Entrainment into the atmospheric boundary layer: lidar observations and LES simulations

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Introduction

Entrainment is the process whereby miscible fluid is exchanged across a density interface bounding a region of turbulent flow [17]. It is of central importance in governing the dynamics of the atmospheric boundary layer (ABL) top. In the exchange process, relatively quiescent fluid is engulfed by turbulent motions penetrating across the interface and is subsequently mixed into the turbulent region. Smaller-scale motion is damped so that a relatively sharp interface is maintained which advances into the quiescent layer causing the turbulent layer to thicken.

There is appreciably less knowledge about the details of the entrainment zone than about the lower part of the mixed layer. This can be attributed to the greater difficulty in taking accurate measurements in this region. Improved observations can be expected through the rapid development, and more common use, of instruments like lidar (light detection and ranging). Because the ABL has a greater aerosol content than the air above, causing more scattering of laser light, lidar can easily detect the boundary between the two layers ([7],[5],[8]). With ranging capabilities over distances of the order of the depth of the troposphere, a resolution of a few meters, and the ability to sample the atmosphere at a very fast rate, lidars are appropriate for analyzing the ABL structure. Here we present observations made with the Johns Hopkins University (JHU) elastic backscatter lidar system (for system specifications see Pahlow et al. [9]).

LES has been successfully used in the past to study numerous aspects of ABL turbulence ([18],[11],[14],[2]), and, to a much lesser extent, entrainment ([12],[15]). Initial results of a comparison study between lidar data and LES simulations will be shown, where we focus on the structure of the ABL top.

Lidar observations

Lidar data, obtained during the Baltimore PM Supersite project, are used to delineate mechanisms that are responsible for entrainment into the ABL. Currently three forms of entrainment at the ABL top are known. These are: penetrative convection; engulfment of air from the free troposphere by mixed layer eddies; and instabilities due to wind shear at the mixed layer top.

Penetrative convection is the process whereby heating from the ground causes the inversion base to rise [16]. Figure 1a shows observations made with the JHU lidar of thermals rising from the surface. These thermals, remote from strong convergence (updraft) regions do not merge, but decay whilst rising through the larger-scale downdrafts. At the top of the boundary layer, the rising air impinges onto the interface, overshoots due to its inertia (here often by some 300m – between z ~800m to 1100m) and spreads laterally producing hummocks and disturbances at the interface. Filaments of the free troposphere air are entrained into the turbulent region and subsequently descend around the updraft region.

Figure 1b illustrates how free tropospheric air from aloft is engulfed by mixed layer eddies at time t ~120s. The large eddies in the turbulent layer induce large random motions in the external layer leading to the engulfment of external fluid [4]. Through this process, the mixed layer gradually penetrates into the stable layer above. Continuous erosion of the lower interface of the turbulent part of the inversion by convective activity in the adiabatic mixed layer region results in a net transfer of air from above to below the inversion.

