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► **To cite this version:**

L. Perret. Scale interaction and the large-scales influence in the urban canopy. International Workshop on Physical Modeling of Flow and Dispersion Phenomena PHYSMOD 2022, Aug 2022, Prague, Czech Republic. hal-04627128

HAL Id: hal-04627128

<https://hal.science/hal-04627128>

Submitted on 27 Jun 2024

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SCALE INTERACTION AND THE LARGE-SCALES INFLUENCE IN THE URBAN CANOPY

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Abstract

Recent investigation of turbulent boundary layer flows developing over urban-like roughness has evidenced the strong similarities of their spatio-temporal organization with that of smooth-wall boundary layers. In particular, the presence of large and very-large scale structures (VLSMs) has been shown in flow at high Reynolds numbers. The objective of the present contribution is to review some of the aspect of the interaction between these boundary-layer large scales and the most energetic structures existing in the roughness sublayer (RSL). In addition to superimpose onto the RSL scales, VLSMs are shown to modulate canopy turbulence, leaving their imprint in high order moments and participating to the transport of kinetic energy turbulence through inter-scale energy transfer.

1. Introduction

Understanding and modeling the flow dynamics over urban terrain still represent a challenge due to the high geometrical complexity of built areas, the existence of numerous interacting thermodynamic processes that take place in the urban canopy, and the mutual influence of atmospheric processes. From a purely aerodynamic point of view, the atmospheric flow over the urban canopy can be considered as a high Reynolds number boundary-layer flow developing over a heterogeneous and multi-scale surface. This flow has therefore an important multi-scale character in both space and time with strong and complex inter-scale interactions. The resulting high complexity limits our ability both to understand the dynamics of urban flows and to model these flows.

Decades of research on the turbulent boundary layer that develops over a flat smooth wall has brought general consensus across the scientific community regarding its organization (Marusic et al. 2010): the turbulent structures existing in such a flow are the well-known near-wall streaks and hairpin vortices, the latter assembling into vortex packets to form a third type of coherent structures, the large-scale motions (LSMs). The fourth type of structures has been identified as very large-scale motions (VLSMs) consisting of narrow low-momentum regions meandering in the horizontal plane and flanked by regions of high momentum (Hutchins & Marusic, 2007). While smaller structures such as streaks and hairpin vortices scale in wall units, LSMs and VLSMs are found to scale with δ , the depth of the boundary layer. VLSMs and near-wall turbulence have been found to interact through a non-linear mechanism that resembles amplitude modulation. Despite the drastic modification of the near-wall turbulent cycle by the roughness elements in flow over very rough surfaces similar to urban terrain, similar types of coherent structures have been shown to exist in direct numerical simulation (DNS) (Coceal et al., 2007), large-eddy simulation (LES) (Kanda et al., 2004), wind-tunnel experiments (Castro et al., 2006), and field experiments (Inagaki & Kanda, 2010). Building upon these past studies and based on the last decade of experimental research conducted at the LHEEA lab in Nantes, France, the objective of the present contribution is to review some of the



aspect of the interaction between the most energetic large scales existing in the boundary layer and those from the roughness sublayer (RSL). Section 2 describes the experimental setup and methodologies. Section 3 is devoted to the presentation of the main results. Discussion and conclusions are presented in Section 4.

