

Studying the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST)

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ABSTRACT

At the end of the afternoon, when the surface heat fluxes start to sharply decrease, the CBL turns from a convective well-mixed layer to an intermittently turbulent residual layer overlying a stably-stratified boundary layer. This transition raises several observational and modelling issues. Even the definition of the boundary layer during this period is fuzzy, since there is no consensus on what criteria to use and no simple scaling laws to apply. Yet it plays an important role in such diverse atmospheric phenomena as transport and diffusion of trace constituents or wind energy production.

This phase of the diurnal cycle remains largely unexplored, partly due to the difficulty of measuring weak and intermittent turbulence, anisotropy, horizontal heterogeneity, and rapid time changes.

The Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) project is gathering about thirty research scientists from the European Union and the United States to work on this issue. A field campaign (BLLAST-FE) is planned for spring or summer 2011 in Europe. BLLAST will utilize these observations, as well as previous datasets, large-eddy and direct numerical simulations, and mesoscale modelling to better understand the processes, suggest new parameterisations, and evaluate forecast models during this transitional period.

We will present the issues raised by the late afternoon transition and our strategy to study it.

1. ISSUES AND BACKGROUND

In the late afternoon, the surface heat fluxes start to sharply decrease until they become negative and turn

the surface layer from unstable to stable. Meanwhile, the convective boundary layer (CBL) is still active but starts to decouple from the surface and the turbulent kinetic energy (TKE) decays. Transitory processes like the late afternoon transition (LAT) are still difficult to observe, describe and represent in models. However, this regime plays a role in the transport and diffusion of trace constituents like pollutants or water vapour, and it also precedes the development of nocturnal jet, sea to land breeze reversal, and valley and slope winds.

1.1 Turbulence decay

Several authors have previously studied the transition regimes of turbulence through laboratory experiments (e. g. Cole and Fernando (1998)). They found that during the decay, the turbulence maintains the initial isotropy, with the energy decay following a power law t^n of time t . The first study with large eddy simulation (LES) of the decaying atmospheric convective mixed layer was performed by Nieuwstadt and Brost (1986). They analyzed an idealized case of the shearless, clear mixed layer, in which turbulence decayed as a result of a sudden shut-off of the upward surface heat flux. The process was also described in terms of time power laws.

Sorbjan (1997) considered a more realistic gradual change of the heat flux with time. The evolution of the decaying shearless mixed layer was found to be governed by two time scales: a scale linked with the decreasing rate of the heat flux and a convective time scale $t_* = Z_i/w_*$, where Z_i is the CBL depth and w_* is the convective velocity:

$$w_* = \left(\frac{g}{T} \langle w\theta \rangle_0 Z_i \right)^{1/3}. \quad (1)$$

In equation (1), g is gravity, T is the mean CBL temperature, and $\langle w\theta \rangle_0$ is the surface buoyancy flux. During the late afternoon transition, the buoyancy flux vertical profile turns from linear to a weak 'S-shaped' profile (Fig. 1).

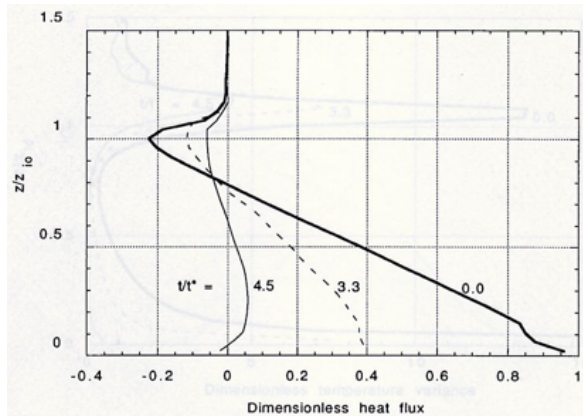


Figure 1: After Sorbjan (1997): The linear vertical profile of buoyancy flux turns to S-shape of weak fluxes in the late afternoon ($t/t^*=0$ when the surface flux starts to decrease).

The decay of convective turbulence has then been further analyzed by use of theoretical models (e. g. Goulart et al. (2003)), LES (e. g. Acevedo and Fitzjarrald (2001), Pino et al. (2006)), single column model (Edwards et al. (2006) and Direct Numerical Simulations (DNS) (Shaw and Barnard (2002)). In those studies, the decay depends to a large extent on the way that the decrease of the surface fluxes is prescribed.

Although literature reports some observations of the decay (e. g. Grant (1997)), the studies based on measurements remain rare.

