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IMPACT OF TERRAIN HETEROGENEITY ON NEAR-SURFACE TURBULENCE : LONG TERM INVESTIGATION AT SIRTA OBSERVATORY

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1. INTRODUCTION

Turbulent exchange of momentum, heat and moisture between a flat, horizontally homogeneous surface and the atmosphere is well described by the Monin-Obukhov (MO) similarity theory (Monin and Obukhov, 1954) where dimensionless flux profile relationships have been estimated from field experiments under "ideal" conditions over flat sites with uniform vegetation (Businger et al., 1971; Dyer, 1974).

In the framework of this theory, the control parameters are mainly the roughness length z_0 and height. However, in "real life", the surface of the Earth is covered with roughness elements, such as crops, forests, and urban areas which form patchworks of varying surface roughness. This wide range of complex surfaces disturbs the turbulent flow over the surface and influences the processes that govern the exchange of momentum, heat, and mass between the "complex" surface and the atmosphere.

Many studies focus on the analysis of the distance to the roughness change, necessary for the flow to reach a new equilibrium. Most of these studies rely on numerical investigation (e.g. Taylor, 1968; Mahrt, 1996; Liu et al., 1996) or laboratory experiments (e.g. Mulhearn, 1978; Morse et al., 2002). Our main objective is to study atmospheric turbulence characteristics downstream surface heterogeneities for different fetches and atmospheric stability conditions. With over 10 months of turbulence data collected by sonic anemometers at 10 and 30 m heights on a 30 m mast at the SIRTA observatory (Haeffelin et al., 2005), a robust statistical analysis of the turbulence structure and persistent patterns could be conducted in various atmospheric conditions.

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Among the relevant issues, the present study aims at investigating the impact of surface heterogeneity (i) on the turbulent kinetic energy (TKE), turbulent surface fluxes (momentum and heat) and local roughness length; (ii) on the dynamics of near surface coherent structures (e.g. Drobinski et al., 2004).

2. CLASSIFICATION AS A FUNCTION OF WIND DIRECTION SECTORS

Figure 1 shows the terrain structure in four different directions (north, east, south, west).

Fig. 1: Campus of the Ecole Polytechnique, hosting the SIRTA observatory. The pictures show the "roughness elements" which can be seen from the observation mast.

As mentioned, one of the aims of the present investigation is to study the variability of turbulence structure downstream different types of surface. We therefore classify our dataset as a function of wind direction. We use four different wind direction sectors:

- Wind direction 320°-40°: Close forest
- Wind direction 100°-170°: Distant forest
- Wind direction 170°-260°: Buildings
- Wind direction 260°-320°: Open field sector

It must be noted that there is an open "green" area with at least 65 m fetch next to the mast in all directions. We did not use the data in the 40°-100° sector because when the flow comes from this direction, the anemometers are in the tower wake and so the data are not reliable (Barthlott et al., 2003).

Figure 2 shows the comparison between the wind directions at 10 and 30 m heights.

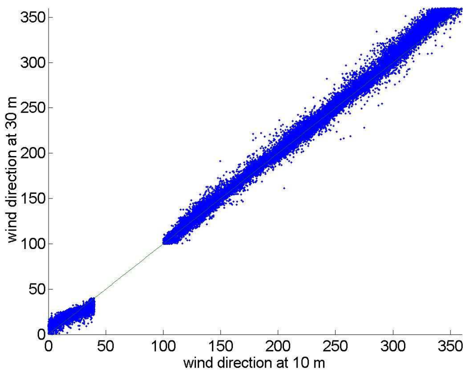

Fig. 2: Wind direction measured at 30 m height versus wind direction measured at 10 m height

For westerly winds, the terrain "seen" by the instrumented tower is flat and homogeneous. We use this wind direction sector as the reference. For this sector, turbulent fluxes as well as the wind direction are constant with height. For northerly wind, the forest edge is about 65 m north of the mast with 15 m trees. In this situation, the wind at 30 m is slightly shifted to the east with respect to that at 10 m. The reason is that the low level flow turns around the forest edge. The flow measured at 10 m is more disturbed than the flow measured at the 30 m measurement point. This result is in good agreement with Nord (1991) who shows that close to a vegetation belt, wind veering depends on the belt leaf distribution. For easterly winds, a distant forest is "seen" from the mast about 400 m upstream. Figure 2 shows a perfect match between wind direction at 30 m and that at 10 m. Hence, we can notice that the wind veering decreases with increasing distance from the forest barrier. This is also true for southerly winds which are associated with laboratory buildings 300 m upstream of the mast.