2. Methods

2.1. Experimental setup

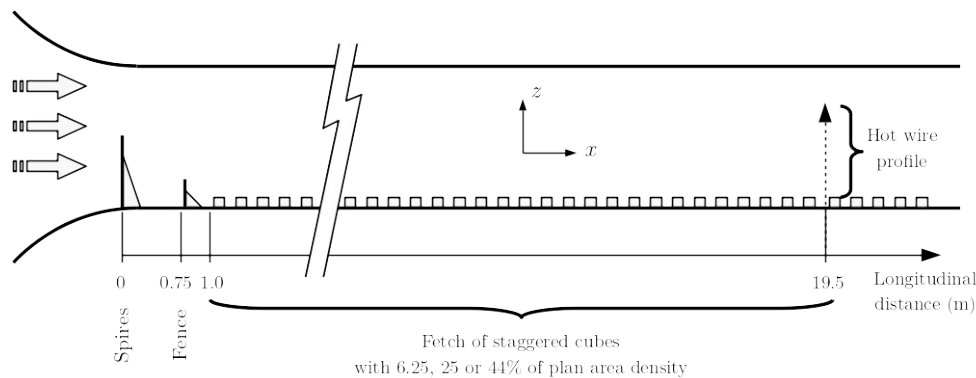


Fig. 1: Wind-tunnel set-up (sketch not to scale).

Experiments were conducted in the boundary-layer wind tunnel of the Laboratoire de recherche en Hydrodynamique, Energétique et Environnement Atmosphérique of Ecole Centrale de Nantes (LHEEA, Nantes, France), which has test-section dimensions of 24 m × 2 m × 2 m (Fig. 1). A reproduction of the lower part of a suburban-type ABL developing over an idealized urban canopy model was achieved by using five vertical, tapered spires of height of 800 mm and width of 134 mm at their base, a 200 mm high solid fence across the working section located 0.75 m downstream of the inlet, followed by a 22 m fetch of staggered cubic roughness elements of various density (6.25%, 25%, 44.4%) or two-dimensional bars. The obstacle height was $h=50$ mm. Extensive details on this facility and set-up can be found in Blackman et al. (2014, 2018b) and Perret et al. (2019).

Measurements were conducted using hot-wire anemometry (HWA) (Perret et al., 2019) and stereoscopic Particle Image Velocimetry (PIV) (Basley et al., 2018, 2019, Blackman et al., 2014, 2017, 2018b). In some of these studies, the two measurement techniques were combined and synchronized to allow for the time-resolved estimation of the coherent structures detected in the boundary layer.

2.2. Method for large scales – small scales separation

The method for the detection and separation of the large scales from the boundary layer and the smaller scales existing within the RSL is briefly presented here. For more details, the reader is referred to the work of Blackman & Perret (2016) and Perret et al. (2019).

Given the strong geometrical heterogeneity of the urban canopy, in most of the results presented here, PIV was retained as a measurement technique to enable the analysis of the spatial variation and features of both the flow and the existing coherent structures within the RSL. However, standard PIV systems suffer from a low temporal acquisition frequency (on the order of 10Hz), too low to



correctly sample the time evolution of the flow. From a spatial point of view, given the typical depth of the

