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EDDY STRUCTURE NEAR THE PLANT CANOPY INTERFACE

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1. INTRODUCTION

It is well established that the transport of scalar and vector quantities is more efficient across the roughness sublayer (RSL) than it is in the logarithmic region above. Momentum transport in the RSL is dominated by sweeps of high velocity fluid from aloft, while ejections of low velocity air from below become the more important mechanism above the RSL. This difference was demonstrated a number of years ago using quadrant-hole analyses (Finnigan, 1979, Shaw et al., 1983), which showed that, within the RSL, relatively infrequent sweeps transfer large portions of the stress. While ejections are more frequent, they are smaller in magnitude and become negligible at a hole size roughly half that of sweeps.

Turbulent structures are more coherent in the RSL than in the layers above; a point demonstrated by the more rapid convergence of the EOF spectrum in the RSL (Finnigan and Shaw, 2000). An outcome of this coherence is the fact that turbulence in the RSL tends to a dominant single length scale throughout its depth, whereas, in the inertial sublayer, the length scale is approximately proportional to distance above the displacement height (*z-d*). Raupach et al. (1989, 1996) proposed that these differences could be explained by equating the elevated shear layer of the canopy RSL to a plane mixing layer rather than a wall layer. The vorticity thickness $\delta_\omega = \left[\bar{u}/(\partial\bar{u}/\partial z)\right]_{h_c}$ (Drazin and Reid, 1981; Michalke, 1964) is then the proper scaling dimension, rather than the canopy height h_c. This has proven to be a valuable concept.

Differences between the RSL and the inertial sublayer must be traceable to the eddy structure, so our recent efforts have been to characterize eddies at the vegetation interface using two particular techniques, as detailed below, in addition to the quadrant analysis mentioned above. Further, and because of serious restrictions imposed by the necessarily limited spatial resolution of field and laboratory studies, we have devoted greatest effort to the analysis of computational flow fields. Large eddy simulation (LES) has proved to be a valuable numerical tool in the creation of realistic flows within and above vegetation canopies (Shaw and Schumann, 1992). Not only do such simulations match with reasonable accuracy the statistical features of canopy flow but they also generate the turbulent structures observed in field and wind tunnel studies.

2. METHODOLOGY

A Large-Eddy Simulation (LES) was performed to model flow in a plant canopy and overlying surface layer. The LES output included the three orthogonal velocity components, *u,v,w*, pressure *p* and the concentration *c* of a passive scalar released from the canopy. The simulation 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

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to match the wind tunnel canopy 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.

Distinctive features of turbulence structure near the canopy top include the downstream ejection and upstream sweep, which are separated by a convergence zone identified by a zone of high pressure and a sloping scalar microfront (Gao et al., 1989; Shaw et al., 1990). Fitzmaurice et al. (2004) and Watanabe (2004) have each used such features to extract and form composite averages of coherent structures from large-eddy simulations of canopy flow. Fitzmaurice et al. (2004) based detection on the high pressure pulse that appears in the convergence zone, while Watanabe (2004) selected a detection scheme based on the steep scalar gradient of the microfront. Results from the two studies are remarkably similar. Here we choose to use the Fitzmaurice et al. scheme to identify and form composite averages of coherent events occurring at the interface of the canopy and the overlying air.

Because the event detection and compositing technique described above includes an element of subjectivity through its choice of identification criterion, we have also applied the empirical orthogonal function analysis proposed by Lumley (1967). This procedure consists of finding the sequence of orthogonal eigenfunctions and associated eigenvalues that converges optimally fast when the variance of the turbulence field is represented as the sum of this sequence. We have applied this methodology to LES output in a manner similar to that of Finnigan and Shaw (2000), who performed EOF analysis on wind tunnel data.

In order to visualize the coherent vortical structures extracted by these techniques, we have employed the so-called *lambda2* methodology. Jeong and Hussain (1995) proposed a definition of a vortex in terms of the eigenvalues of the symmetric tensor $S^2+\Omega^2$, where S and Ω are the symmetric and antisymmetric parts of the velocity gradient tensor ∇u. They specify a vortex core as "a connected region with two negative eigenvalues of $S^2+\Omega^2$" and point out that since $S^2+\Omega^2$ is symmetric, this reduces to the requirement that the second eigenvalue λ_2 be negative. We select a value for λ_2 by trial and error in order most clearly to visualize the vortex cores contained in the eddies that we extract from the LES.