3. TURBULENCE STRUCTURE

3.1. *Turbulent kinetic energy*

The turbulent kinetic energy (TKE) which characterizes the turbulence intensity is a common variable analyzed in studies dealing with roughness change. Figure 3 represents TKE averaged over 10 degree sectors as a function of the wind direction.

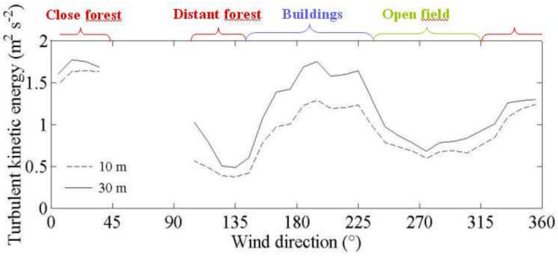

Fig. 3: Turbulent kinetic energy (TKE) at 30 m (solid line) and 10 m (dashed line) as a function of the wind direction measured at 10 m height.

For westerly winds (corresponding to homogeneous terrain upstream of the mast), TKE has the same value at 10 and 30 m. For northerly flow, TKE has similar values at 10 and 30 m despite the presence of a close forest edge. For this case, the result is in a good agreement with large-eddy simulation (LES) by Liu et al. (1996). Indeed, for northerly winds, the tower is located in the wake region of the forest, so turbulent mixing is high, thus explaining the similarity of the measurements collected at the two levels. In case of easterly wind, we are in a situation of long fetch. Large differences are found between 10 and 30 m when the flow blows from the south since the 30 m measurement point feels the presence of the buildings whereas the footprint for the 10 m measurement point hardly reaches the building area (Hsieh et al., 2000).

TKE thus strongly depends on the roughness elements upwind of the mast, and on the distance to the roughness change (fetch).

3.2. *Roughness length*

The roughness length is a key parameter for surface/PBL coupling in numerical models. Roughness length values z_0 can be found in tables as a function of the land-cover. In this study, we diagnose z_0 using the MO similarity theory and more precisely the Businger-Dyer equation:

$$\overline{u} = (u_* / k)\ln(z / z_0 - \Psi_m) \qquad (1)$$

where k is the Von Karman constant, z_0 the roughness length, u_* the friction velocity, z the measurement height and L the MO length.

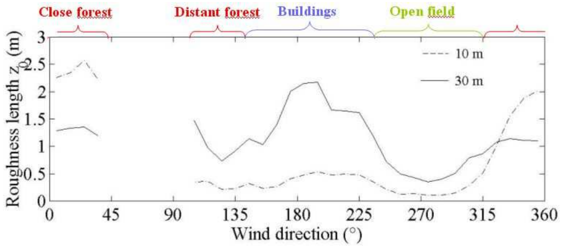

Fig. 3: Roughness length (z_0) at 30 m (solid line) and 10 m (dashed line) as a function of the wind direction at 10 m height.

Figure 4 represents the roughness length z_0 averaged over 10 degree sectors at 10 and 30 m heights. We can notice that negligible difference is visible for the west sector (i.e. within the statistical uncertainty). This result is not surprising according to the terrain properties in this direction (flat and homogeneous). For northerly winds, z_0 diagnosed from the 10 and 30 m measurements differ substantially. Indeed, the roughness length at 10 m is about twice as large as the roughness length at 30 m. For easterly wind, the difference between z_0 at 10 m and 30 m is much smaller, probably because the flow readjusts to the new surface roughness. In case of southerly wind, z_0 at 30 m is larger than at 10 m since the 30 m measurement point feels the presence of the buildings whereas the 10 m measurement point does not (see section 3). The fact that the values of z_0 differ between the two measurement heights means that the vertical profile of wind velocity does not follow Eq. (1).

The present study shows that the terrain heterogeneity has an important impact on the turbulence parameters like the roughness length, the turbulent fluxes (not shown) and the turbulent kinetic energy. Hence, in our case, these parameters strongly depend on the rough elements upwind of the measurement mast (close forest, open field, buildings or distant forest), on the measurement height and on the fetch.