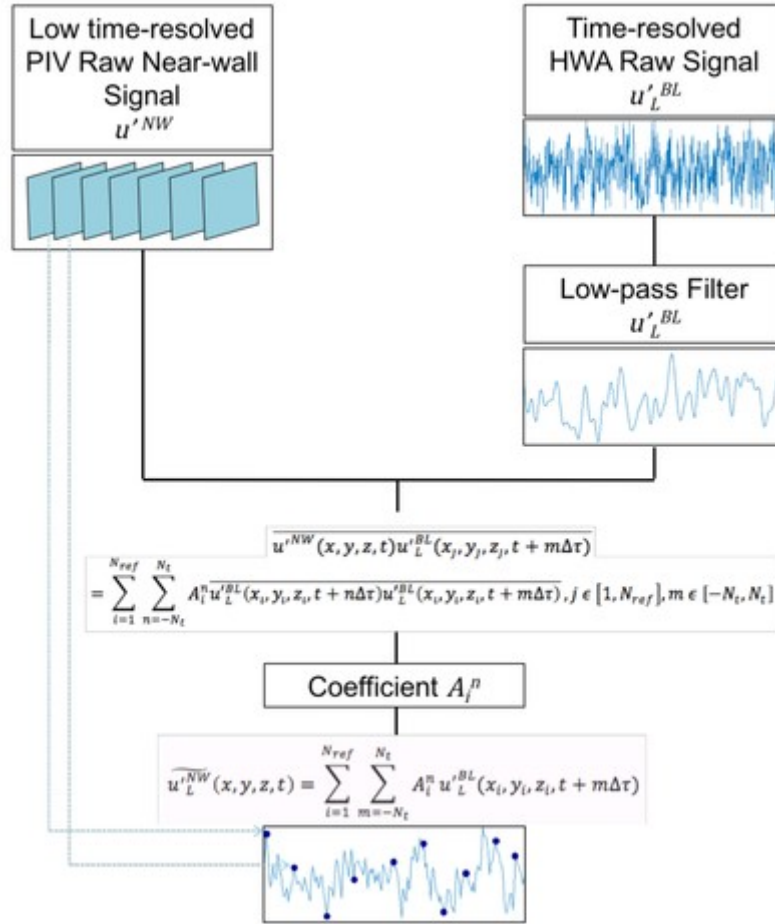


Fig. 2: Schematic of process used for large-scale eduction (Blackman & Perret, 2016).

boundary layers generated in the LHEEA's wind tunnel (on the order of 1m), the PIV field of view is generally too small to capture the spatial extent of the largest scales existing in the boundary layer.

A method using synchronized HWA (to measure the large-scales) and PIV (to capture the flow characteristics within the RSL) has been designed, based on the use of the Linear Stochastic Estimation (LSE). This method enables the estimation of the part of the velocity field that is the most correlated with a given reference signal. In the present case, the reference signal is u'^{BL} the low-pass filtered streamwise velocity component measured using HWA in the logarithmic region of the boundary layer characterizing the large-scales. The large-scale contribution $\widetilde{u_L'}$ to the velocity field measured via PIV is estimated using LSE as described in figure 2, and is written as a linear combination of the large-scale signal measured at different time intervals. The coefficients A_i^m directly depend on the temporal correlation between the velocity measured by PIV and the time-resolved HWA signals, a statistics that can be measured as the two measurement systems are synchronized. A spectral version of this approach has been proposed by Perret et al. (2019), based on the use of the cross-spectra between two HWA located in the RSL and in the log-region, respectively. Note that an

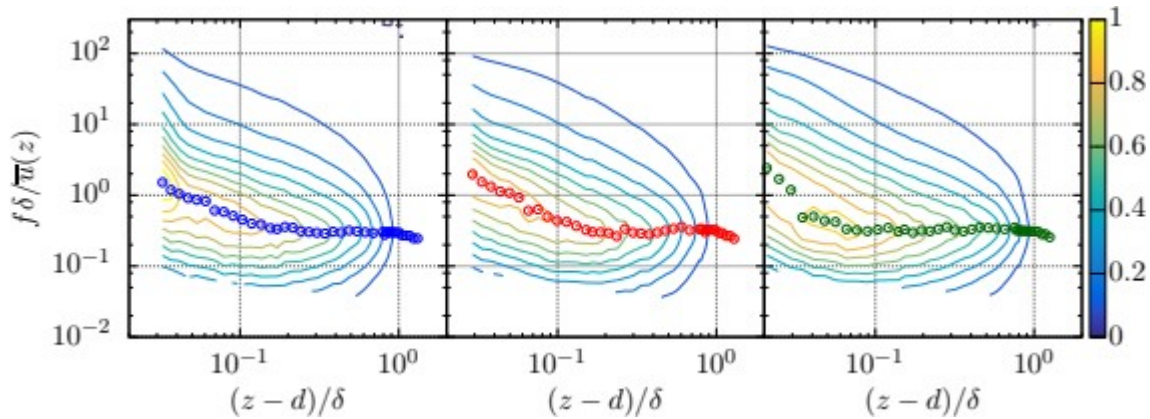


Fig. 3: Pre-multiplied spectra of the streamwise velocity component as a function of the distance from the wall z and the normalized frequency by $\langle u(z) \rangle$ and δ . Symbols show the energy maxima (Perret et al, 2019).

alternative approach based on the use of the Proper Orthogonal Decomposition (POD) with a modified kernel has been proposed and validated by Perret & Kerhervé (2019) for the large-scale extraction from PIV data only.