3. RESULTS

In Figure 1, we demonstrate the variation with height of the relative importance of quadrant 2 (ejections) and quadrant 4 (sweeps) to the momentum flux. Clearly, sweeps dominate throughout most of the depth of the canopy and through the layer immediately overlying it but a crossover appears at a height of approximately *1.7h* above which upward ejection of low momentum air becomes the more important contribution.

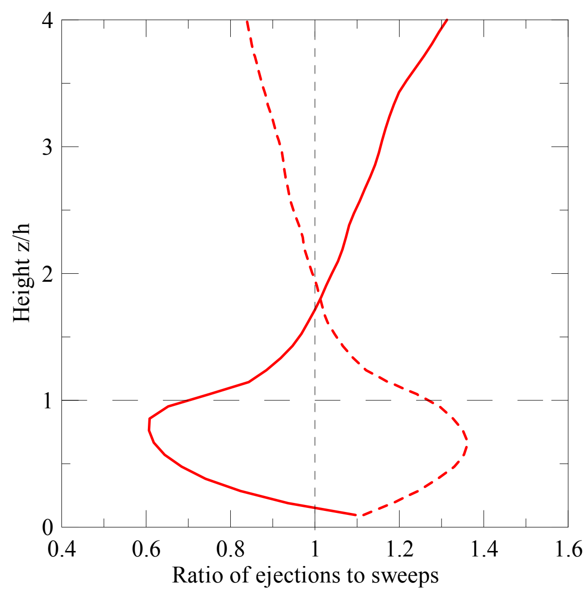

Figure 1. Ratio Q2/Q4 of the contributions to momentum flux (solid line) from ejections and sweeps, and ratios of the frequency of occurrence of ejection and sweep events (dash line).

Examples of the composition of the composite average eddy extracted by identifying regions in which the pressure at the canopy top exceeds a predetermined threshold are shown in the next two figures. Further examples can be found in Fitzmaurice et al. (2004) and Watanabe (2004). Figure 2 shows an *x,z* slice of streamwise velocity fluctuation through the centre of the structure. Flow is from left to right. Near the level of the canopy top, a low velocity region associated with an ejection precedes the high velocity region of the sweep. In the lower canopy, a positive velocity perturbation, in advance of that at the higher level, is associated with the region of overpressure. Figure 3 presents an equivalent picture of scalar concentration fluctuation. The sharp scalar gradient or microfront, separating the region of high concentration air being ejected from the canopy from the low concentration air swept down from aloft, is clearly apparent.

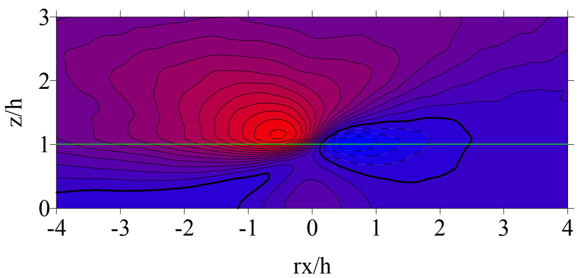

Figure 2. Contours of streamwise velocity fluctuation normalized by u_* across an x,z slice through the centre of the composite average structure. Solid lines: positive, dash lines: negative.

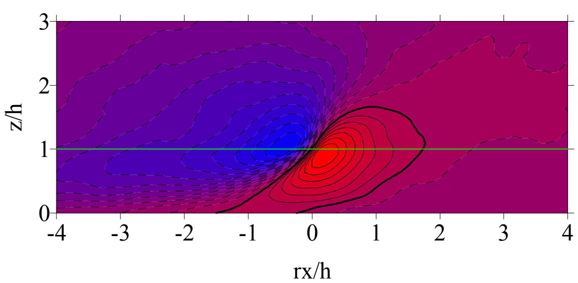

Figure 3. Contours of scalar concentration normalized by c_* across an x,z slice through the centre of the composite average structure. Solid lines: positive, dash lines: negative.

