Atmospheric Boundary-Layer over Complex Terrain

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ABSTRACT

The Atmospheric Boundary Layer (ABL) over land is intrinsically anisotropic, due to varying soil and vegetation fields and to topographically diverse terrain. Some of the current known key points related to these issues are briefly reviewed here. The sensitivity of the ABL to the soil thermal conductivity is discussed, basically in terms of the moisture content, and the complexity of the vegetation canopies is described. The terrain variability that induces horizontal thermal gradients in the ABL is addressed, from the simple slope to the large mesoscale basins.

1 Introduction

For a field like the study of the meteorology of the Atmospheric Boundary-Layer (ABL), the definition of complex terrain is relatively easy to make: every piece of terrain that is not spatially homogeneous. This comes from the ideal conditions for which ABL studies were designed some decades ago, oftentimes including stationarity as well.

The ABL is characterized by the existence of turbulence, and we only have a well established theory for isotropic, stationary and homogeneous regimes (Kolmogorov, 1941). Basic studies looked for these conditions and therefore tried to avoid surface heterogeneities or any other generator of anisotropy (like stable thermal stratification). In the last decades, these requirements have been relaxed, especially stationarity since the study of the diurnal cycle has become a major subject, but implicitly stationarity at the time scale of the turbulence eddies is assumed.

However, real-world ABL is over heterogeneous terrain and this heterogeneity takes place at practically all the spectrum of spatial scales. To search for ideal homogeneous locations is, in practical terms, impossible, and the analysis of the experimental data must take into account the heterogeneities around the measuring site.

Three-dimensional numerical models represent explicitly only part of the variability through the information on the surface, either fixed (topography, soil structure) or variable (vegetation, state of the soil). The sub grid variability is many times ignored. To introduce these effects in models it is necessary to understand their characteristics prior to develop or improve parameterizations of them.

In this work, different features related to terrain complexity will be briefly discussed. First, in section 2, the changing characteristics of soil and vegetation in a column are commented, since they introduce complexity in the vertical dimension. Then, in section 3, the low-level jets (LLJs) induced by horizontal thermal gradients are briefly discussed.

Since real-world terrain is normally sloped and irregular, related effects will be shown in section 4, focusing on simple slopes and terrain depressions prone to generate cold pool areas. Section 5 illustrates the basic concepts of valley flows and section 6 the mesoscale heterogeneities that can develop in large basins with almost closed topography. A concluding summary ends the document.

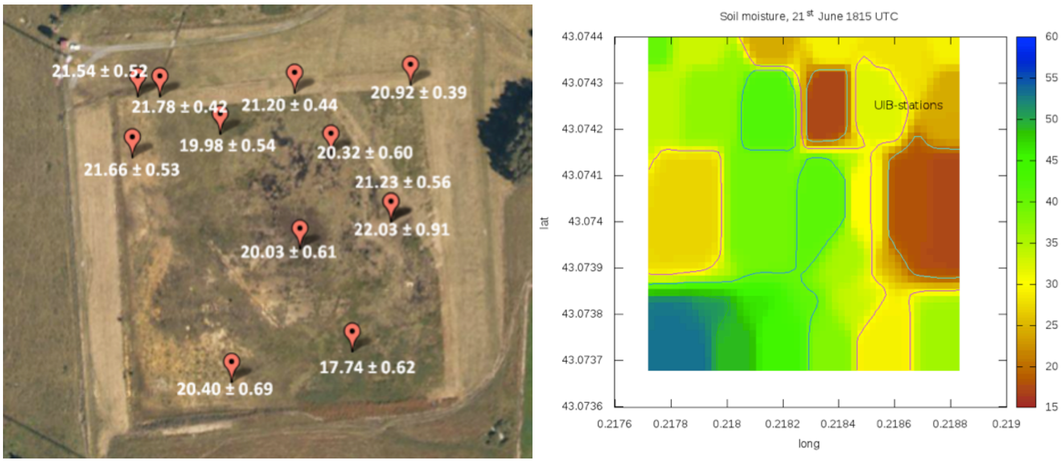

Figure 1: BLLAST campaign, June 21st 2011, 18 LST. Left: Surface temperature in a square of 150 m obtained with a thermal camera over sections 4m x2 m (average and standard deviation); Right: Soil moisture field for the upper 5 cm of soil obtained from 30 point-measurements

2 Vertical complexity: soil and vegetation

When a study (either experimental or numerical) is made over a location surrounded by relatively homogeneous terrain, the characterization of the soil and the vegetation parts must be properly done in order to have the best possible control of the lower boundary conditions of the atmosphere. The soil is fixed for a given point, but variations of horizontal and vertical structure can be very important for small distances and consequently the thermal conductivity can vary enormously. Instead, the vegetation is dynamic, especially in its temporal evolution, since it can change surface roughness and energy budget largely as the plants evolve.