3. Results

3.1. Evidence of the presence of very large-scale structures

VLSMs in the smooth-wall turbulent boundary layer have been identified as turbulent structures similar to high- and low-speed streaks of very large streamwise extent (several times δ) and that scale with δ and the local mean streamwise velocity $\langle u(z) \rangle$. Their contribution to the variance and the Reynolds shear-stress in the near-wall region remains small.

Studying the most energetic structures of the streamwise velocity component in the boundary layer developing over cube arrays of different packing density, Perret et al. (2019) evidenced the presence of VLSMs. In the outer region of the boundary layer, these structures have a streamwise extent of 3.3δ , independent of the distance from the wall and of the packing density (Fig. 3). Their two-point analysis of the spectral coherence between a fixed point within the log-region and a moving point within the RSL showed the large vertical extension of these structures. The part of the velocity signal correlated between the two points indeed corresponded to the VLSMs wavelengths.

The characteristics of the VLSMs have been further investigated in the horizontal plane by Basley et al. (2019), confirming the associated wavelengths and their meandering behavior. VLSMs were also detected within the RSL, through the presence of a secondary energy peak in the spectra at low wavenumbers.

Blackman et al. (2018b) evidenced the presence of VLSMs in boundary layers developing of two-dimensional obstacles (i.e a series of street canyons) with different spacing. They showed the same characteristics as those detected in flow over cube canopies (Fig. 4). It is worth noting here that the same type of coherent structures have also been deduced from boundary layers developing over vegetation canopies (Perret & Ruiz, 2013), confirming that are a key ingredient common to all turbulent boundary layer types.

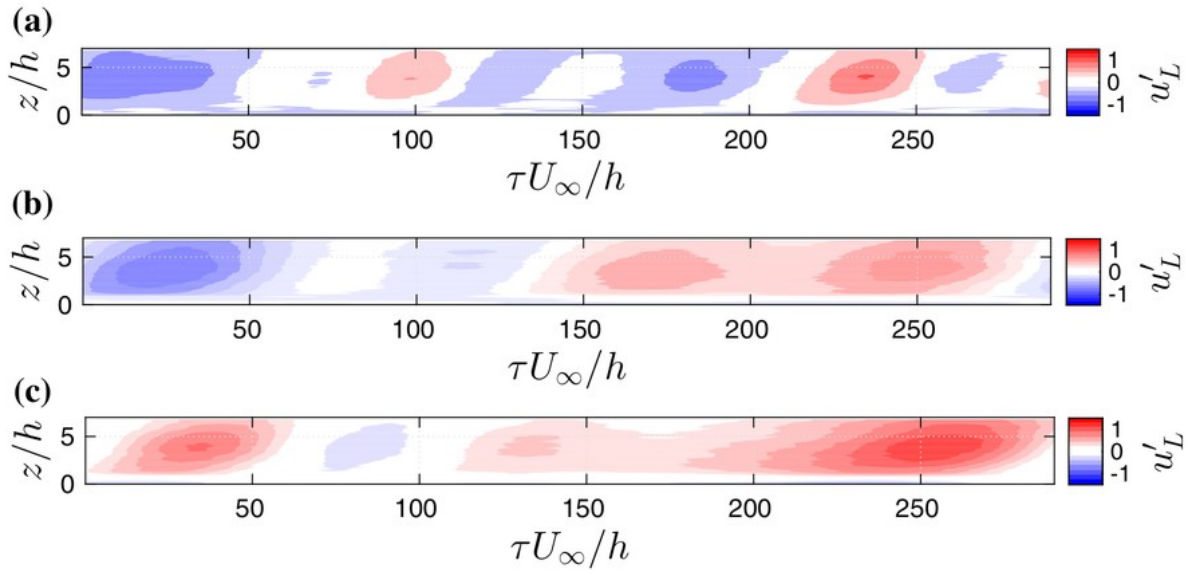
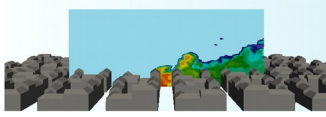


Fig. 4: temporal evolution of the VLSMs associated with the streamwise velocity component in flows over (a) a 25% cube array, (b) and (c) two-dimensional obstacles with spacing of $W/h=1$ and $W/h=3$, respectively (Blackman et al, 2018).