Vorticular motion is illustrated in Figure 4, which shows *v,w* vectors across a *y,z* slice through the sweep. The counter-rotating pair of vortices, at this cross-section displaced one canopy height upstream of the pressure centre, appears at a height of about *1.2h*. They have a lateral separation of about *2h*. While the lateral separation does not change significantly as *y,z* slices are selected at different streamwise locations, the height of the centre of each vortex increases with downstream distance over the extent of the sweep, with a slope of approximately 1:3. Included in Figure 4 is a calculation of λ_2 such that the blue shaded area is the region within which λ_2 is more negative than a specified value. It is clear that λ_2 does not produce an exact match for the visual centre of rotation of the velocity vectors in the *y,z* plane. Rather, λ_2 is more strongly influenced by the shear component of vorticity evident near the core of the downdraft.

A similar but slightly less intense vortex pair, with rotation in the opposite sense, is associated with the downstream ejection. To illustrate the relationship between the two vortices, we present Figure 5, which shows the iso-surface of a selected negative value of λ_2.

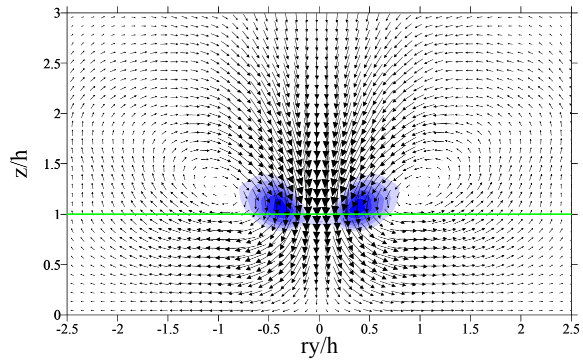

Figure 4. Vectors of v,w velocity across a y,z slice displaced one canopy height upstream of the centre of peak pressure. Blue shaded area denotes λ_2<-0.0015

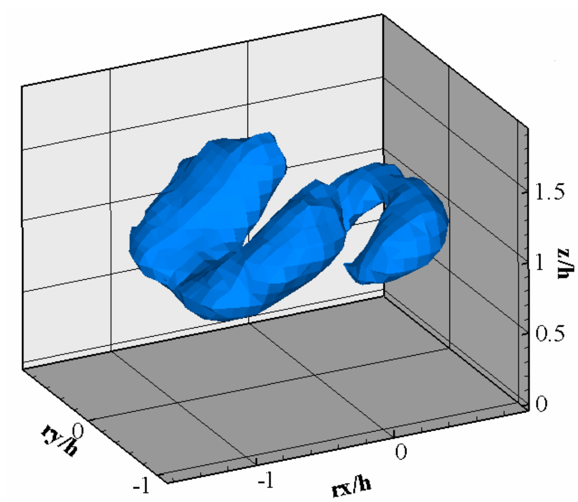

Figure 5. Iso-surface of λ_2 for the composite average structure showing the head-down vortex associated with the sweep (left) and the head-up vortex associated with the ejection (right).

The resulting image is interpreted as a combination of head-down and head-up hairpin vortices (Gerz et al.,1994). The leading vortex is head-up and is associated with the ejection, while the trailing vortex is head-down and is associated with the sweep. The tails of the head-down vortex overlie the tails of the head-up vortex. The region of convergence between them is coincident with the scalar microfront.

A continuing effort of ours has been to extract the characteristic eddy using the less prejudicial EOF method first proposed by Lumley (1967). Such a method offers substantial rewards in terms of the potential construction of a low-dimensional model of canopy turbulence. While the technique provides significant insight into canopy turbulence and shows that a relatively small number of eigenmodes are sufficient to describe the characteristic eddy, some important details are lost. For example, Figure 6 shows the vortex structure extracted from the first few eigenmodes outlined by λ_2 iso-surfaces. Examination of the velocity field shows this vortex to be associated with a sweep. The downstream vortex we previously associated with the ejection is missing from the picture. Otherwise, the head-down vortex is very similar to that of the composite average in terms of lateral spacing and in terms of the tilt in the downstream direction.

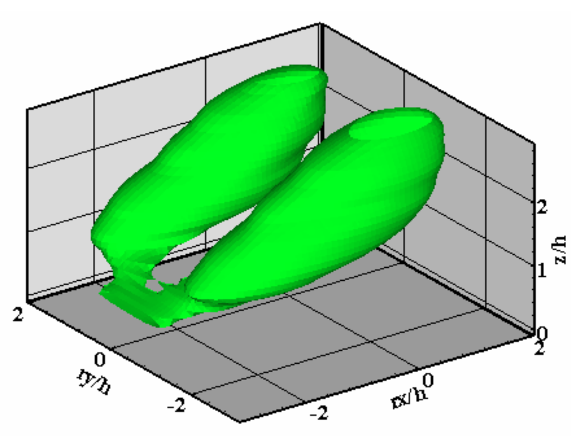

Figure 6. Iso-surface of λ_2 for the EOF characteristic eddy show a head-down vortex associated with a sweep.

