P5.2 ENTRAINMENT ZONE DEFINITIONS: A LARGE EDDY STUDY

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1. INTRODUCTION

Recent developments in wavelet analysis techniques for determining the entrainment zone have prompted this study of different entrainment zone definitions. The adequacy of each will be investigated and a study of their physical interpretation of the mechanisms involved in the entrainment process.

The entrainment zone (EZ) is the region at the top of the mixed layer where the free atmosphere above is entrained downward into the mixed layer, and thermals overshoot upward of the mixed layer. Entrainment is responsible for the growth of the boundary layer (BL). The height of the mixed layer is important for understanding the dilution and transportation of pollutants emitted from the surface and also the turbulent structure within the mixed layer under unstable conditions, due to the height of the mixed layer limiting the vertical growth of the eddies (Gryning et al., 1987). Entrainment also plays a key role in determining the distribution and structure of stratiform clouds, particularly marine stratocumulus which is an important factor affecting the global radiation budget, and hence climate.

Entrainment is a result of turbulence driven by the surface heat flux, and turbulence generated by wind shear. Thermals which are positively buoyant at the surface rise through the mixed layer until they reach the warmer free atmosphere and become negatively buoyant; they overshoot a small distance because of their momentum (Stull, 1988). The negatively buoyant air sinks back down into the mixed layer intact due to low turbulence in the free atmosphere, so pollutants from within the mixed layer stay within the mixed layer. In the process of overshooting into the free atmosphere, free atmosphere air is drawn into the mixed layer and is quickly mixed in due to the strong turbulence within the mixed layer – thus the mixed layer grows.

2. ENTRAINMENT ZONE DEFINITIONS

The entrainment rate is impossible to measure directly in the real world, and must be inferred from other measurements. It is commonly assumed that the depth of the entrainment zone relates directly to entrainment rate, thus determining a measure of entrainment zone depth becomes important for understanding entrainment. The entrainment zone has been defined in various ways which do not necessarily produce the same result or represent the same physical mechanisms; currently there is no universally applicable definition of the entrainment zone.

The entrainment zone can be defined as the region around the inversion where the mean buoyancy flux is negative, signifying consumption of turbulent energy as less dense air is mixed down into the boundary layer. This is perhaps the most physically meaningful of the common definitions, but is almost impossible to use in the real world. The top of the EZ may be defined as the top of the highest thermal within a region and the bottom as the altitude where about 5 to 10% of the air on a horizontal plane has tropospheric properties (Deardorff, et all., 1980, Wilde et al., 1985). This definition is well suited to use with lidar if it is assumed that the lidar backscatter signal acts as a scalar quantity. An alternative definition is the region over which the mean profile of this scalar quantity has a significant vertical gradient.

These definitions may often give very different results. Figure 1 shows a typical buoyancy flux profile and corresponding water vapour mixing ratio profile (a scalar quantity) obtained as horizontal averages across the domain of a Large Eddy Simulation. The vertical lines show the variability in EZ top and bottom for

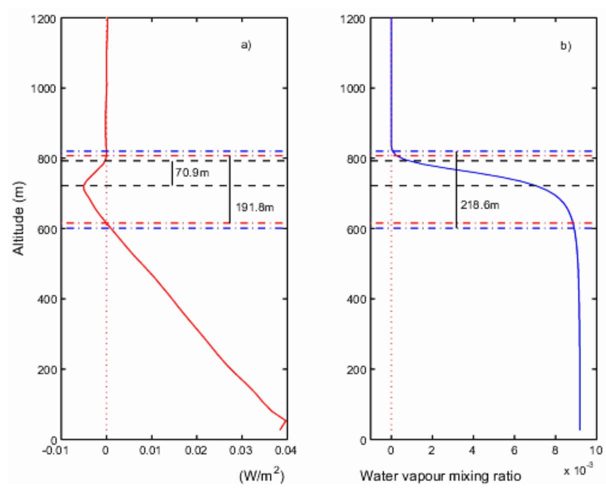

Figure 1. Comparing area averaged values for EZ top and bottom. (---- 95% and 5% limits of the variability in boundary layer top, defined by the maximum gradient in some scalar; red dot dash line area of negative buoyancy flux, blue dot dash line area of significant gradient in some scalar). These are compared with a) the buoyancy flux profile and b) the profile for the water vapour mixing ratio.

different EZ definitions applied to the same data set. For these three definitions of EZ the depth is seen to vary from 70.9m for the variability in boundary layer top method to 218.6m for the estimate based on the region

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of significant gradient in a scalar. This is a substantial difference; complicating the comparison of different studies. If the differences between EZ definitions vary in a systematic manner it may help to reveal details of entrainment of process and allow more information to be retrieved from a single data set. In this example the EZ defined by the region of negative buoyancy flux and the region of significant gradient appears to be very similar, but as will be seen this is not always the case.

