[id:272,1]

Advances in Turbulence IX
Proceedings of the Ninth European Turbulence Conference
I.P. Castro & P.E. Hancock (Eds.)

pp. 457-460

Evolution of turbulent convective entrainment in heterogeneously versus linearly stratified fluids

E. Fedorovich[1] and R. Conzemius[1]

[1]School of Meteorology, University of Oklahoma
Norman, Oklahoma 73019-1013, USA.

Contact address: *fedorovich@ou.edu*

1 Introduction

In the atmospheric boundary layer heated from below, buoyant forcing at the surface generates up- and downward turbulent motions that effectively mix momentum and scalar fields inside the layer. The resulting convectively mixed layer is separated from the stably stratified, turbulence-free fluid aloft by a comparatively narrow interfacial sublayer, through which the more buoyant fluid from the outer region is entrained into the growing boundary layer. The dynamics of convective entrainment crucially depends on thermal stratification in the outer turbulence-free flow. The particular case of continuous linear stratification corresponds to a height-constant temperature lapse rate. The stratification can also be discrete in the vertical (the case of a multilayer fluid with discontinuities in the temperature lapse rate at the interfaces between layers), or nonlinear (the case of the lapse rate gradually changing with height). The changes of flow velocity direction and magnitude with height in the stratified fluid additionally affect the properties of convective entrainment.

The convective entrainment in continuously and linearly stratified fluid has been subject to extensive field, laboratory, and numerical studies, see *e.g.* review by Stevens and Lenschow [2]. However, a consensus has not yet been reached regarding the dependence of the integral parameters of convective entrainment on the stability in the outer flow region, and on wind shear across the entrainment zone. Evolution of convective entrainment in heterogeneously (discretely or nonlinearly) stratified fluids has been studied much less. There is evidence, however, from both atmospheric observations and numerical studies that nonstationarity plays an important role in this case, and convective entrainment passes through a sequence of transition regimes accompanied by strong variations of entrainment parameters.

In our study, turbulence structure in the entrainment zone and the characerisctics of entrainment have been investigated numerically, by means of a high-resolution large eddy simulation (LES), in conjunction with relevant data from atmospheric and laboratory studies, and predictions of analytical models for particular entrainment regimes. The considered entrainment characteristics included the entrainment rate, the entrainment layer depth, and the buoyancy increment across the entrainment layer. Emphasis has been placed on entrainment parameter variations associated with sheared and shear-free convection in heterogeneously stratified fluids versus those in linearly stratified media.

2 LES of convective entrainment

The employed LES code was a modified version of the Nieuwstadt and Brost code [1] designed for convective boundary layer applications. It uses the Deardorff subgrid turbulence closure, which takes subgrid eddy diffusivities proportional to the products of subgrid length scales and square roots of subgrid turbulence kinetic energy values. The numerical simulations were performed in a rectangular domain with periodic lateral boundary conditions and no-slip conditions at the bottom, where temperature and velocity gradients were related by the Monin-Obukhov similarity functions. The buoyancy (heat) flux through the bottom of the domain was kept constant. A sponge layer was introduced in the upper one-fifth of the domain. For pressure, Neumann boundary conditions were applied at the bottom and at the top. The time advancement was carried out by a leapfrog explicit time-integration scheme with a weak time filter.

The LES data have been interpreted in terms of buoyancy, introduced as $b = (g/T_0)(T - T_0)$, where T is the temperature (potential temperature in the atmosphere), T_0 is its reference value, and g is the gravity acceleration. The mean buoyancy profile was obtained by spatially averaging the LES temperature data over horizontal planes. The LES predictions of the entrainment dynamics have been compared with analytical zero-order solutions of Zilitinkevich [3] for the equilibrium entrainment regime in a linearly stratified fluid: $\hat{z}_i = [2(1 + C_1)/\hat{t}]^{1/2}$ and $\Delta\hat{b} = C_1[2\hat{t}/(1 + 2C_1)]^{1/2}$, where $\hat{t} = tN$, $\hat{z}_i = z_i B_s^{-1/2} N^{3/2}$, and $\Delta\hat{b} = \Delta b B_s^{-1/2} N^{-1/2}$ are the scaled time t, inversion height z_i (taken as elevation of the buoyancy flux minimum within the entrainment layer), and zero-order entrainment-layer buoyancy increment Δb, respectively, N=const is the buoyancy frequency in the outer region, B_s=const is the bottom buoyancy flux, and $C_1 = \Delta b(dz_i/dt)/B_s$ is the so-called entrainment coefficient that is supposed to be constant in the equilibrium regime. Direct estimation of C_1 from the LES data provided C_1 about 0.17, which is rather close to the commonly accepted C_1=0.2.

Relationships between different parameters of shear-free entrainment in the linearly stratified fluid were evaluated and analyzed. Among them are dependencies of the relative entrainment zone thickness $\delta z_i/z_i$ on the capping inversion strength expressed in terms of different Richardson numbers: $\mathrm{Ri}_N = {z_i}^2 N^2/{w_*}^2$, $\mathrm{Ri}_{\Delta b} = \Delta b z_i/{w_*}^2$, and $\mathrm{Ri}_{\delta b} = \delta b z_i/{w_*}^2$ (left plot in Fig. 1) and on the dimensionless entrainment rate $E = (dz_i/dt)/w_*$ (right plot in Fig. 1), where $w_* = (z_i B_s)^{1/3}$ is the Deardorff convective velocity scale, and δb is the actual buoyancy increment across the entrainment layer ($\delta b > \Delta b$). It is clearly seen that the behavior of $\delta z_i/z_i$ as function of $\mathrm{Ri}_{\delta b}$ (-1/2 power law) principally differs from its dependencies on Ri_N and $\mathrm{Ri}_{\Delta b}$ (-1/3 power law). The relation between $\delta z_i/z_i$ and E in the equilibrium entrainment regime is fairly well described by the 1/3 power law.

