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Quantification of the rate of dissipation of turbulent kinetic energy within arrays of rigid emergent stems with PIV and LDA

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In natural conditions, the flow within plant canopies is generally turbulent. Vortex shedding from individual stems constitutes the main source of turbulent kinetic energy (TKE). The spatial distribution of the variables that describe turbulence is complex, being mostly determined by the distribution of the stems. A complete description of the processes occurring at all points in space is impossible, even in the statistical sense, since the stems are randomly placed with a variety of staggered arrangements.

Upscaling the analysis to spatial scales larger than the mean distance between a stem and its nearest neighbour has allowed for major progresses in the characterization of momentum and scalar fluxes (Finnigan, 2000; White Nepf, 2008). The theoretical background for this upscaling process has been laid out by (Raupach, 1992, Finnigan 2000), among others, and has been termed Double-Averaging Methodology (D-AM, Nikora et. al., 2001). Conservation equations for mass, momentum and second-order moments of turbulent fluctuations (and thus for the TKE) have been developed within the D-AM. However, the terms in the momentum and TKE equations that come into being through the formalism of space averaging require parametrization. A crucial example, addressed in this paper, is the mean (time- and space-averaged) rate of dissipation of TKE, for which existing methods of calculation may be unreliable since they incorporate major simplifications (Finnigan Shaw, 2008).

The objective of this paper is the calculation of the rate of dissipation of TKE in the inter-stem space. The work is fundamentally experimental and is based on the analysis of a Particle Image Velocimetry (PIV) database, for which the spatial resolution is of the order of magnitude of Taylor's microscale, and of a Laser Doppler Annemometry (LDA) database, with a temporal resolution comparable to that of the PIV. Both databases were obtained in the same experimental conditions, i.e. a 0.41 m wide horizontal channel with a 3.5 m reach populated with stems of 0.011 m diameter. The discharge was 2.33 l/s, water depth at the downstream reach was 0.052 m and the mean water-depth slope of 0.012. Stem density varied periodically between 400 and 1600 $\mathrm{stems/m^2}$ with a wavelength of 0.5 m. The point-wise time-averaged rate of dissipation of TKE can be easily calculated for homogeneous and isotropic turbulence (HIT), within Kolmogorov's theory, requiring only a spectral description of the fluctuating motion or the computation of structure functions. If turbulence is not homogeneous, as is the case of the flow in the inter-stem space, there are several competing theories expressing the dissipation tensor (Nazarenko et. al. 1999) but they are not analytically tractable. Instead of employing a non-homogeneous theory, we propose to further exploit the D-AM as a means to salvage the formalism of HIT and to allow the calculation of the rate of dissipation from the third-order structure function. For the PIV database, two point-correlations and statistics are space-averaged. The LDA database is treated in the time domain but resulting correlation functions and structure functions are space averaged before obtaining the rate of dissipation that characterizes the inter-stem space. Taylor's hypothesis is discussed by comparing PIV (spatial) and LDA (temporal) measurements.

We find that the mean dissipation rate of TKE exhibits a pattern of spatial variation close to that of the stem density. In both wavelengths of the array modulation, the rate of energy dissipation increases with stem density. Most of the energy produced in the inter-stem space seems to be dissipated locally, downstream the producing stems in a manner similar to the decay of grid turbulence. As a consequence, the spatial distribution of the rate of dissipation of TKE presents a local maximum at some distance downstream the producing stems.

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