These definitions all treat the entrainment zone as an average property of the boundary layer top either over some area, linear distance or time. Davis et al. (1997) suggested that this may not necessarily be the true entrainment zone thickness but rather a measure of variability in the boundary layer top, and that the local entrainment zone might be better represented by the layer over which the individual measurements of a conserved quantity change from the boundary layer to free troposphere values. Area averaged values of the EZ depth will also be affected by, for example, gravity waves which vary the BL depth without contributing to entrainment. Figure 2 shows the variability of the boundary layer top compared to the area averaged values for the EZ.

Brooks (2003) developed an automated technique for retrieving estimates of the top and bottom of the local EZ at individual locations using a wavelet covariance transform; improving on the previous implementation, which estimated a single value of BL top (Davis et al. 2000), by using multiple wavelet dilations. This technique is less sensitive to mean vertical gradients in the background signal than gradient methods. As seen in Figure 3 this method shows the top of the EZ is much less variable than the bottom of the EZ.

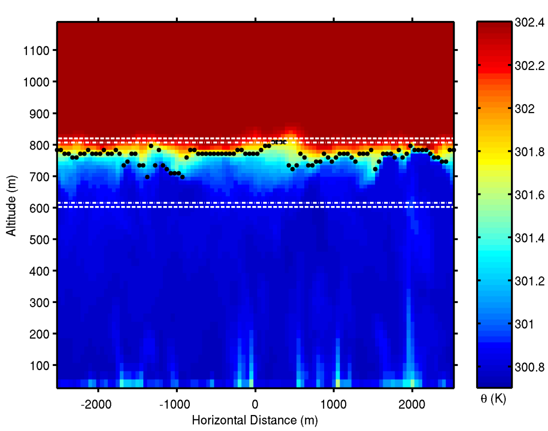

Figure 2. Cross-section of potential temperature with – White dash dot line: EZ estimated by area of negative buoyancy flux, white dashed line: area of significant gradient in some scalar quantity, black dots: boundary layer top estimated by maximum gradient in water vapour mixing ratio.

The behaviour of the local inversion depth in relation to the boundary layer conditions and area-averaged measures of entrainment zone depth could provide significant understating of the nature and scale of the mixing process. Sullivan et al. (1998) discusses dependence of entrainment mechanism on the local Richardson number $Ri_l = N^2_l L^2_H / u^2_H$, where N_i is the buoyancy frequency of the inversion, and L_H and u^2_H are the integral length scale and variance of the turbulence in the absence of the density interface. At low Ri entrainment is caused by folding of the interface due to strong rotational motions, but at a higher Ri entrainment is caused by the plumes pulling down pockets of warmer air due to strong stability and string horizontal and downward motions.

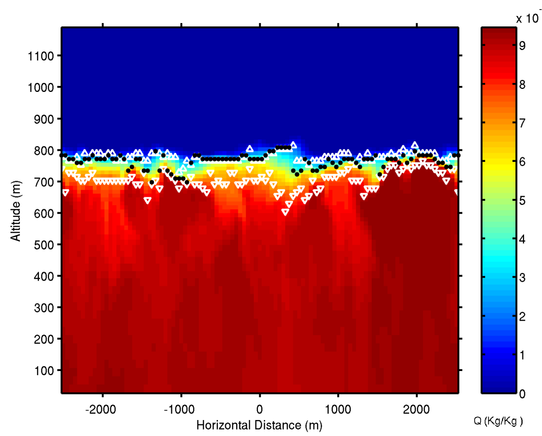

Figure 3. Cross section of water mixing ratio with – White triangle pointing up: EZ top, white triangle pointing down: EZ bottom, black dots: boundary layer top estimated by maximum gradient in mixing ratio.

3. MODELLING THE ENTRAINMENT ZONE

To simulate entrainment accurately it is important to reproduce physical processes, such as overturning of material surfaces drawing air from the stratified free atmosphere into the well-mixed boundary layer, or vertical structures in the boundary layer scouring material off the base of the inversion, (Stevens et al. 2000). Large Eddy Simulation (LES) provides a means of examining the entrainment zone through controlled numerical experiments where the entrainment rate can be directly evaluated and the inversion structure examined in detail.

It is important to use a sufficiently high resolution to resolve the small-scale entrainment mixing, particularly in cloud capped cases. Stevens et al. (2000) found the inversion structure to be a function of resolution.

The model used in this investigation of entrainment zone definitions is the UK Met Office's LEM (v2.3) which is used here to simulate the convective boundary layer in cloud free cases; so that forcing is limited to surface driven convection, and the effects of radiative forcing of convection at cloud top will not be taken into account.

The LEM will be used to simulate a variety of convective boundary layers. Various methods for defining the EZ will be explored and related to the entrainment rate: the region of negative buoyancy flux, the region of significant vertical gradient in a scalar quantity, the width of the probability distribution of estimates of boundary layer top location, and the statistics of upper and lower limits of the local entrainment zone derived from Brooks (2003) wavelet covariance transform. The intention is to find a robust way of defining the EZ depth over small scales which can then be applied to lidar data obtained in-situ over a wide range of conditions. The ultimate aim is to improve the parameterization of entrainment, and its practical assessment of BL properties from operational lidar measurements.

Within this work we will be looking at the ways in which these various area-averaged values relate and if this relationship is affected by the entrainment rate and inversion structure.

5. REFERENCES

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