2.1 Ground

When a location is chosen for an ABL study, it is normally a point similar to its immediate surroundings, in the middle of vegetated field, for instance. However, even in apparently very homogeneous locations the variability is very high. Figure 1 shows the measured variability of a square of 150 m of side in the Centre de Recherches Atmosphriques (CRA) in Lannemezan, where the BLLAST campaign took place in June and July 2011 (Lothon et al., 2010)

Figure 1a shows the value of the surface temperature estimated with a thermal camera over an area of 4 m x 2m (image from Google Earth), when the sky was overcast and just before sunset, made by students of the Wageningen Research University. The temperature variability within the square is of about 3K, and the standard deviation for each picture is of the order of 0.5 K. This indicates that it is difficult to achieve better accuracy than 0.5 K in temperature measurements over natural surfaces.

The square has similar soil everywhere, but the underlying structure has different water load (see volumetric percent of water in Figure 1b -self made measurements- than can vary between 15 and 60%). Since the thermal conductivity in the soil is a function of the type of material and of the contents of water, the variability of surface heat flux will also be large at this very small scale. Therefore, the inherent variability of soil properties should be taken into account in applications at the subgrid scale, allowing for indetermination in the values of these quantities.

2.2 Vegetation

The vegetation layer in one point can be extraordinarily complex and dynamic, even if there is horizontal homogeneity. The surface roughness and the displacement height of a canopy vary with time, as the crop grows. For instance, a sunflower canopy, can grow about 1 m in few weeks with a significant increase of the Leaf Area Index (LAI) within the canopy. Missing this evolution in any study may lead to significant errors in the parameters governing the exchange of matter and energy between the surface and the atmosphere.

Complex canopies pose different challenges. Dead grass usually has a much larger LAI than green grass and it can be lying on the field for the whole year. The temperature of both grasses can differ substantially at the leaf level, and these two also from the bare soil, of the order of 1 K (Geiger et al, 1995).

If the vertical structure of the atmosphere inside and across the canopy is inspected, we realize how strong is the anisotropy induced by the canopy (see, f.i., fig. 16.5 in Monteith and Unsworth, 2008). For a dense canopy, its top acts as the effective surface and it is where most of the diurnal heating and nocturnal cooling takes place. Inside the canopy there may be stable stratification in the daytime and top-driven convection in the nighttime. Across the top, very large vertical variations of radiation and momentum take place and act as sources of heat and momentum in the layer. The interaction of the wind with trunks and leaves can also be a source of turbulence in the within-canopy flow (Kaimal and Finnigan, 1994).

The reduction of the vegetation to a non-evolving simple layer is an over-simplification, especially if the canopy changes rapidly during part of the year. The displacement of the first model layer in respect to the effective surface may affect the representation of the near-the-surface structures, at very high vertical and horizontal resolutions. Complex canopies, like mixtures of dead and green grass with bare soil put into question even the definition of surface, since the dead-grass may isolate the soil from the air.

3 Structure of terrain-induced jets

Baroclinity is related to the presence of horizontal gradients of temperature, almost always related to surface heterogeneities, the effect of which is maximal close to the surface and much less noticeable above the ABL. The associated circulations are in form of low-level jets (LLJs) with more loosely defined returned circulations aloft. Examples can be land and sea breezes, valley-plain circulations or even downslope and upslope flows, to illustrate different relevant scales.

In consequence, LLJs are usually found wherever complex terrain -able to generate surface thermal gradients- exists. In this section we will describe the behaviour of a LLJ blowing over cold surface as an example of its vertical structure and of the interaction with the surface conditions, using a LES made by Cuxart and Jimenez (2007).

This jet is thought to be a combination of katabatic flow and a barocline jet blowing from a mountain range towards the center of the large flat Duero basin, in NW Spain. The observed jet has preferred ranges of direction (easterly), wind speed at the maximum (5 to 9 m/s) and height of the wind maximum (80 to 150 m AGL) at the measuring point, over the Torozos terrace.

