A NOTE ON THE CONTRIBUTION OF DISPERSIVE FLUXES TO MOMENTUM TRANSFER WITHIN CANOPIES

Research Note

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(Received in final form 1 September 2003)

Abstract. Dispersive flux terms are formed when the time-averaged mean momentum equation is spatially averaged within the canopy volume. These fluxes represent a contribution to momentum transfer arising from spatial correlations of the time-averaged velocity components within a horizontal plane embedded in the canopy sublayer (CSL). Their relative importance to CSL momentum transfer is commonly neglected in model calculations and in nearly all field measurement interpretations. Recent wind-tunnel studies suggest that these fluxes may be important in the lower layers of the canopy; however, no one study considered their importance across all regions of the canopy and for a wide range of canopy roughness densities. Using detailed laser Doppler anemometry measurements conducted in a model canopy composed of cylinders within a large flume, we demonstrate that the dispersive fluxes are only significant (i.e., $> 10\%$) for sparse canopies. These fluxes are in the same direction as the turbulent flux in the lower layers of the canopy but in the opposite direction near the canopy top. For dense canopies, we show that the dispersive fluxes are $< 5\%$ at all heights. These results appear to be insensitive to the Reynolds number (at high Reynolds numbers).

Keywords: Canopy density, Canopy turbulence, Dispersive fluxes, Mean momentum equation.

1. Introduction

The need to understand and quantify momentum transfer close to roughness elements, such as canopies or buildings within a city, has ignited substantial interest in the structure of turbulence within a matrix of roughness elements. Obvious applications include carbon dioxide and water vapour exchange between the biosphere and the atmosphere, ozone dry deposition on canopies, pollen or seed dispersal within or among landscapes, and pollutant transport within the airspace of buildings, to name a few. Progress on such complex problems can only be achieved after

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firm understanding is developed for flow within morphologically simple canopies (Finnigan, 2000).

The most poorly understood terms in the time and horizontally averaged momentum equation are the dispersive fluxes (Raupach, 1994; Finnigan, 2000); these terms are the subject of the present investigation. A study by Bohm et al. (2000) compared dispersive fluxes of momentum and heat with horizontally-averaged turbulent fluxes in a sparse wind-tunnel model plant canopy. The comparisons showed that the dispersive momentum fluxes were much smaller in the upper canopy than the turbulent momentum fluxes at the same height. In contrast, the dispersive momentum fluxes were shown to be of the same order of magnitude as the turbulent momentum fluxes for the lower layers of the canopy. Raupach (1994) and Kaimal and Finnigan (1994) reported dispersive momentum fluxes of about 1% of the turbulent flux using wind-tunnel measurements with a dense canopy (Raupach et al., 1986). Also, from wind-tunnel experiments, Cheng and Castro (2002) found negligible dispersive momentum fluxes throughout the depth of urban-like, densely placed roughness elements. These preliminary studies suggest that the relative importance of dispersive to turbulent fluxes may depend on both canopy density and height within the canopy volume. Hence, the objective of this note is to quantify the relative contribution of dispersive fluxes to momentum transfer throughout the canopy sublayer (CSL) for a wide range of canopy roughness densities. The broader implications of this work are to guide future model development and CSL experiments on the significance of these fluxes over a broad range of canopy densities.

2. Theory

Upon applying time and spatial averaging to the momentum equations, the resulting stress tensor is given by

$$\tau_{ij} = -\langle \overline{u_i' u_j'} \rangle - \langle \overline{u}_i'' \overline{u}_j'' \rangle + \nu \frac{\partial \langle \overline{u_i} \rangle}{\partial x_j}, \tag{1}$$

where x_i ($x_1 = x, x_2 = y, x_3 = z$) are the longitudinal, lateral, and vertical directions, respectively; u_i ($u_1 = u, u_2 = v, u_3 = w$) are the instantaneous velocity components along x_i, and ν is the kinematic viscosity. All flow variables are decomposed into temporal and planar averages with turbulent excursions defined from the time-averaged (denoted by overbar) and horizontally-averaged (denoted by angular brackets) quantities as in Raupach and Shaw (1982) and Finnigan (1985, 2000). The τ_{ij} contains the conventional turbulent and viscous stresses and a dispersive flux term $\langle \overline{u}_i'' \overline{u}_j'' \rangle$ resulting from spatial correlations in the time-averaged velocity field. To address our objective, we compute the relative importance of dispersive to conventional fluxes. The measurements used in such calculations are described next.

