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AN EOF ANALYSIS OF THE STRUCTURE OF THE LARGE-EDDY MOTION IN A SIMULATED VEGETATION CANOPY

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1. INTRODUCTION

Despite at least 20 years accumulation of evidence that the dominant turbulent motions in uniform canopy flows are large coherent eddies, this body of evidence is still primarily circumstantial. Most field studies of eddy motion have been performed on time series and really translate into statements about temporal rather than spatial structure. The most direct evidence of spatial coherence comes from the correlated appearance of ramp structures in time series collected simultaneously at several heights in a canopy, e.g. Gao et al. (1989) but such data give little clue to the three-dimensional structure of these dominant eddies. In an attempt to address this, Finnigan and Shaw (2000) conducted an Empirical Orthogonal Function (EOF) analysis of an extensive wind tunnel data set obtained in a model wheat canopy. We have now performed an equivalent analysis based upon the output from a large-eddy simulation.

2. EOF ANALYSIS

EOF analysis in the context of turbulent flows was introduced by Lumley (1967). It consists of finding the sequence of orthogonal eigenfunctions and associated eigenvalues that converges optimally fast when the variance of the turbulent field is represented as the sum of this sequence. In horizontally homogeneous flows, this requires the solution to the following eigenvalue problem:

$$\int_D \Phi_{ij}\left(k_x,k_y,z,z'\right)\hat{\phi}_j^*\left(k_x,k_y,z'\right) = \lambda\left(k_x,k_y\right)\hat{\phi}_i\left(k_x,k_y,z\right) \quad (1)$$

where Φ_{ij} is the spectral density tensor defined as

$$\Phi_{ij}\left(k_x,k_y,z,z'\right) = \frac{1}{4\pi^2}\iint e^{-ik_xr_x-ik_yr_y}\,R_{ij}\left(r_x,r_y,z,z'\right)dr_x dr_y$$

R_{ij} is the spatial covariance, where r_x and r_y are separations in the streamwise and spanwise directions. There is a denumerable infinity of solutions, $\phi_i^{(n)}$ (eigenvectors), each associated with a real positive eigenvalue $\lambda^{(n)}$.

The spatial structure of the turbulent field is contained in the eigenvectors. We see from eq. (1) that the eigenvectors are expanded as fourier series in the directions of flow homogeneity, *x* and *y*. The rate of convergence of the sequence of eigenvalues is a sensitive indicator of the presence and relative importance of coherent structures. EOF analysis provides not only an objective measure of the existence of dominant, spatially-extensive structure but with minimal additional assumptions allows us to deduce the 3-D structure of the dominant eddies in their 'mature' phase.

The spatial structure derived by Finnigan and Shaw (2000) matched measured time-height profiles of velocity in the *xz* plane and also revealed a double-roller vortex structure in the *yz* plane that was consistent with the mixing-layer hypothesis of canopy turbulence (Raupach et al., 1996). The study was limited, however as only two velocity components were available from the wind tunnel study and the two-point measurements necessary for the EOF analysis were only performed in the *y*=0 and *x*=0 planes.

3. LARGE-EDDY SIMULATION

We have now extended this work by conducting an EOF analysis of the output from a Large-Eddy Simulation (LES) of flow in a forest and overlying surface layer. The LES output included the three orthogonal velocity components, *u,v,w* and a passive scalar *c*. It was based on the scheme of Moeng (1984) and Moeng and Wyngaard (1988) and integrated a set of three-dimensional, filtered Navier-Stokes equations under the Boussinesq approximation. Terms were added to represent the aerodynamic drag of elements of the canopy and the exchange of the scalar at the leaf surfaces and ground. A pseudospectral differencing technique was employed for the horizontal derivatives, and a second-order centred-in-space finite difference scheme determined vertical derivatives. The domain comprised 228x144x100 equally spaced grid intervals in the *x*-, *y*-, and *z*-directions. The canopy occupied the lowest ten grid intervals according to an assigned element area density to match the wind tunnel canopy

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of Finnigan and Shaw (2000). Lateral boundary conditions were periodic, while the upper boundary of the domain was rigid but frictionless. A uniform driving force was applied throughout the domain.