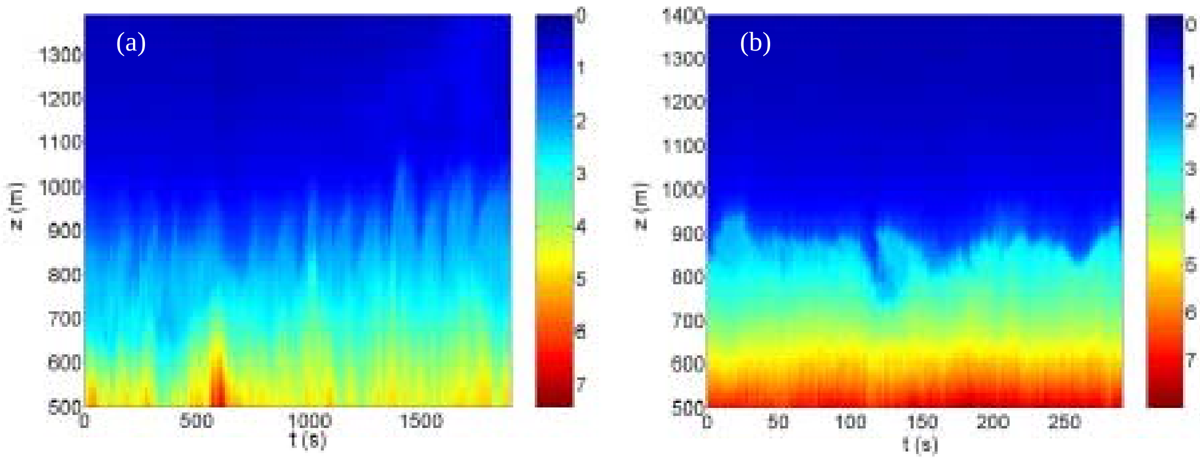

Figure 1. Penetrative convection (a) and engulfment of free tropospheric air by mixed layer eddies (b). The data was taken with the JHU lidar in a vertically upward pointing mode (time domain scan). The color scale depicts the relative magnitude of backscatter.

Figure 2 depicts a process that is not solely characterized by any of the previously described mechanisms. The process can best be described as detachment, most likely due to strong wind shear above the ABL top. Atmospheric conditions in the free troposphere are geostrophic. In that region, planetary forces dominate and the winds are driven by the pressure gradient force and the coriolis force. At time t ~200s to 800s and a height z of ~1000m to 1200m ABL air is being “sheared off”. It can also be seen from Figure 2 that thermals overshoot at the boundary layer top. Yet under the prevailing atmospheric conditions the additional strong winds cause sheets (‘wisps’) of mixed layer air to detach, rather than to descend back into the ABL. Furthermore, this lidar scan provides visual proof for the observation made by Crum et al. [6], who found that above the mixed layer, advection generates a variety of layers with differing moisture and aerosol content.

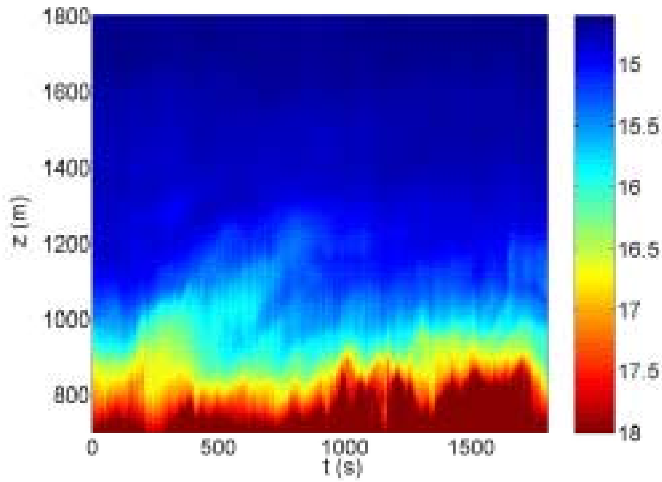

Figure 2. Detachment of mixed layer air caused by strong wind shear at the ABL top

Lidar – LES comparison

A comparison of experimental data and numerical techniques provides insight into some of the benefits and shortcomings of both.

The lidar used in this comparison is the JHU lidar described previously. The LES was developed by Albertson and Parlange ([1],[2]) and further improved by Porté-Agel et al. [10]. The code was used to simulate boundary layer dynamics and the entrainment process. An additional feature was included to allow computation of boundary layer top.

Figure 3 depicts the atmospheric boundary layer as scanned by the lidar (3a) and simulated by the LES (3b). Note that lidar data is plotted as a time series since the laser was pointed vertically upward and scanning was done with time. The LES plot is a conventional vertical-horizontal plane scan. The lidar, due to its better resolution (~1.5 m compared to 15 m vertical resolution and 90 m horizontal resolution for the LES), depicts small features in the ABL better. On the other hand, LES simulations allow investigation of dimensionless parameters. For example, the use of elastic backscatter lidar alone does not provide Richardson number or wind velocity at the top of the ABL. These parameters are available from LES simulations.

Figure 4 is a plot of inversion height probability density function (PDF) with a plot of a Gaussian PDF on the same figure. It should be noted that the distribution of inversion height is not necessarily Gaussian in all circumstances. LES simulations (4b) have a more "idealistic" distribution than lidar scans (4a).