3. Experiments

While much of the setup is described in Poggi et al. (2004), for completeness we provide a brief review. The experiment was conducted at the hydraulics Laboratory, DITIC Politecnico di Torino, in an 18 m long, 0.90 m wide and 1 m high recirculating rectangular flume. The ‘model’ canopy is an array of 120 mm tall ($= h$) and 4 mm diameter ($= d_r$) steel cylinders arranged in a regular pattern along a 9 m long working section. We focus on five canopy roughness densities: 67, 134, 268, 536, and 1072 rods m^{-2}, which are equivalent to an element area index a (frontal area per unit volume) of 0.27, 0.53, 1.07, 2.13, and 4.27 m^2 m^{-3}, respectively.

The longitudinal and vertical velocity components were measured by two-component Laser Doppler Anemometry (LDA). A key advantage of LDA over hot-film anemometry, which is commonly used in wind tunnels, is its non-intrusive nature and its ability to measure velocity excursions close to the cylinders. Another benefit of LDA is that it resolves reverse flow and is not subject to rectification errors in high turbulence intensity, unlike hot wires. Further details about the LDA configuration and signal processing can be found in Poggi et al. (2002).

Given the non-homogeneity in the flow statistics within the canopy, 11 measurement locations were used. These locations were chosen such that sampling locations were more densely placed in regions where the flow statistics exhibit highest spatial variability, as shown in Figure 1. At each of the 11 horizontal positions, measurements were made at 15 elevations (see Figure 1). The sampling duration and frequency for each run were 300 s and 2500–3000 Hz, respectively. For each statistic, an area-weighting scheme was applied to each of the 11 measurement locations (Poggi et al., 2004).

The experiments were conducted for each canopy density at two bulk Reynolds numbers (defined by the depth-averaged velocity U_b across the entire water surface profile h_w) to assess whether the dispersive flux fractions vary strongly with Reynolds number (for high Re_b). The computed Re_b ($= U_b h_w/\nu$) were significantly high: 116,560 and 172,300.

4. Results

The dispersive fluxes are estimated as follows: Let α_i be the area-weight assigned to each of the 11 measurement location shown in Figure 1 (i.e., $\sum_{i=1}^{11} \alpha_i = 1$). The relevant flow statistics were computed as

$$\langle \overline{u'w'} \rangle = \sum_{i=1}^{11} \alpha_i \overline{u'w'}_i$$

$$\langle \overline{u} \rangle = \sum_{i=1}^{11} \alpha_i \overline{u}_i$$

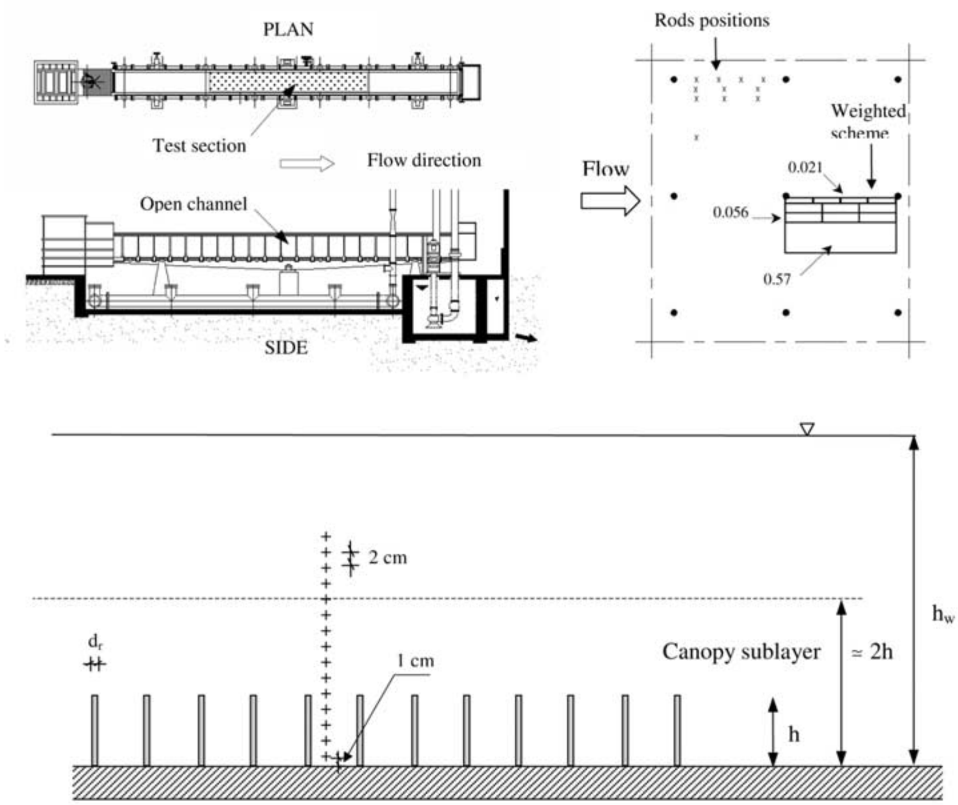

Figure 1. The channel flow facility and the working section (top left), the plan view of the spatial sampling points and their area-weighted contribution to the spatial averaging (top right), the section view of the measurement locations (bottom).