As shown in figure 2a, the modelled jet has strong vertical wind shear below the jet maximum (from 9 m/s to calm in 80 m) and moderate above it (from 9 m/s to 1 m/s in 200 m). This allows the generation of turbulence, many times the upper and lower layers being disconnected. There is normally a local maximum of N_{BV} and of Ri at the height of the maximum wind, and the stratification in the lower layer is only moderately stable, less than it would be without the wind shear that the LLJ generates.

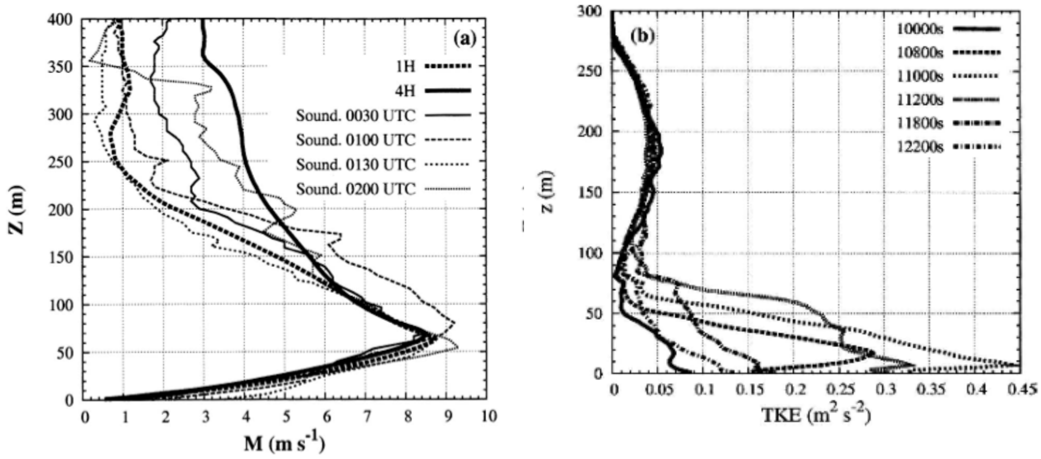

Figure 2: LLJ as simulated in Cuxart and Jimenez (2007). Left: Wind speed profile from soundings and simulation; right: evolution of the turbulence kinetic energy profile during a mixing event

A test made nudging to the observed 2m values of wind and temperature instead of imposing the similarity theory (figure 2b) shows intermittent turbulence similar to the observations, with mixing events that can be intense and last several tens of minutes with calm episodes in between.

Since the LLJs seem to be ubiquitous over complex terrain and the associated dynamics are extremely sensitive to the proper representation of the surface conditions, it is clear that a good representation of the latter is a necessity to have a realistic representation of observed intermittent mixing in nighttime.

4 Slopes and terrain depressions

Complete flat terrain is almost never encountered over land. Terrain flat to the eye may in fact be tilted some tenths of degree, which is enough to generate downslope flows for scales of tens of kilometers. Besides, terrain irregularities generate local depressions and steeper slopes aside. Therefore, effects of very gentle complex terrain have also to be taken into account since they may diminish or enhance air nocturnal cooling close to the surface. Numerical models may explicitly capture the effects of these features or, if their resolution is too coarse, miss partly or totally their contribution.

4.1 Downslope flows

Downslope flows are usually considered two-dimensional (following the slope) and two-layered, the bottom one being the mass flowing downslope and the upper one the ambient flow, as in Mahrt (1982).

However, Martinez and Cuxart (2009) selected a very simple slope over the Mallorca island to check how the proposal of Mahrt fitted to the simulation outputs and they found large separations from the closure of the momentum budget which indicate that the hypothesis are not fulfilled even for this very simple case. The processes thought to be miss-represented are the lack of a jet profile, implying that the shear production of turbulence is missing, and the interaction with larger scales that may limit the validity of the two-dimensional approach.

There are other issues that have been addressed recently related to downslope flows. Grisogono et al (2007) showed that MO similarity is not apt for sloping terrain, which would imply it is applicable almost nowhere, and that a more relevant length scale would be the Obukhov length. Smith and Skyllingstad (2005) and Shapiro and Fedorovich (2007) showed respectively that changes of slope and changes of surface temperature induce accelerations of the downslope flows and, consequently, associated vertical motions.

4.2 Cold pools

Cold pools are usually formed at topographic depressions when the synoptic wind is weak and the skies are clear. These terrain depressions do not have to be very well marked. High Resolution mesoscale simulations for the Duero valley (Jimenez et al, 2008) show that very shallow valleys 30 m deep and 10 km wide (flat to the eye) can generate well defined cold pools that become decoupled from downslope flows that blow above them.