3.2. Boundary layer – canopy flow scale interaction.

Studies of smooth boundary layers have shown that the VLSMs contribution becomes prominent in the outer region of the flow with increasing Reynolds number. In addition to the superimposition mechanisms described above, the interaction between the VLSMs and the near-wall turbulence has been shown to resemble an amplitude modulation (AM) mechanism, through which the smaller-scales near the wall are amplified or attenuated by the very-large scale high- or low-speed streaks, respectively (Hutchins & Marusic, 2007; Mathis et al., 2009). The identification of such a mechanism is based on the decomposition of the velocity field into a large- and a small-scale contributions, as $u = u_L + u_s$. In the present case, this decomposition has been performed using the method described in section 2.2. This decomposition is then used to compute the statistics $\langle u_L u_s^2 \rangle$ (one of the four components of the scale-decomposed skewness), which serves as a diagnostic tool to identify non-linear scale interactions such as amplitude modulation (Mathis et al., 2011). This statistics, being similar to the correlation coefficient between the large scales and the envelope of the small scale, takes positive values when large-scale high- (low-) speed streaks are correlated with high (low) level of near-wall turbulence. Conversely, negative values correspond to attenuated small scales in the presence of high-speed VLSMs. An example of the one-point version of $\langle u_L u_s^2 \rangle$ estimated in the RSL of turbulent boundary layers developing of staggered arrays of cubes is shown in figure 5. It shows that, in addition to the above-mentioned superimposition effect, most of the RSL turbulence is under the influence of the VLSMs (which do not correspond to the most energetic structures in this region of the flow) through an AM-like mechanism, independent of the canopy-flow regime (Blackman et al., 2019). Similar results were found in flows over two-dimensional obstacle arrays (Blackman et al., 2018b).

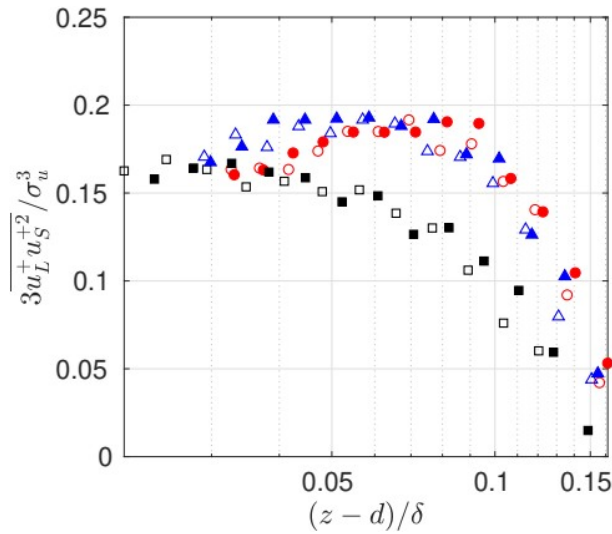


Fig. 5: Influence of the packing density λ_p of cube canopies on the amplitude modulation mechanism. Red symbols: $\lambda_p=6.25\%$, blue symbols: $\lambda_p=25\%$, black symbols: $\lambda_p=44.4\%$ (filled symbols: $\delta^+=45000$, open symbols: $\delta^+=30000$) (Blackman et al., 2019).