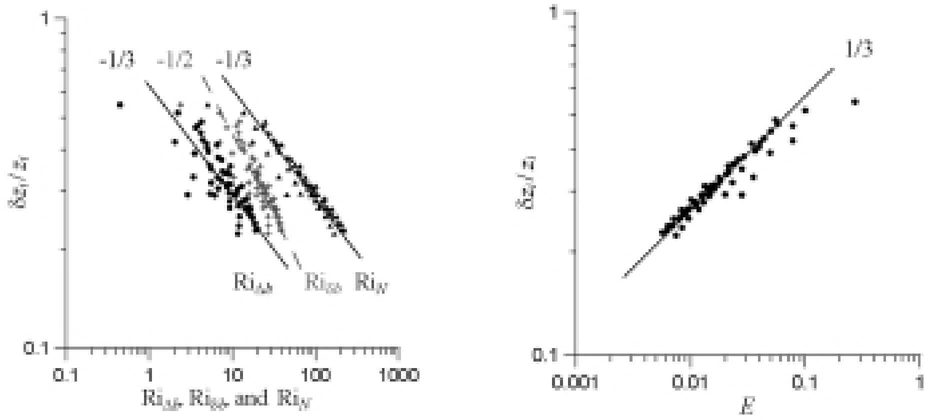

Figure 1: Parameters of convective entrainment in the linearly stratified fluid.

A series of LES runs was conducted to investigate convective entrainment in discretely stratified fluids, in continuously nonlinearly stratified fluids, and in fluids that contained shear layers co-located with temperature/density interfaces. In the experiments with discretely stratified fluids, two cases of the vertical composition of fluid were considered. In the first case (WS case in Fig. 2), the entrainment initially took place in a weakly (small N) stratified fluid with a subsequent abrupt change to a relatively strongly (large N) stratified fluid. The second investigated case (SW case in Fig. 2) was opposite to the first one: the entrainment initially occurred in a strongly stratified fluid and then proceeded to a weakly stratified fluid.

The evolution of horizontally averaged temperature profiles for the SW and WS cases is shown in Fig. 2 (two left plots). The initial temperature profiles are given by thin solid lines. In the WS case, the time lag between plotted profiles is about 500s, while in the SW case it is about 5000s. The sequence of profiles in time is as follows: solid, long-dashed, short-dashed, dotted, dashed-and-dotted.

The dependencies $z_i(t)$ shown in the right plot of Fig.2 indicate that the evolution of entrainment in heterogeneously stratified fluids can be rather different from that in the equilibrium entrainment regime ($z_i \sim t^{1/2}$) characteristic of the linearly stratified fluid (the LES data for this regime are shown by filled

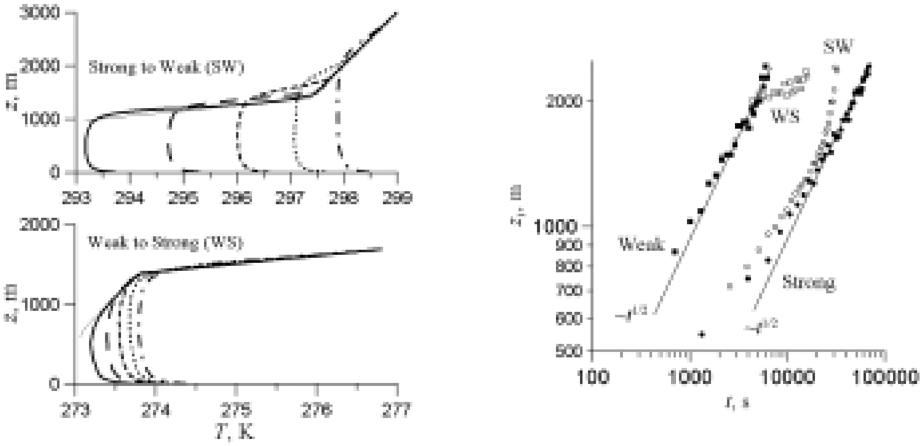

Figure 2: Convective entrainment in the WS and SW two-layer fluid systems.

markers). In the both simulated cases with heterogeneous stratification (WS and SW), the nonstationarity becomes an important feature of the entrainment evolution after the CBL top reaches the stratification discontinuity, and the $z_i(t)$ dependencies (open markers) depart sharply from the square-root behavior. The time scales of such entrainment transition have been found to be much larger than internal time scales of turbulent convection beneath the stratified fluid.

3 Conclusions

- Relations between actual parameters of entrainment in a linearly stratified fluid may be very different from zero-order model predictions.
- Adjustment of entrainment to new stratification occurs on time scales much larger that the CBL turnover time scale.

Assistance of Mathieu Pourquie in the LES code modification is gratefully acknowledged. The study was in part supported by the NSF Grant ATM-0124068.

References

[1] F. T. M. Nieuwstadt and R. A. Brost. Decay of convective turbulence. *Journal of the Atmospheric Sciences*, 43:532–546, 1986.

[2] B. Stevens and D. H. Lenschow. Observations, experiments, and large eddy simulation. *Bulletin of American Meteorological Society*, 82:283–294, 2001.

[3] S. S. Zilitinkevich. *Turbulent Penetrative Convection*. Avebury Technical, Aldershot, 179 pp., 1991.