The intensity of a cold pool depends on its topographical shape, on what Whiteman (2000) calls the topographic amplification factor (TAF), indicating that in a depression, the surface that exchanges energy with air is larger than in flat terrain, leading to warmer conditions in a sunny day and colder conditions in a clear and calm night. As the Jimenez et al (2008) simulation shows, the value of the near-the-surface temperature gradient can be more than 3 times stronger in a shallow cold pool than over a neighboring gentle slope.

Vosper and Brown (2008) investigated the importance of the wind speed and the cloudiness in the generation of a cold pool through a series of two-dimensional simulations. They found that cloudiness is the most limiting factor, since even for moderate geostrophic winds of 7.5 m/s a cold pool can be formed if the shape of the terrain is deep enough. An experiment in the Arizona Crater (Whiteman et al, 2008) shows that three-dimensional effects have also to be taken into account, especially due to solar differential heating.

5 Valley flows

The TAF is also useful to understand why the air in a valley is warmer in the daytime and cooler in the nighttime compared to the adjacent flatter areas. This results in valley-plain pressure gradients that generate theoretically closed circulations upvalley in the daytime and downvalley in the nighttime. The detailed understanding of these flows and their interaction with the surrounding plains is still a subject of research. A way to explore them is through numerical modeling.

A vertical cross-section from a high-resolution simulation (Jimenez et al, 2012) for the Aure valley, in the Pyrenees close to the location of the BLLAST campaign, shows that the daytime up valley flow advects the plain ABL air into the valley at about 4 m/s and has a weaker return flow aloft (2 m/s) much less defined (figure 3). At night, the down valley flow is more than 600 meters thick with speed at the nose of the jet near 5 m/s, relatively well mixed but allowing the establishment of cold pools in the terrain depressions and weakening over the plain allowing for stronger surface inversions.

6 Large basins

If we move to a larger scale, we can focus on the properties of large basins. Usually, these features are currently well represented in most numerical models, except in the climate models at low resolution or in very stable conditions. For instance, figure 4 shows a satellite image of the surface temperature anomaly in the Duero basin on a winter calm night with clear skies. Mesoscale gentle slopes at the NW and SE are warmer than the bottom part of the basin, where cold pools are formed in the river valleys. The Torozos plateau in the center lies higher and is decoupled from the lower basin currents. These features are difficult to capture for models in very stable conditions because the short time scale changes

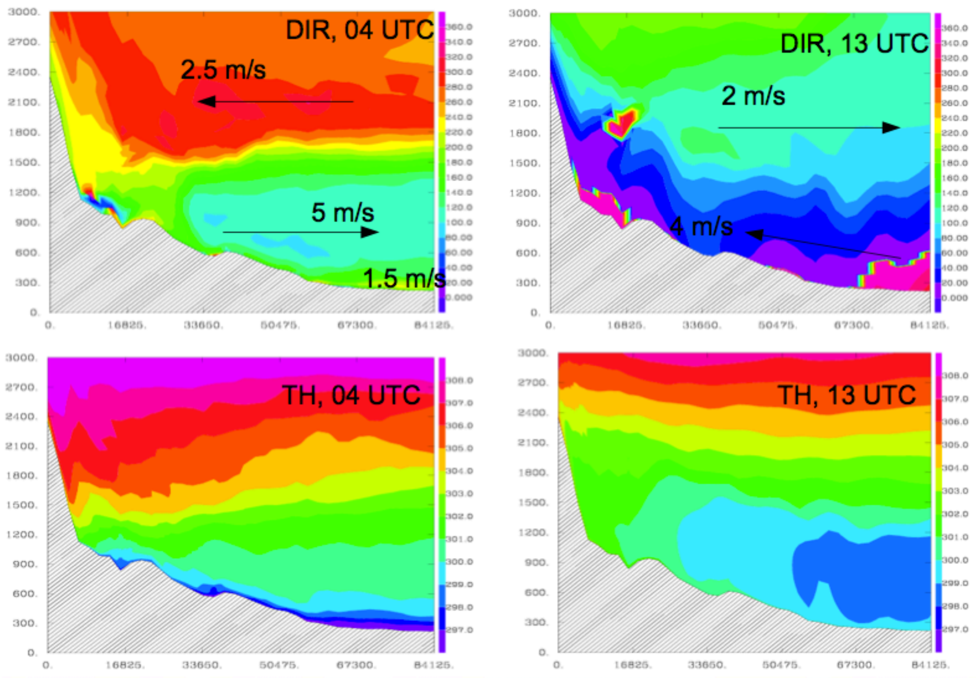

Figure 3: Nighttime (left) and daytime (right) circulations in the Aure valley (French Pyrenees) for the Jimenez et al (2012) simulation of June 30 and July 1st 2010. Upper panels: wind direction, lower panels: Potential temperature

in surface conditions are not taken into account. In consequence, the related thermally induced flows will be ill-represented.