Thus, the TKE decay has been extensively studied, especially with numerical models and surface-layer observations. But the decay of turbulence up to the top of the mixed or residual layer is poorly documented, and has to be related in the real world, not only to a decreasing surface heating, but also to competing processes such as cloud evolution, radiation, shear, and advection.

1.2 Characteristic length-scale

In the late afternoon, the surface buoyancy flux becomes too small to maintain turbulent mixing. Yet vertical motions of about 1 m s^{-1} extending horizontally over several km have been observed (Pagen and Bryden, 1982). The reason for this large-scale uplift remains unclear; Possibilities to explore include horizontal variations in surface heating and orography, both of which can induce mesoscale circulations. The few available

observations suggest that the scale of these updrafts during the transition are larger than the turbulent scales of vertical transfer during the middle of the day (less than, or of the order of 1 km).

There appears to be a lack of agreement in the literature on the evolution of the characteristic length scales during the late afternoon transition, partly due to the difficulty of observing and/or modelling this period. By using LES, Nieuwstadt and Brost (1986) found that the wavelength of the maximum of spectral density of vertical velocity multiplied by frequency remains constant during the decay process. In contrast, Grant's (1997) observations showed that this scale decreases during the LAT. Sorbjan (1997) found that small eddies had a tendency to decay earlier than large eddies. These results were later confirmed by DNS (Shaw and Barnard, 2002). Pino et al. (2006) have shown that a characteristic length scale based on a weighted integral of the zonal wind component spectrum, can increase or decrease during the decay, depending on the shear (Fig. 2).

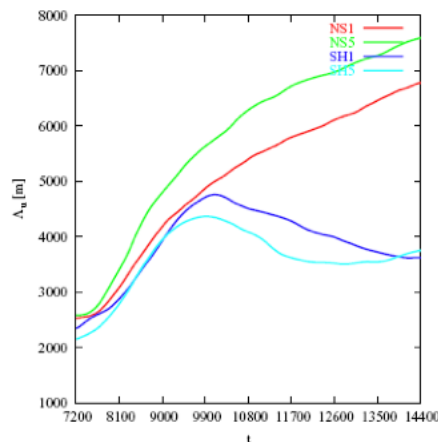


Figure 2: After Pino et al. (2006): Evolution of the scale of the wind zonal component during four different LESs. NS1 and NS5 have no-shear, SH1 and SH5 have a 1 ms^{-1} wind speed jump across the PBL top. NS5 and SH5 have a larger potential temperature jump.

Thus the scale issue remains unclear and only partly understood.

1.3 Transport

Spatial distributions of scalars such as gases and aerosols vary rapidly during the LAT, at least in the surface layer. Recent studies (e. g. Vilà-Guerau de Arellano et al. (2004); Casso-Torralba et al. (2008)) have shown that morning and afternoon transitions are indeed important for the vertical exchange of species. In the evening, water vapour and pollutants, which were

emitted at the surface and diluted into the convective layer during the day can be incorporated into the free troposphere as the residual layer forms over the developing stably-stratified surface layer. As part of the free troposphere, they can thus be transported horizontally over long distances. Vertical variations in timing of the afternoon/evening reduction of turbulence modifies the vertical rate of scalar transport (Fig. 3). There is a great amount of knowledge to be gained on this topic.

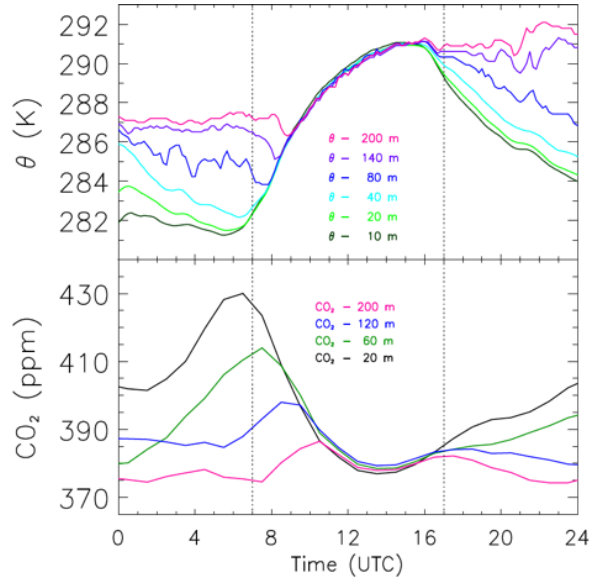


Figure 3: After and complement of Casso-Terralba, 2008: Evolution of potential temperature and carbon dioxide concentration during an entire day, at several levels of the instrumented tower of Cabauw, NE.

