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Evaluation of dominant momentum transfer mechanisms across a part of the city of Abu Dhabi

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Abstract

Quantifying and understanding momentum transfer close to and above buildings within a city, and the mixing and transport within the Urban Canopy Layer (UCL) are important to tackle problems such as air pollution, the heat island effect and other transport phenomena. The correct temporal and spatial averaging of the Navier-Stokes equations give rise to three new terms that constitute the fluid's shear stress. The two most significant are the turbulent stress and the dispersive stress. Their relative importance has been studied in the literature but, as Manes, et al. [1] point out, analysing only the value of these stresses might be misleading for assessing the dominant momentum transfer mechanisms involved. The derivate of the turbulent and dispersive stresses dictate the Navier-Stokes equations and thus, these should be studied. Furthermore, the flow's turbulent characteristics and the turbulent stress inside the urban canopy and right above it, have been extensively studied in field campaigns, laboratory experiments and numerical simulations, although most of these studies make use of arrays of cuboids as proxies for buildings. Numerical simulation of real cities, rather than arrays of cuboids, involve much greater model complexity and computation time. A 3D steady-state Reynolds Averaged Navier-Stokes equations (RANS) simulation is conducted to derive and evaluate the dominant transfer mechanisms across a real city – Abu Dhabi.

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Keywords: Momentum transfer; turbulent stress; disspersive stress; real city

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1. Introduction

The Navier-Stokes equations describe the wind flow in and above cities which, neglecting buoyancy effects and Coriolis forces, is given by

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \nabla^2 u_i, \tag{1}$$

where ρ and v are the density and kinematic viscosity of air, respectively.

It is common practice to spatially average equation 1 for flows over rough surfaces that are spatially heterogenous, like cities, as long as the averaging volume is thin in the vertical and large enough in the horizontal to eliminate flow variations due to individual obstacles [2].

Through Reynolds decomposition, the velocity components, u_i, can be re-written as

$$u_i = U_i + \tilde{u}_i + u_i', \tag{2}$$

where $U_i = \langle \bar{u}_i \rangle$ is the time and space averaged velocity, $\tilde{u}_i = U_i - \bar{u}_i$ is the spatial variation of the time-averaged velocity, $u_i' = u_i - U_i - \tilde{u}_i$ is the turbulent fluctuation and the index i denotes the velocity component (1, 2, 3 in the streamwise, spanwise and vertical direction, respectively). Overbar represents a time-average and angle brackets a spatial average. Applying the spatial and temporal average to the Navier-Stokes equations yields the spatially averaged momentum equation:

$$\frac{\partial \langle \bar{u}_i \rangle}{\partial t} + \langle u_j \rangle \frac{\partial \langle \bar{u}_i \rangle}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \langle \bar{p} \rangle}{\partial x_i} - \frac{1}{\rho}\left\langle \frac{\partial \tilde{p}}{\partial x_i} \right\rangle + \nu \left\langle \nabla^2 \tilde{u}_i \right\rangle + \frac{\partial \tau_{ij}}{\partial x_j}, \tag{3}$$

where

$$\tau_{ij} = -\rho \left[\left\langle \overline{u_i' u_j'} \right\rangle + \left\langle \tilde{u}_i \tilde{u}_j \right\rangle - \nu \frac{\partial \left\langle \overline{u_i} \right\rangle}{\partial x_j} \right]. \tag{4}$$

The averaging procedure produces three new terms which constitute the total shear stress, τ_{ij}. Firstly, the turbulent or Reynolds stress, $\langle \overline{u_i' u_j'} \rangle$, represents the spatially averaged momentum transport due to turbulent velocity fluctuations; secondly, a dispersive stress $\langle \tilde{u}_i \tilde{u}_j \rangle$, due to momentum transport by the spatial deviations from the spatially averaged flow; and thirdly, a viscous stress, $\nu\, \partial \langle \bar{u}_i \rangle / \partial x_j$, in charge of dissipating energy from the smallest eddies into heat. This last term is usually insignificant in comparison to the Reynolds and dispersive stresses and is not calculated in this paper.

Raupach [3] and Finnigan [4] argue that the dispersive fluxes are the most poorly understood terms in the time and horizontally averaged momentum equation. Their relative importance to the momentum transfer within the canopy sublayer is frequently neglected in model calculations and in nearly all field measurement interpretations. Nonetheless, studies in several fields, including urban canopies, show that these terms should not be ignored [5]. They suggest that dispersive stresses are significant in “sparse” canopies and insignificant in “dense” canopies. However, different definitions of the packing density of canopies can be found in the literature, making the comparison of results delicate. For instance, Belcher, et al. [6] distinguish between canopies using characteristic length scales. Nonetheless, this review only aims to gain a qualitative understanding of dispersive and turbulent stresses throughout canopies without quantifying the exact packing density of these.