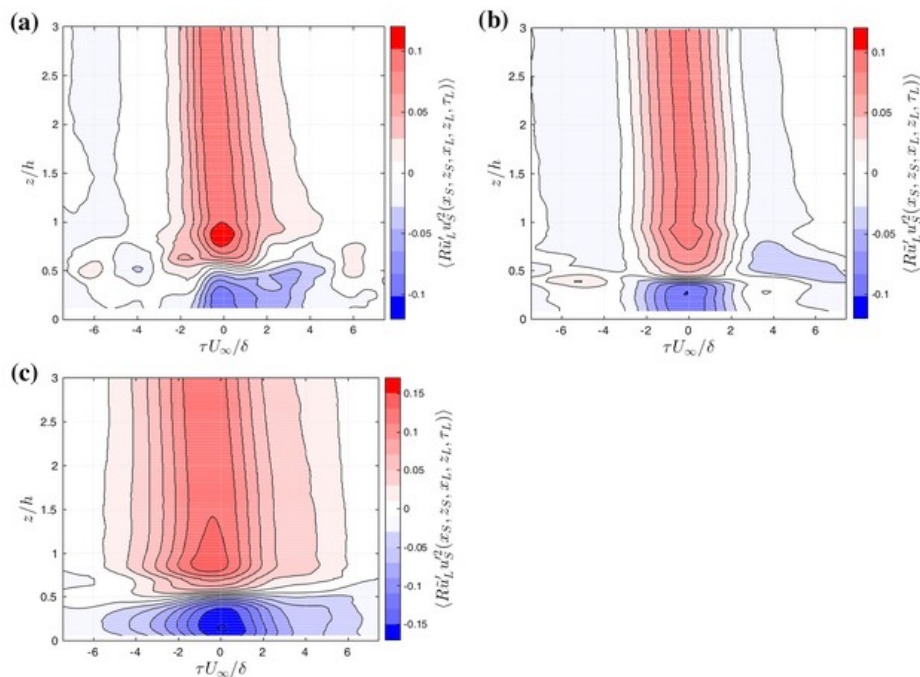


Fig. 6: Spatio-temporal two-point correlation $R_{u_L u_S^2}(z_L, z_S, \tau_L)$: fixed point $z_S=0.75$: small scales, moving point z_L : large-scales ($x_S=x_L$) for (a) 25% cube canopies, (b) and (c) two-dimensional obstacles with spacing of $W/h=1$ and $W/h=3$, respectively (Blackman et al., 2018).

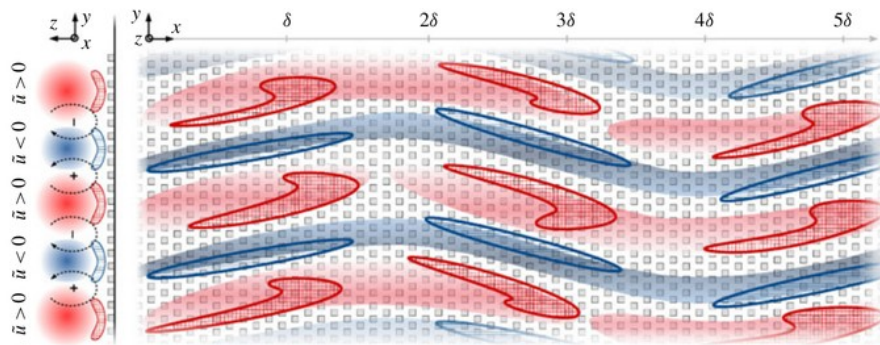


Fig. 7: spatial organization of the coherent structures of in a horizontal plane within the RSL. Red and blue shaded areas correspond to large-scale high- and low-speed regions, red and blue hatched areas correspond to locations of amplification or attenuation, respectively, of the small scales by the large through the AM-like mechanism (Basley et al., 2018).

To further investigate the spatial structure of the interaction and allow for the study of the interaction between the VLSMs and the inner-canopy flow, the two-point version (both in time and space) of the statistics $\langle u_L u_S^2 \rangle$ has also been used. Results from figure 6 show that the RSL and the top half of the canopy, the flow is under the positive influence of the VLSMs (i.e high-streaks correspond to amplified small-scale turbulence), in the bottom part of the canopy, u_L and u_S are out of phase (i.e negative values of $\langle u_L u_S^2 \rangle$) (Blackman et al., 2018b). Overall, the influence of the large scales onto the smaller scales is independent of the nature of the canopy, the differences being attributed to the change of flow regime and the subsequent small-scale turbulence modification rather than a change in the interaction mechanism (Blackman et al., 2018b).