$$
\begin{aligned}
\langle \overline{w} \rangle &= \sum_{i=1}^{11} \alpha_i \overline{w}_i \\
\overline{u}_i'' &= \overline{u}_i - \langle \overline{u} \rangle \\
\overline{w}_i'' &= \overline{w}_i - \langle \overline{w} \rangle \\
\langle \overline{u}'' \overline{w}'' \rangle &= \sum_{i=1}^{11} \alpha_i \overline{u_i}'' \overline{w_i}'' .
\end{aligned}
$$

The relative importance of the dispersive flux when compared to the conventional momentum flux is quantified using their ratio $\xi = \langle \overline{u}'' \overline{w}'' \rangle / \langle \overline{u'w'} \rangle$. These results are presented in Figure 2 for all a, normalized height (z/h), and the two Reynolds numbers. For sparse canopies the dispersive flux can be up to 35% of the mean momentum flux within the lower-layer of the canopy $(z/h < 0.5)$. For the top 1/3 of the canopy, however, the dispersive flux decreases to about 10% of the total, but with an opposite sign. For dense canopies the dispersive fluxes are negligible.

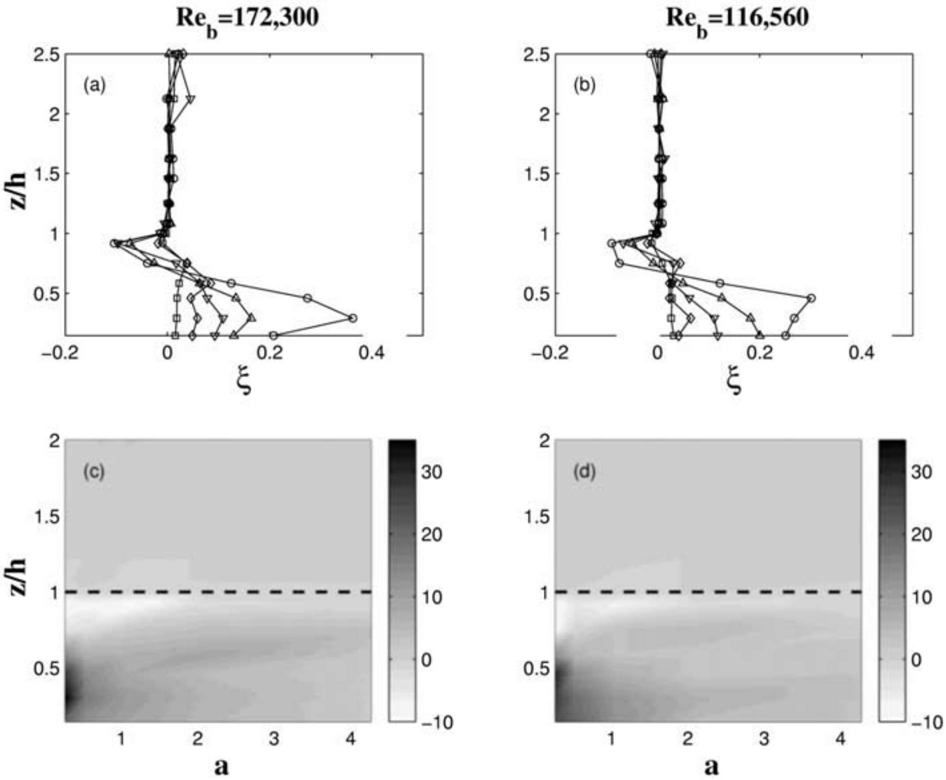

Figure 2. (a) Measured $\xi = \langle \overline{u''w''} \rangle / \langle \overline{u'w'} \rangle$ for the 5 canopy densities and for Re_b = 172,300 across all z/h. The open circles are for the sparsest canopy and the open rectangles are for the densest canopy. The up-triangle, the down-triangle, and the diamond are for progressively increasing roughness density. (b) The same as (a) but for Re_b = 116,560. (c) A colormap of ξ as a function of a and z/h generated from the data in (a), where color intensities reflect the percentages of ξ. (d) The same as (c) but using the data in (b).

