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Studying the Afternoon Transition of the Planetary Boundary Layer

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The planetary boundary layer is the part of the atmosphere that interacts directly with the Earth's surface on a time scale of a few hours or less. In daytime, solar heating of the surface can generate buoyant turbulent eddies that efficiently mix the air through a depth of more than a kilometer. This convective boundary layer (CBL) is a conduit for trace gases such as water vapor and carbon dioxide that are emitted or absorbed by the surface (and surface vegetation) to be transported into or out of the layer nearest the surface.

The CBL has been extensively observed and relatively successfully modeled. But the early morning transition—when the CBL emerges from the nocturnal boundary layer—and the late afternoon transition—when the CBL decays to an intermittently turbulent “residual layer” overlying a shallower, stably stratified boundary layer—are difficult to observe and model due to turbulence intermittency and anisotropy, horizontal heterogeneity, and rapid time changes. Even the definition of the boundary layer during these transitional periods is fuzzy; there is no consensus on what criteria to use and no simple scaling laws, as there are for the CBL, that apply during these transitions.

These transitions play an important role in such diverse atmospheric phenomena as wind energy production and convective storm initiation. After the CBL decays, the residual layer can be incorporated into the overlying free troposphere, so that water vapor and pollutants emitted at the surface and diffused throughout the CBL during the day can become isolated from the boundary layer and may be transported over long distances with no interaction with the surface.

In a concerted effort to learn more, the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) project is gathering about 30 research scientists from the European Union and the United States to work on this issue (see <http://www.aero.obs-mip.fr/spip.php?article668&lang=en>). Initiated 2 years ago, BLLAST seeks to make more and better observations of the

late afternoon transition not only to better understand the physical processes that control it but also to elucidate the role of this transition in turbulence structure and trace species transport.

An Incomplete Picture of CBL Transitions

At some point in the afternoon the surface buoyancy flux is not large enough to maintain turbulent mixing throughout the CBL, especially for a deep CBL. Yet vertical motions of up to 1 meter per second extending horizontally over several kilometers have been observed, most notably by free-flight pilots [Pagen and Bryden, 1982; Aupetit, 1989]. The reason for this large-scale uplift is unclear; possibilities include surface variability and complex terrain features that can induce mesoscale eddies (scales from tens to hundreds of kilometers). The horizontal scale of these updrafts during the transition seems to be larger than the most energetic vertical velocity scales during the middle of the day. Previous large-eddy simulation (LES) studies showed that during late afternoon, a decoupled residual layer, within which turbulence is still active [Pino *et al.*, 2006], develops above the stably stratified surface layer and is characterized by larger-scale updrafts than the midday eddies [Sorbján, 1997]. These updrafts persist even when the surface buoyancy flux turns negative (when the ground becomes cooler than the air just above it) and stabilizes the air in contact with it.

Quantitative observational evidence for these late afternoon mesoscale eddies is lacking, partly due to the difficulty of measuring weak turbulence and mean circulations in transitory conditions and at larger scales. Thus, this phase of the diurnal cycle remains largely unexplored, from both modeling and observational perspectives.

Specifically, several issues need special attention when examining the late afternoon transition. First, several standard boundary layer definitions are not directly applicable during the transition, including the definition of the boundary layer

itself, which turns from a well-mixed layer to a residual layer overlying a stable layer during this transition (see Figure S1 in the online supplement to this *Eos* issue; http://www.agu.org/eos_elec/). Further, the usual convective scaling laws (e.g., Deardorff scales) and some parameterizations (e.g., entrainment rate), which can be used to predict the vertical structure of the low troposphere and its evolution, are difficult to apply, partly due to small surface heat flux. Additionally, there is no agreement in the literature on the evolution of the characteristic length scales, i.e., the scales of motion that contribute the most to the transport of energy and trace constituents. Second, the occurrence of anisotropic turbulence as well as the transition from continuous to intermittent turbulence as one moves from the CBL to the late afternoon transition need to be better described and understood. A better understanding of those issues will help to evaluate the impact of the associated processes on the vertical transport of momentum, heat, and trace constituents.

BLLAST Strategy and Objectives

To start addressing those issues, BLLAST scientists have begun analyzing previous data sets collected during afternoon transitions (with some limitations, because these experiments were not designed to study this phenomenon). Several key processes will be investigated through these data sets, including entrainment of drier, cleaner, and nonturbulent air from the free troposphere across the CBL top; surface heterogeneity (patches of varying vegetation types and surface roughness); mesoscale horizontal temperature and pressure gradients; horizontal advection of air with varying properties; and the roles of clouds, radiation, and gravity waves.

These analyses should help in the design of a BLLAST field campaign focused on the late afternoon transition. The BLLAST field campaign is planned for June 2011 in Europe (likely France, near the Pyrénées Mountains) and will combine aircraft, unmanned aerial vehicles (UAVs), remote sensing instruments, radio soundings, tethered balloons, and tracer releases in the vicinity of a measurement tower.

Sonic anemometers will be deployed over different surfaces in the surrounding

area to measure the differences in the structure and evolution of the transition over different vegetated surfaces. Wind profilers will give continuous vertical profiles of the wind speed and direction and CBL depth. Doppler lidar (light detection and ranging) will measure the fine-scale structure of air velocity components with high resolution in time and space, which will be useful for turbulence statistics studies and fine-scale exploration of the entrainment zone (the interface between the turbulent CBL and the non-turbulent free troposphere). The surface layer and entrainment zone will be extensively probed by one or two tethered balloons. Radio ascents, which will probe the vertical structure of the atmosphere, will be conducted periodically throughout the day, with increased density of launches during the late afternoon transition. Concurrently, airplanes of various airspeeds

and capacities will probe an area several tens of kilometers across, with horizontal legs at different levels within and just above the CBL, mainly to measure the energy and characteristic scales of the most important eddies.

The results obtained from analyses of prior data sets as well as the BLLAST field data set will be combined with results from direct, large-eddy, and mesoscale numerical simulations so that scientists can better understand the processes, suggest new parameterizations, and evaluate forecast models throughout the afternoon transition. It is hoped that this will lead to improved predictions of atmospheric structure during this critical regime, which in turn will result in not just a keener understanding of atmospheric physics but also better forecasts of pollutant dispersal, wind energy production, and convective storms.

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