3B.6 A PARAMETERIZATION FOR MIXING IN MOIST TURBULENT THERMALS

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1. INTRODUCTION

With the ultimate goal of improving convective parameterization schemes used in atmospheric general circulation models, we perform numerical simulations of an initially warm and saturated thermal rising through a stably stratified atmosphere. The simulations are performed using the two-dimensional version of a fully compressible and nonhydrostatic model, the Advanced Regional Prediction System or ARPS (see Xue *et al.*, 2000 for a detailed description of ARPS). Our main objective is to evaluate the following parameterization for the thermal's fractional mixing rate:

$$\mu_T \equiv \frac{1}{M_T}\frac{dM_T}{dt} = \frac{\alpha_m U_{TKE}}{R_T} \quad , \qquad (1)$$

where M_T is the thermal's mass per unit length, α_m is a non-dimensional mixing coefficient, R_T is the the thermal's equivalent-area-radius, ρ_0 is the density of the air in the thermal's environment, and U_{TKE} is the root-mean-square velocity of air as measured in a frame of reference moving upwards with the thermal at speed w_T. Note that (1) is formally equivalent to Morton *et al.*'s (1956) "turbulent entrainment hypothesis" (TEH) when U_{TKE} is replaced by w_T. The physical interpretation of both is that the mixing of environmental air into the thermal is driven by turbulence.

2. EXPERIMENTAL SETUP

The model domain is 15 km tall and 30 km wide with 50 m grid spacing in both directions. The base-state atmosphere is in hydrostatic balance and the dry Brunt-Vaisalla frequency, i.e. N =1.2 x 10^{-2} s^{-1}, is constant with height. Momentum advection is performed using a fourth-order quadratically conservative scheme while scalar advection is performed using monotonic flux-corrected transport. The effects of SGS mixing are represented using a 1.5-order turbulence kinetic energy parameterization. Moist physical processes are handled using a simple saturation adjustment scheme and precipitation processes are neglected. Sponge layers are added above 10 km to damp the reflection of vertically propagating gravity waves. All boundaries act as rigid walls.

The saturated thermal is generated by introducing a uniform 1 K potential temperature perturbation over a circular area whose radius is 1 km. The thermal is initially centered on the left boundary at height of 1.5 km. The mass of the thermal, M_T, is determined using a passive scalar threshold, $\psi = 0.02$, where, initially, ψ =1 inside the thermal and zero everywhere else.

3. RESULTS

Results from two experiments are presented here. In the first, the atmosphere is dry while in the second the relative humidity is constant with height at 70%. Figure 1a compares the evolution of z_T, the thermal's mean height, in the two experiments. Not surprisingly, the thermal in the moist environment (the ME thermal) travels higher than the one in the dry environment (the DE thermal). Two factors contribute to this result: First, environmental air which is mixed into the DE thermal is drier and thus, there is a potential for larger amounts of evaporative cooling (evidence for this can be found in Figure 1b which show time-series of each thermals net latent heating rate); second, between t = 0-10 mins, the fractional mixing rates are larger in the DE experiment (see the solid curves in Figure 1c which represent time-series of μ_T diagnosed from each experiment).

To evaluate our mixing parameterization, we compute the right-hand side of (1) at 15 sec intervals choosing α_m = 0.4 in each case. The results, given by the dotted curves in Figure 1c, show that (1) captures the gross differences in the "observed" μ_T time-series. Note: although qualitatively similar differences are obtained when (1) is used with U_{TKE} replaced by w_T (results not shown), the overall agreement is not as good; the predicted values of μ_T are much larger (smaller) than the observed values when w_T is large (small).

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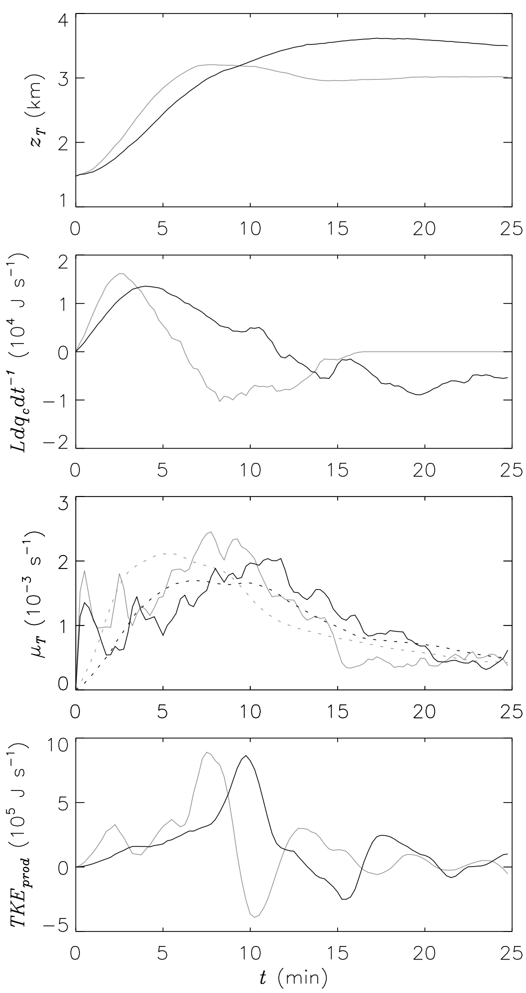

Figure 1. Bulk evolution of thermal in the moist (black curves) and dry (grey curves) environment.

The consistency between our mixing parameterization and the results of the two experiments provides evidence to suggest that the enhancement in the DE thermal's mixing rate between t = 0-8 minutes is primarily driven by higher levels of turbulence. To understand the physical mechanism for turbulence generation, Figure 1d shows time-series of each thermal's net upward turbulent buoyancy flux, *i.e.*

$$TKE_{prod} \equiv \sum_i \bar{\rho}_i (w'_i b'_i) \Delta x \Delta z, \qquad (2)$$

where i is a summation index over all grid points inside the thermal, $w_i' = w_T - w_i$ is the vertical velocity in the thermal's moving frame of reference, b_i is the buoyancy, and $\bar{\rho}_i \Delta x \Delta z$ is the mass of the ith grid cell, respectively. As expected, we see that the DE thermal is generally characterized by larger values of TKE_{prod} between t = 0-8 mins. Unexpectedly however, upon breaking the TKE_{prod} down into components associated with rising and sinking motion (results not shown), we find that the larger values between t = 0-6 minutes are primarily due to more intense warm updrafts - not cold downdrafts.

4. Discussion

Both Lin (1999) and Gregory (2001) have recently aimed to improve formulations for describing entrainment in simple plume models used in convective parameterization schemes. A common feature in both of these studies is that the equation describing the plume's fractional entrainment rate depends on coefficients that must be empirically adjusted to match either the type of convection or the properties of the large-scale environment.

Here, we have taken the first step towards developing a physically based cloud mixing formulation that may be applicable to all forms of cumulus convection (shallow or deep, squall or non-squall). Of course, implementation of this formulation in a convective parameterization will require an additional equation for predicting the cloud's turbulent kinetic energy. A simple thermal model that includes such an equation is currently being developed.

Acknowledgements: This research was supported by NSF grant ATM-9812384. ARPS was developed by the Center for Analysis and Prediction of Storms (CAPS), University of Oklahoma. CAPS is supported by the NSF and the FAA through combined grant ATM92-20009.

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