2. FURTHER CHALLENGES

2.1 Definitions and scaling

Due to its transitional aspect, this phase puts several basic boundary layer definitions into question. The period that we are considering, which lasts 2 to 3 hours, starts as soon as the surface buoyancy flux begins to sharply decrease (late afternoon transition), and it covers the change of sign of the surface buoyancy flux (evening transition). Within this context, the mixed layer, the residual layer and the surface layer are non-stationary. As a consequence: The surface layer cannot be defined in the same way from the start to the end of this few-hour transitory phase (from super- to sub-adiabatic surface layer). The mixed layer evolves from a well-mixed (adiabatic) layer with vigorous turbulence, to the decoupling of a stable layer overlaid by a residual layer. The residual layer during the night will be a weakly stable layer with intermittent turbulence. The

mixed and residual layers each have different interactions with the entrainment zone and capping inversion above and the surface layer below.

During the day, in convective conditions, most of the moments can usually be scaled with w_* . This scaling is the basis for a robust parameterization in bulk models. On the other hand, the stable boundary layer scaling is usually based on the surface wind stress. During the LAT, the surface buoyancy fluxes are small, and other small forcing processes come into play. So, neither the convective scaling, nor the stable boundary layer scaling are dominant.

Other parameterizations are put into question during this phase, like that of entrainment. It is usually parameterized through the ratio of the buoyancy flux at the ABL top to the surface buoyancy flux. Because the latter becomes very small during the LAT, this ratio is no longer relevant then (Fig. 4).

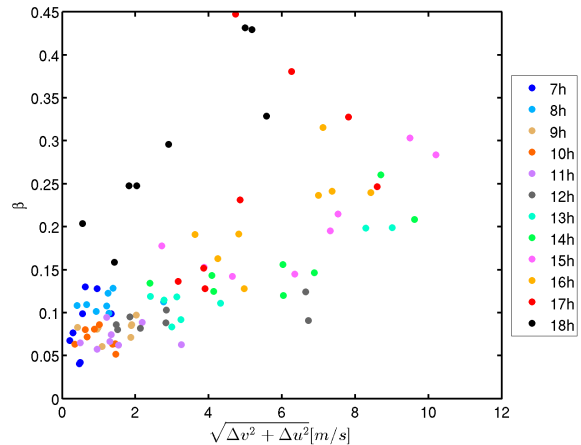


Figure 4: Ratio β of the buoyancy entrainment flux to surface flux as a function of the shear at the top inversion, during several LESs made over daytime with various initial condition of the mean vertical structure of the CBL, and similar surface sensible heat flux. (Here, a sinusoidal law is used to represent the daytime evolution of the surface flux.) β increases with increasing shear. Due to very weak fluxes at the end of the simulation, β starts to be an unreliable parameter for the study and parameterization of entrainment.

2.2 Observational issues

There are also some issues raised when trying to probe the boundary layer during the LAT. For example, weak and intermittent turbulence is difficult to measure with any in situ (aircraft, towers) or remote sensing device. Also if the turbulent characteristic length scales are larger, they require larger samples to be well probed. The same holds true for intermittent turbulence.

Linked to the definition issues, there is also a challenge in interpreting remote sensing observations during the LAT, either by UHF wind profiler or aerosol lidar, due to the change of the vertical distribution of the echo sources.

3. STRATEGY

As sensed from the state of the art drawn up previously, the role of several key elements will be important to study, including: (1) entrainment, (2) surface heterogeneity, (3) baroclinicity and advection, (4) clouds, (5) radiation, (6) gravity waves.

A new field experiment is planned in June 2011 over 3 weeks, in the vicinity of a measurement tower somewhere in Europe and will combine aircraft, Unmanned Aerial Vehicles (UAVs), remote sensing instruments, radiosoundings, tethered balloons, and tracer releases in the vicinity of a measurement tower. Several sonic anemometers will be deployed over different surfaces in the surrounding area, to measure the differences in the structure and evolution of the transition among different vegetated surfaces. A network of UHF and sodar wind profilers will give continuous profiles of the mean wind and CBL depth, and Doppler lidar(s) will give the fine-scale structure of the radial velocity component, with high resolution in time and space for turbulence statistics studies and entrainment zone exploration. The surface layer and entrainment zone will be probed by one or two tethered balloons. Radiosoundings will be conducted throughout the day, with increased density of launches during the LAT. Concurrently, airplanes of various airspeeds and capacities will probe an area of several tens of kilometres across, with horizontal legs at different levels within and just above the CBL mainly for flux measurement. The results obtained from analysis of previous as well as the BLLAST field dataset will be combined with results from LES, direct numerical simulations (DNS), and mesoscale simulations in order to better understand the processes, suggest new parameterisations, and evaluate forecast models during this transitional period.

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