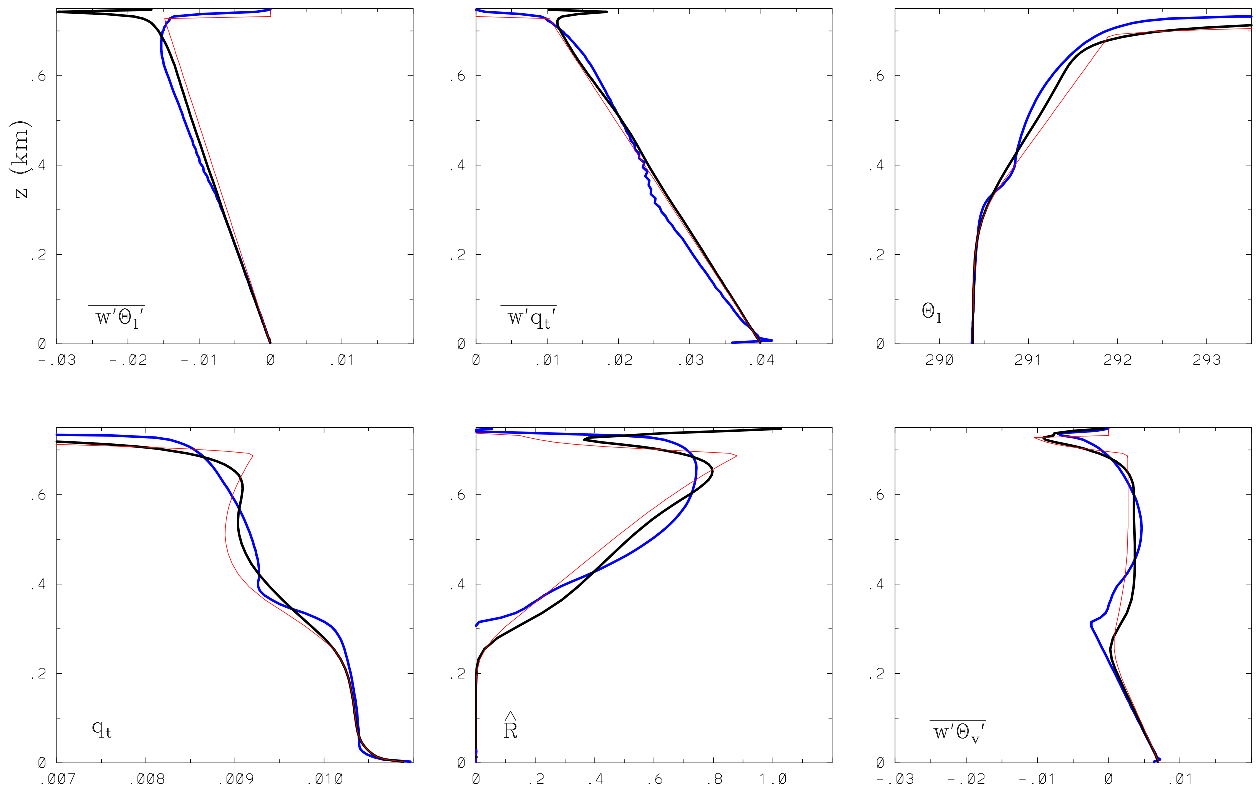

Figure 4: Results from the single-column model described in the text (blue lines) for case R1. Black and red lines as in fig. 3.

their respective jumps across the top of the layer at z_i, and specified vertical profiles of any sources they may have within the layer).

Figure 3 illustrates an example of the results, compared with LES, for the same case as in fig. 1c (predictions for the other cases in fig. 1 are included in plots in the following section). The linearity of the $\overline{w'\theta_l'}$ and $\overline{w'q_t'}$ profiles follows from quasi-steadiness; the slopes and intercepts are determined by satisfying the entrainment conditions for the subcloud circulation (together with the surface fluxes and the ratio of the θ_l and q_t jumps at cloudtop). A one parameter family of θ_l profiles is postulated (chosen linear within the cloud layer and then interpolated smoothly to cloudtop and subcloud values above and below). Simple mass flux relations then lead to the corresponding family of q_t, $\hat{R}$, and $\overline{w'\theta_v'}$ profiles. Finally, the member of the one parameter family of solutions that satisfies the entrainment conditions for the cloud layer is singled out. Again details and a broader range of examples may be found in LL04.