A major feature of topographically confined basins is the large persistence of fog under winter high-pressure conditions, covering most of the bottom of the basin, because the air can not be easily displaced. However slope flows over the fog layer can interact with it and, through entrainment processes, drive the dynamics at the top and make the layer deeper then in flat conditions (Cuxart and Jimenez, 2011).

7 Perspectives

Complexity arises from the presence of multiple features in the terrain surface, namely in vegetation and topography. Here some of the effects induced by these heterogeneities in general high-pressure conditions have been described. The understanding is still basically in a descriptive stage, although efforts are under way to arrive to a level of understanding that can be parameterized soundly.

A realistic treatment of complex multilayer vegetation is a necessity in modeling as the community has reached the hectometric horizontal resolution and vertical resolution of the order of the meter, which also implies that canopies can have different vertical computation layers in the models. The treatment of the surface boundary condition, with a mixture of vegetation types, soil and heterogeneous distribution of the soil moisture contents, is a challenge that deserves a coordinate effort between the related scientific communities.

The effects of the topography can be thought in terms of scale, going from the local slope flow to the valley structures and to the basin mesoscale organizations. However since the scales can be rarely separated, analysis is still in a qualitative phase but the progress is expected to increase as more field

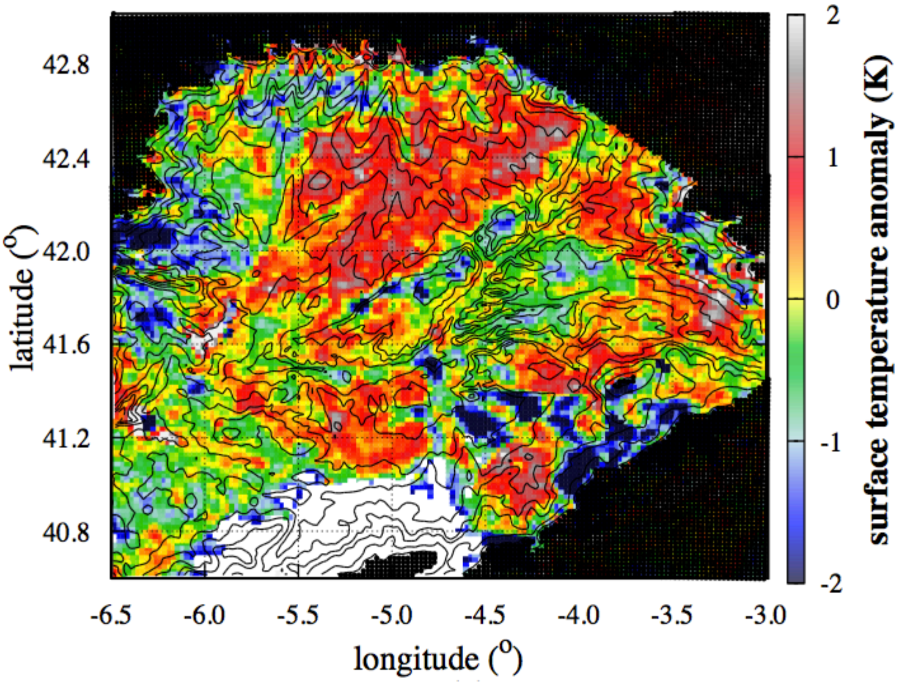

Figure 4: Surface temperature anomaly derived from MODIS for a winter clear and calm night in January 2005 (from Martinez et al, 2010)

experiments are made. Nevertheless, at the model resolution and conditioned to the quality of the surface data fields, the models can resolve many of the topographically induced circulations. However, they miss the subgrid effects and their interaction with the resolved scales, which is the same problem as for the turbulence. The latter point is comprehensive since the topographic heterogeneities are generators of thermal gradients and turbulence will act to try to reduce them.

To end, indicate that, in absence of other time scales, the topographic flows are determined by the diurnal cycle and the analysis of the transitions is pending an extensive analysis, which will probably be undertaken in the next years.

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