4. COHERENT STRUCTURES IN THE ATMOSPHERIC SURFACE LAYER

Coherent structures in the atmospheric surface layer contribute to about 40 to 70% of energy and matter transport between the surface and the atmosphere. The aim of this part is to detect the coherent structures and to study the impact of terrain heterogeneity on their dynamics (occurrence, life time, momentum and heat transport). The identification of coherent structures consists in detecting ramp-like pattern in the time series of the temperature fluctuations recorded by the sonic anemometer at 10 m with wavelet analysis.

Figure 4 shows an example of coherent structure detection over a 30 min time period. The wavelet analysis of the temperature fluctuations allows the detection of sweeps or ejections (Foster et al., 2006) associated with the presence of coherent structures at the instrumented mast. The wavelet analysis allows us to localise the coherent structures in time, to quantify their life time and their occurrence and to estimate their contribution to turbulent transport.

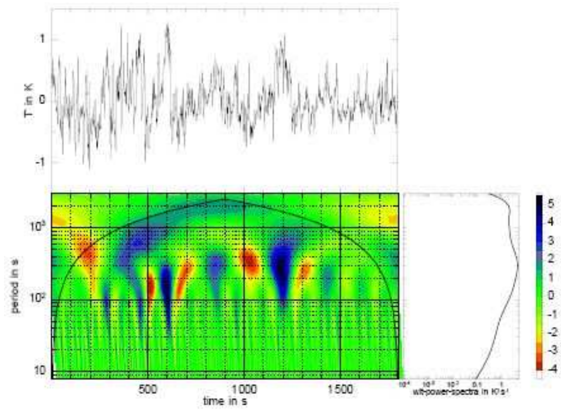

Fig. 4: Upper panel: time series of temperature fluctuations measured by the 10-m sonic anemometer. Lower panel: wavelet analysis corresponding to the temperature time seriesof the upper panel. The color code indicates the perturbation amplitude.

Figure 5 represents the mean occurrence of coherent structures detected at 10 m (green) and at 30 m (yellow) in all stability conditions.

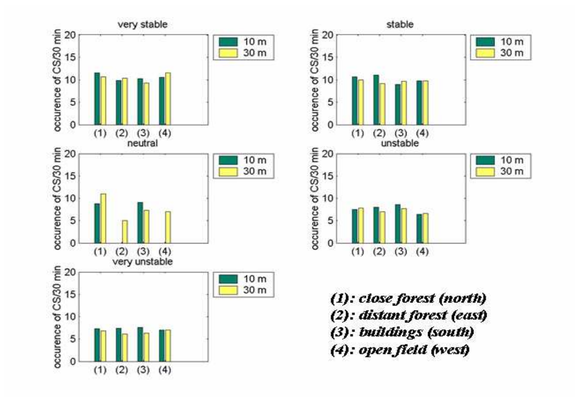

Fig. 5: Coherent structures occurrence per 30 minutes as a function of stability conditions and wind direction.

We can notice that the terrain heterogeneity (associated with the four different wind direction sectors) seems to have no impact on coherent structures occurrence. So, the results are similar to the homogeneous terrain case. Within the statistical uncertainty, we can also notice that there is no difference between the two heights, only the stability seems to have an impact on coherent structures occurrence. Similar results have been found for the duration of the coherent structures and their contribution to momentum and heat surface fluxes.

4. CONCLUSION AND PERSPECTIVES

This preliminary study shows that the terrain complexity has an important impact on the turbulence parameters like the roughness length, the turbulent fluxes (not shown) and the TKE. Hence, in our case, these parameters strongly depend on the rough elements upwind of the measurement mast (close forest, open field, buildings or distant forest), on the measurement height and on the fetch.

In comparison, near-surface coherent structures are not affected by the terrain heterogeneity from a structural point of view (duration, occurrence) as well as from an energetic point of view (momentum and sensible heat fluxes). Our statistics also appears to be independent of the measurement height but strongly depends on the atmospheric stability.

Future works will be focused on the derivation of an effective roughness length, depending on the upwind roughness, the downwind roughness, the measurement point height and the fetch. This could help us to predict the vertical profiles of velocity in heterogeneous conditions and hence to improve models parameterization over complex terrain. Our effort will also be concentrated on the determination of the reasons why coherent structures properties do not depend on the terrain complexity.

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