Given the limitations of the one parameter family of θ_l profiles chosen, the predictions prove to capture the basic structure of the quasi-steady LES results quite well. Much is predicted from a minimal set of physical inputs, without invoking a posteriori features of the LES results such as the buoyancy flux, cloud fraction, entrainment rate, or temperature and moisture differences between the cloud and subcloud layers. The success of the predictions for many different cases supports the picture of the physical feedbacks on the large-eddy scale that are assumed responsible for constraining the buoyancy flux. This may explain in part the results from LES studies (e.g., Brown (1999)) showing insensitivity to resolution and subgrid model of the mean flux profiles for quasi-steady cumulus simulations even though the structure of the individual cumulus plumes shows a clear sensitivity.

4. LARGE-EDDY SINGLE-COLUMN MODEL

In attempting to formulate a unified single-column model to handle a broad range of cloudy boundary layer dynamics, we join company with many related existing efforts (e.g., Lappin and Randall (2001); Golaz et al. (2002); Cheinet (2004)). The quasi-steady model above does not predict any time dynamics, but its success suggests that a fully coupled single-column model might perform well given some (even crude) mass-flux type representation of the fluxes, together with the nec-

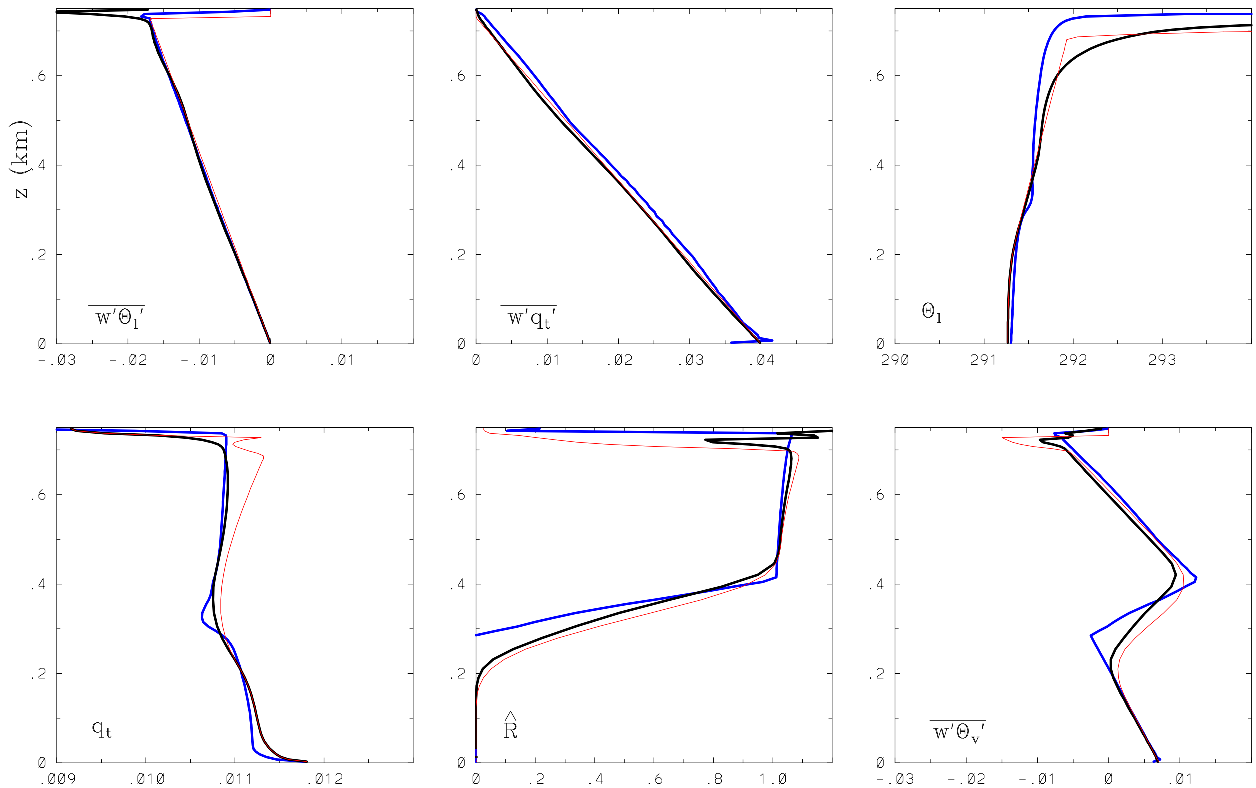

Figure 5: As in fig. 4 for case T0.

essary feedbacks to represent the proper entrainment constraints. To test this idea we start from an existing TKE-based single column model (in fact the subgrid parameterization of our LES model), which performs well in many shear-driven or well-mixed regimes, and attempt to extend its success in a unified way into the shallow cumulus regime. Since the model is in many aspects still under development we provide only a schematic description of the equations and give some preliminary results.