4. RESULTS

The analysis was applied to (i) only the vertical direction; (ii) the *x,z* and *y,z* planes; and (iii) the full three dimensions, and was formulated to include two, three or four of the variables *u,v,w,c*. In general, a large fraction of the total variance is captured by the first few eigenmodes. For the two- and three-dimensional cases, an even smaller number of eigenmodes and only a few wavenumbers are needed to adequately capture the structure of the turbulent field. An example of the relative contribution to the total variance by the first five eigenmodes is shown in Figure 1 for the 2-dimensional analysis in the *xz* plane. The first four wavenumbers of the first eigenmode exceed any wavenumber contribution from the second eigenmode.

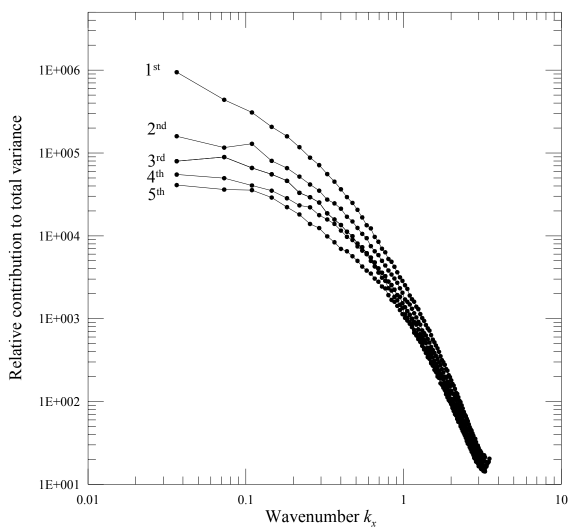
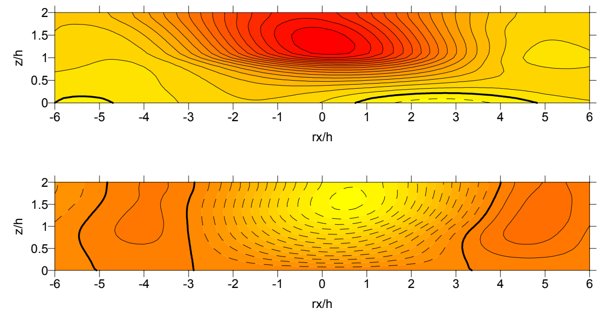


Figure 1. k_x spectra of the relative contributions to the total variance from the first five eigenmodes for the 2-dimensional case in the xz plane.

An example of the reconstruction of the streamwise and vertical velocities of the *characteristic eddy*, based on the first four wavenumbers of the first eigenmode, is illustrated in Figures 2a and 2b. The eddy is interpreted as a downward sweep of high momentum air penetrating the canopy from above. Note that the structure shown by the eigenvector is not identical to images, such as those shown in Gao et al. (1989), of instantaneous distributions of velocity and scalar quantities. Rather, the *characteristic eddy* reconstruction reveals the instantaneous perturbation velocity field of the eddy as it penetrates the canopy.

Our EOF analysis provides further evidence of the importance of large coherent structures in canopy turbulence. EOFs provide the 3-dimensional structure of canopy coherent structures with only trivial *a priori* assumptions. We will demonstrate that they exhibit the double roller vortices characteristic of plane mixing layers. Further, we show that, in both the *xz* and yz planes of symmetry, momentum and scalars are transferred by the same parts of the eddy.



Figures 2a and 2b. Characteristic eddy constructed from the first eigenmodes and first four wavenumbers of a 3-dimensional analysis of the streamwise and vertical velocities. Top: u-velocity; bottom: w-velocity. Solid lines: positive; dashed lines: negative values.

5. REFERENCES

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