These results do not appear to be sensitive to the bulk Reynolds number. These findings are consistent with Bohm et al. (2000)'s sparse canopy measurements and the dense canopy measurements of Cheng and Castro (2002) and Raupach et al. (1986).

5. Discussion and Conclusion

For a height-independent roughness density, this study demonstrated that the dispersive fluxes can be neglected in dense canopies across the entire canopy depth. However, for sparse canopies, the dispersive fluxes can be large in the bottom layers of the canopy. Moreover, they are opposite in sign to the mean momentum flux within the upper layers of the canopy. In the limit, when the roughness density is zero (i.e., a smooth wall), the dispersive fluxes also approach zero. Hence, the magnitude of the dispersive fluxes bounded by our minimum roughness density to the case of zero roughness density needs to be further explored.

Extrapolating these findings to real canopies remains a major challenge not yet undertaken. For example, in a pine forest, the leaf area density is small in the top 1/3 of the canopy yet dense in the middle layers. Hence, it is conceivable that the dispersive fluxes are large near the canopy top yet small in the middle layers. For a hardwood forest at maximum leaf area, the opposite may be true. Hardwood forests tend to concentrate their maximum foliage in the top layers and hence the dispersive fluxes may be small for such regions. However, in the lower layers of the canopy, the canopy density is sparse and the dispersive fluxes might be large. For a leafless (dormant) hardwood forest, which is perhaps most analogous to our sparse canopy setup here, the dispersive fluxes may be sufficiently large to significantly impact CO_2 transport near the respiring forest floor. Hence, how the precise distribution of leaf area density affects the dispersive fluxes remains an open question and requires extensive and rather technically difficult experiments.

Acknowledgements

The authors acknowledge the support of the National Science Foundation (NSF-EAR and NSF-DMS), the Biological and Environmental Research (*BER*) Program of the U.S. Department of Energy, through the Southeast Regional Center (*SERC*) of the National Institute for Global Environmental Change (*NIGEC*), and through the Terrestrial Carbon Processes Program (*TCP*) and the *FACE-FACTS* project.

References

Bohm, M., Finnigan, J. J., and Raupach M. R.: 2000, ‘Dispersive Fluxes and Canopy Flows: Just How Important Are They?’, in *American Meteorology Society, 24th Conference on Agricultural and Forest Meteorology*, 14–18 August 2000, University of California, Davis, CA, pp. 106–107.

Cheng, H. and Castro, I. P.: 2002, ‘Near Wall Flow over Urban-Like Roughness’, *Boundary-Layer Meteorol.* **104**, 229–259.

Finnigan, J.: 1985, ‘Turbulent Transport in Flexible Plant Canopies’, in B. A. Hutchison and B. B. Hicks (eds.), *The Forest-Atmosphere Interaction*, Reidel, Dordrecht, pp. 443–480.

Finnigan, J.: 2000, ‘Turbulence in Plant Canopies’, *Annu. Rev. Fluid Mech.* **32**, 519–571.

Kaimal, J. C. and Finnigan, J. J.: 1994, *Atmospheric Boundary Layer Flows: Their Structure and Measurement*, Oxford University Press, 289 pp.

Poggi, D., Porporato, A., and Ridolfi, L.: 2003, ‘An Experimental Contribution to Near-Wall Measurements by Means of a Special Laser Doppler Anemometry Technique’, *Exp. Fluids* **32**, 366–375.

Poggi, D., Porporato, A., Ridolfi, L., Albertson, J. D., and Katul, G. G.: 2004, ‘The Effect of Vegetation Density on Canopy Sub-layer Turbulence’, *Boundary-Layer Meteorol.* **111**, 565–587.

Raupach, M. R.: 1994, 'Simplified Expressions for Vegetation Roughness Length and Zero-Plane Displacement as Functions of Canopy Height and Area Index', *Boundary-Layer Meteorol.* **71**, 211–216.

Raupach, M. R. and Shaw, R. H.: 1982, 'Averaging Procedures for Flow within Vegetation Canopies', *Boundary-Layer Meteorol.* **61**, 47–64.

Raupach, M. R., Coppin, P. A., and Legg, B. J.: 1986, 'Experiments on Scalar Dispersion within a Model Plant Canopy. Part I: The Turbulence Structure', *Boundary-Layer Meteorol.* **35**, 21–52.