The model is built around the vertical velocity variance equation written as:

$$\frac{\partial \sigma_w^2}{\partial t} = 2\overline{wB} - \beta\frac{\partial (S_k\sigma_w^3)}{\partial z} + \frac{\partial}{\partial z}(\nu_e\frac{\partial \sigma_w^2}{\partial z}) - 2\sigma_w^3/\Lambda_d \quad . \tag{3}$$

The first term on the right-hand side is the buoyancy flux; the next two are turbulent transport terms, the first representing a large-eddy, plume-like flux and the second a small-eddy diffusive flux; the final is the dissipation term. An expected turbulent pressure gradient term is omitted, but the magnitude of the large-eddy flux and dissipation terms are adjusted with the intent of capturing some of its effect. The thermal and humidity conservation equations are also modeled with both a mass-flux and a diffusive turbulent flux term as (with ψ representing either θ_l or q_t):

$$\frac{\partial \psi}{\partial t} = -\frac{\partial}{\partial z}(\gamma\sigma_w(\psi_p - \psi) - \nu_e\frac{\partial \psi}{\partial z}) \tag{4}$$

$$\frac{\partial \psi_p}{\partial z} = -(\psi_p - \psi)/\Lambda_m \quad . \tag{5}$$

$\overline{wB}$ is related to the θ_l and q_t fluxes using $\hat{R}$ as sketched above in section 2 and detailed in LL04. The plume mixing length, Λ_m, is governed (in different parts of the layer) by either the distance to the surface, the layer depth, or the scale σ_w/N (with N the local Brunt-Väisälä frequency). The dissipation length, Λ_d, depends, in addition, on the vertical velocity skewness, S_k. The simple top-hat updraft-downdraft model motivates the S_k dependence in the equations and parameters such as Λ_d and γ; the profile of S_k itself is currently chosen to be piecewise linear with its value tied to $\hat{R}$. The eddy viscosity, ν_e, and much of the remaining model structure (such as the surface parameterization) are currently simply carried over from the existing TKE model.

Figures 4-7 show results of the model after several hours of simulation, compared with LES results at the same time and the quasi-steady predictions of section 3. The four cases are those of fig. 1. In general the model performance is good, and it handles well-mixed