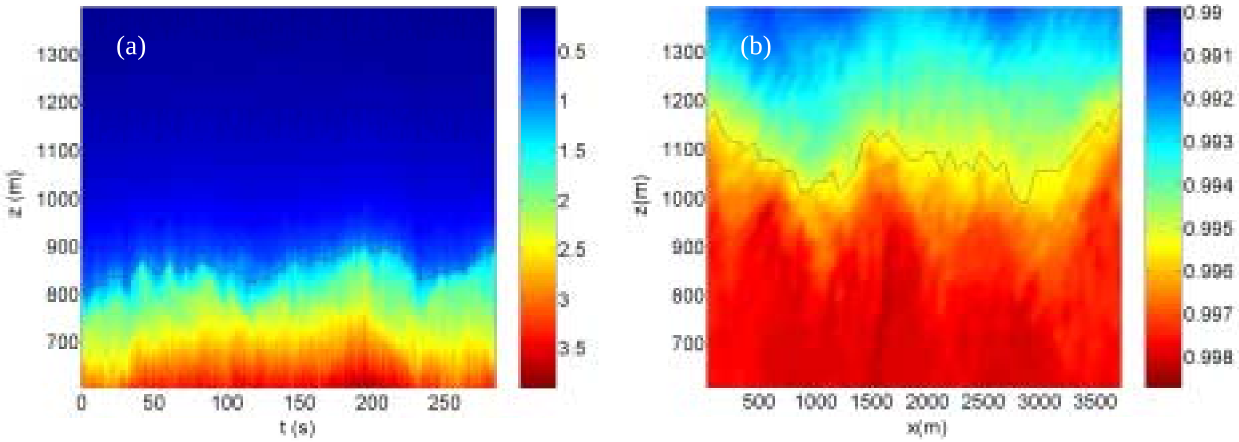

Figure 3. ABL height (solid line) from lidar data (a) and LES simulation (b)

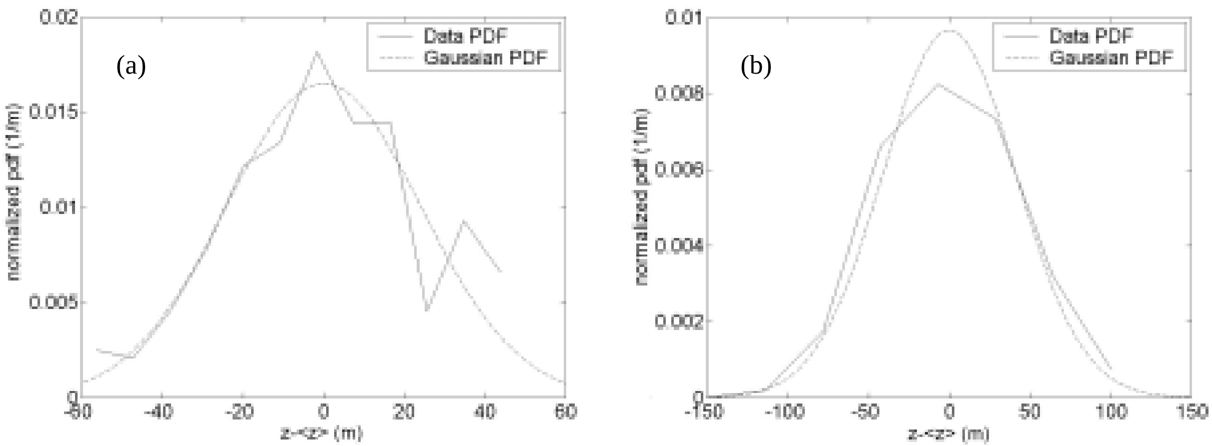

Figure 4. ABL height PDF from lidar data (a) and LES simulation (b)

Summary

Penetrative convection is a mechanism that has been observed frequently with lidar ([13],[5]). The detachment mechanism (see Figure 2) observed in this study is an additional example for ABL top mixing. Future work will include a comparison of lidar data and LES for similar atmospheric conditions combined with a sodar (sound detection and ranging) system to provide wind field information.

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