The spatial structures of the large-small scale interaction has been further investigated in the horizontal plane within the RSL by Basley et al. (2018). By taking into account the sign of both the streamwise and spanwise large-scale velocity components u_L and v_L , respectively, they computed conditional two-point AM coefficients. By doing so, they broke the symmetry imposed by the spanwise statistical homogeneity of the flow and accounted for the meandering behavior of the VLSMs. They evidenced the preferred spatial organization of the AM mechanism (Fig. 7): the VLSMs influence is non-symmetric, the maximum influence being on their flank, and on their upstream portion, in agreement with the literature finding that small scales are phase-leading.

These findings are summarized in figures 8. Strong similarities with the interaction mechanisms identified in smooth-wall flows are found, in particular regarding the nature and the organization of coherent structures in the logarithmic and outer regions of the boundary layer and the existence of a superimposition – amplitude modulation mechanism of the near-wall canopy flow by the VLSMs. The only differences (from a qualitative point of view) seem to be due to the obvious change of the structure of turbulence within the RSL due to the presence of the canopy obstacles and the change of in flow regimes induced by the canopy morphology. Despite the apparent strong decoupling of the lower portion of the canopy flow from the outer flow induced by the canopy itself (not discussed here), the upper half of the canopy and the portion of the RSL above, are influenced by the mechanisms discussed above. It therefore suggests an influence of the larger scales of the boundary layer onto the instantaneous exchange processes between the canopy and the flow above.

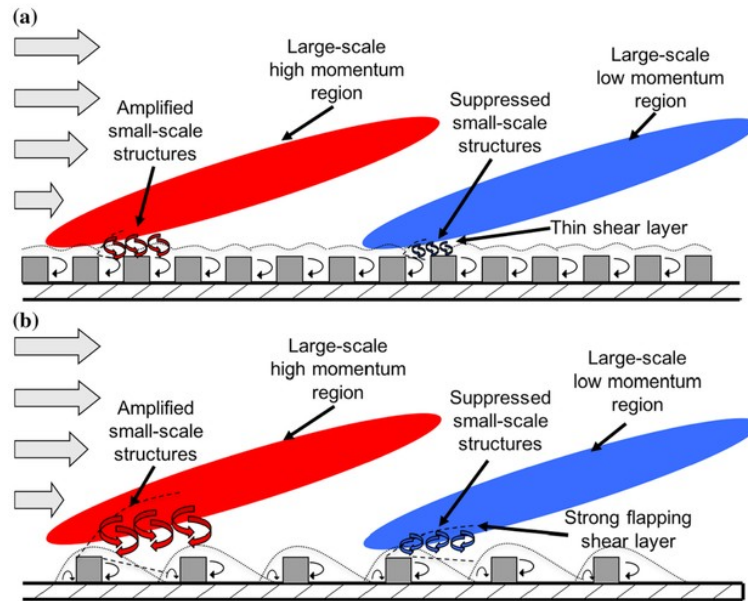
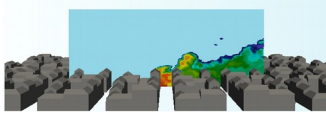


Fig. 8: Influence and interaction of the VLSMs with the canopy flow for (top) skimming flow and (bottom) wake-interference flow regimes (Blackman et al., 2018b).