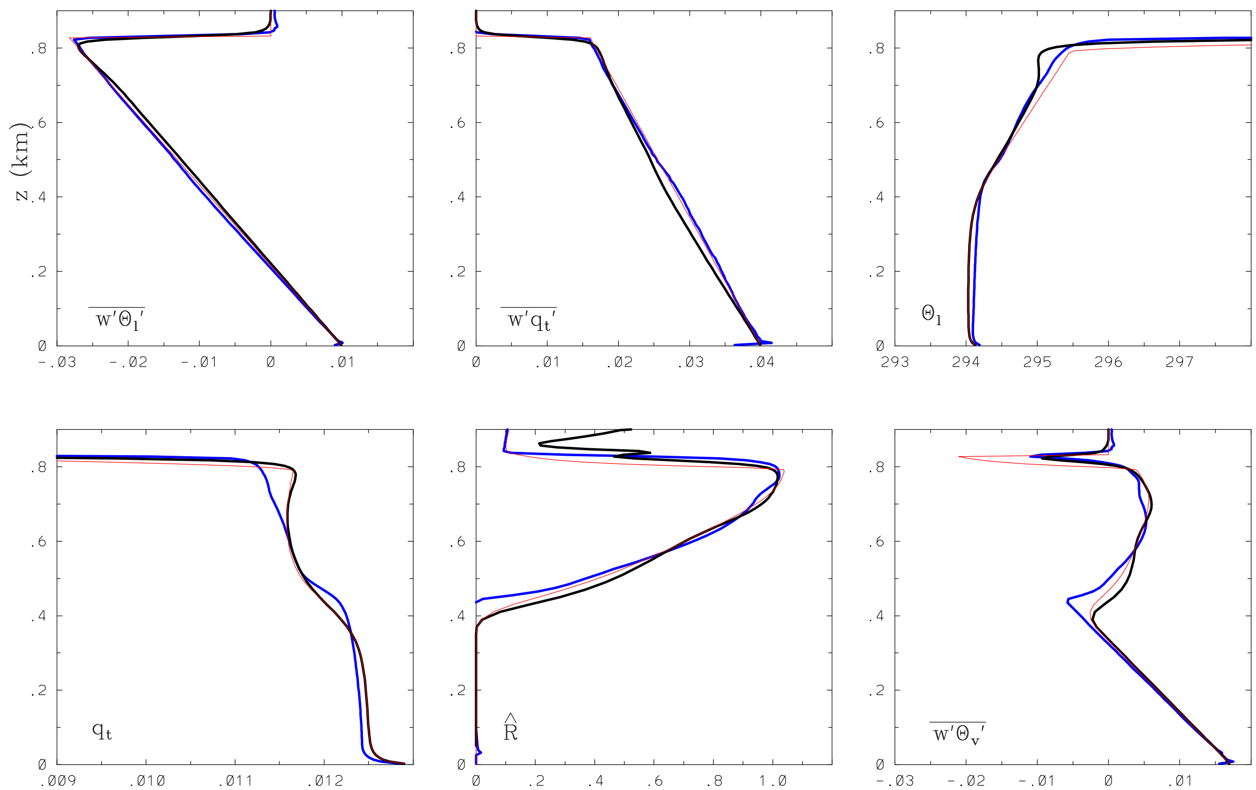

Figure 6: As in fig. 4 for case NHb.

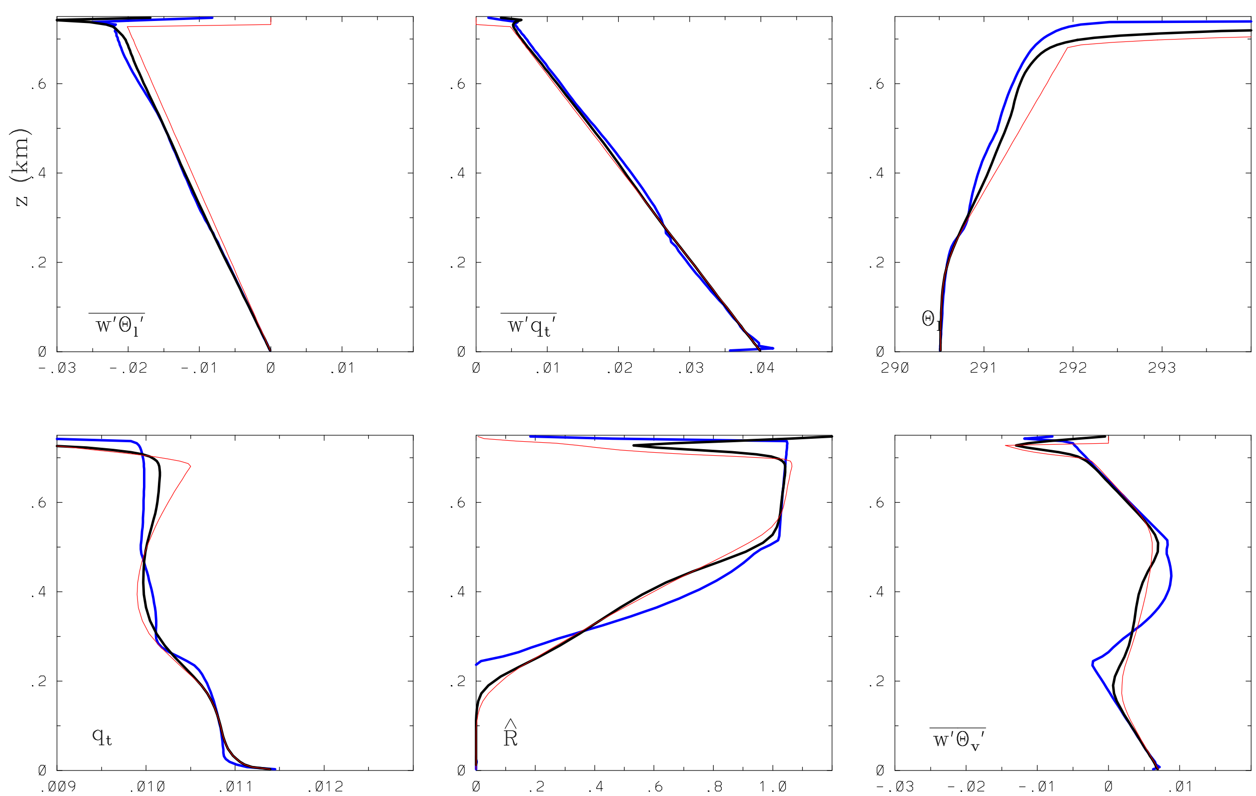

Figure 7: As in fig. 4 for case M1.

layers equally well. Compared to the results of LES and the quasi-steady model, $\hat{R}$ turns on at a systematically greater height in the coupled single column model (likely because the fluctuation contributions to $\hat{R}$ have not yet been included there). There are many issues to be improved upon in the model, and others that remain to be addressed. Nonetheless, it is promising in that it seems to correctly capture the basic feedback between entrainment, the θ_l and q_t profiles, $\hat{R}$, and the buoyancy flux, that is responsible for setting up the equilibrium structure in the cumulus-coupled boundary layer.

5. ACKNOWLEDGMENTS

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