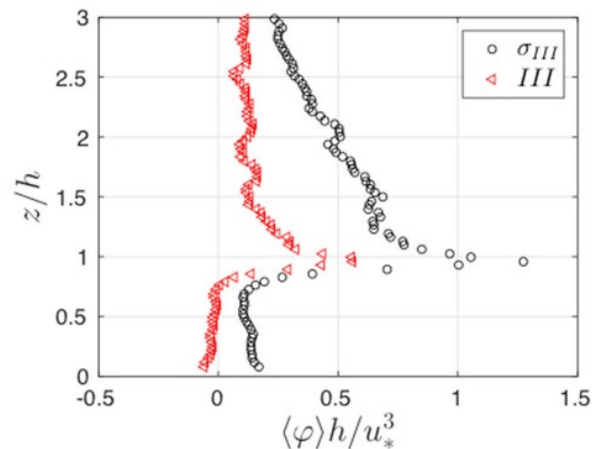
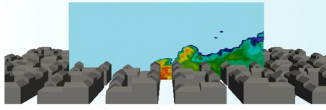


Fig. 9: Mean (red) and standard deviation (black) of the inter-scale energy transfer term between the VLSMs and the canopy turbulence in the boundary layer developing over a 25% staggered cube array (positive values indicate energy transfer from the VLSMs to the smaller scales) (Blackman et al., 2018a)

3.3. Amplitude modulation and inter-scale energy transfer

Besides leaving their imprint on the smaller-scales and modulating their amplitude, the large most energetic coherent structures from the boundary layer do interact with the RSL turbulence via an energy transfer mechanism. This point has recently been investigated by Blackman et al. (2018a) by estimating the inter-scale turbulent kinetic energy transfer between the VLSMs and the RSL flow in the boundary layer developing over a 25% staggered cube array. As expected, the average energy



transfer is from the VLSMs toward the smaller scales (i.e. classical forward scatter of energy). Interestingly, instantaneous energy transfer were found of larger magnitude and were found from VLSMs to small scales but also the other way around (i.e. backscatter of energy), implying a more complex interaction mechanism than what can be observed in average. This energy transfer has been found to be well correlated with the amplitude modulation mechanism firstly observed, confirming the non-linear nature of the latter. Similar findings have been obtained in atmospheric boundary layers developing over vegetation canopies for various atmospheric stability regimes by Perret & Patton (2021). The extension of this analysis to various of urban-like canopies is the subject of ongoing research.

4. Conclusion

Recent results obtained at LHEEA, Nantes, and based on wind tunnel investigation on the interaction between the most energetic large scales existing in the outer region of boundary layers developing over urban-like canopies and those existing in the RSL have been presented. Focusing first on the identification of these coherent structures, it has been shown that despite the strong disruption of the near-wall flow by the presence of the obstacles, the spatio-temporal organization of the turbulent boundary layers over very rough wall share many features with those developing over smooth walls. In particular, it has been shown that the interaction between the inner and the outer region of the flow is driven by the same type of mechanism, namely the combination of the superimposition of the large scales onto the RSL turbulence with a non-linear interaction that resembles an amplitude modulation mechanism, influencing all three velocity components. This feature has been found in all the investigated flow configurations with different types of canopy morphology: cube arrays of different packing densities, arrays of two-dimensional obstacles with different streamwise spacing and vegetation-like canopies. This amplitude modulation mechanism, being non-linear, leaves its imprint into the third-order moment of the velocity components (i.e. their skewness) and is directly linked to inter-scale energy transfer.

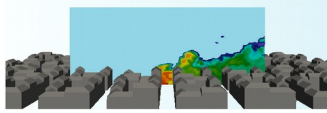
The modulation of small-scale turbulence by larger scales discussed in this paper clearly demonstrates the importance of large-scale turbulence on higher-order velocity statistics and the instantaneous dynamics of smaller-scale turbulence in the RSL. It therefore reinforces the need for the proper physical modeling of all the relevant scales within the wind tunnel if one wants to perform accurate wind-tunnel simulations of flows relevant to atmospheric processes. Furthermore, the VLSMs being an order of magnitude larger than the RSL scales, the amplification/attenuation of the latter by the former can lead to long-standing spatial heterogeneity in the RSL flow characteristics. Even if this will average out in the case of horizontally homogeneous terrains, presence of surface heterogeneity caused for instance by topography, preferential roughness obstacle distribution, presence of tall isolated building will induce a locking effect of the location of those VLSMs and therefore of their influence.

Acknowledgments

The author warmly thank the colleagues and students who contributed to the presented work.

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