4. DISCUSSION

Evidently the coherent eddy responsible for a large fraction of the momentum and scalar transfer between a porous canopy and the overlying air is a combination of head-up and head-down hairpin vortices. These vortices are associated, respectively, with the commonly observed ejections and sweeps of organized canopy flow structures.

Regarding the difference we observe between the composite average eddy and that extracted using the EOF analysis, we note that the two components of the eddy, the head-up and the head-down hairpins, would both give contributions of the same sign to the two-point covariance field. Thus, the EOF analysis, which is based on the eigenmodes of this two-point covariance field and extracts the velocity pattern making the dominant contribution to the turbulent kinetic energy (TKE), is unable to distinguish between and separate the two components of the eddy. Instead the head-up, ejection-generating and the head-down, sweep-generating hairpins, are superimposed in the EOF analysis. The more energetic head-down hairpin dominates the summed structure so that the eddy structure inferred from the EOF is naturally interpreted as producing a sweep (Finnigan and Shaw, 2000).

As outlined in the introduction, the characteristics of the RSL that must be inherent in its eddy structure are first, the more energetic transport across it; second, its single length scale; third, the coherence of RSL eddies; and fourth, the dominance of sweeps in the RSL, changing to dominance of ejections in the inertial sub layer above. We now propose a phenomenological model to explain these features.

The mixing layer analogy advanced by Raupach et al. (1989, 1996) ascribes the coherent eddy structure in the RSL and canopy layers to an inviscid instability of the inflected mean velocity profile that characterizes flows over vegetation canopies. Indeed, the point of inflection in the mean velocity $\bar{u}(z)$ can serve as an operational definition of the canopy height. Stability analysis of this inflected profile reveals a sequence of instability modes occurring first in two and then in three dimensions. The initial instability is a Kelvin-Helmholtz wave, which can be interpreted as regions of positive and negative perturbations in spanwise vorticity, alternating in the streamwise direction with a wavelength λ that is proportional to the vorticity thickness δ_ω (Drazin and Reid, 1981; Michalke, 1964). This wavelike perturbation is unstable and the vorticity 'clumps' into finite amplitude transverse vortices which are spaced in the streamwise direction with the original wavelength λ (Stuart, 1967). This train of 'Stuart' vortices within the inflected mean velocity field is itself unstable to spanwise perturbations and Pierrehumbert and Widnall

(1982) have identified a mode of three-dimensional instability which would result in a streamwise sequence of alternating head-up and head down hairpins retaining the streamwise spacing λ. According to their analysis, the most unstable spanwise mode corresponds to a separation of the legs of the hairpin of approximately $2/3\lambda$.

Of course, these results of laminar instability theory must be interpreted with care in the fully turbulent regime of the RSL-canopy. While the vortical structures obtained by compositing or EOF analysis match the predictions of stability theory surprisingly well, individual realisations of the eddies are strongly distorted around their composite averages by the ambient turbulence. The eigenmodes predicted by stability theory should be viewed as the preferred shapes towards which the fully turbulent flow tends. Nevertheless, these models offer a compelling explanation for the dominance of a single preferred length scale for the RSL-canopy eddies.

Head-up hairpins generate ejections whilst head-down hairpins produce sweeps so the dominance of sweeps in the RSL-canopy region requires some symmetry breaking agency. Gerz et al. (1994) proposed a mechanism whereby the transverse vortex lines inherent in the mean shear are deflected locally up or down and the resulting loops of vorticity or hairpins are stretched and rotated by the mean shear, amplifying the vorticity in the legs of the hairpins and producing sweep- and ejection-generating eddies. We propose that this model be combined with the instability sequence leading to Stuart vortices. Thus, coherent vortex tubes are deflected by random turbulent perturbations, and then stretched and rotated to produce the head-up and head-down hairpins we observe.

Gerz et al. (1994) note that, close to smooth walls, strong downward deflections become impossible so that only head-up hairpins are observed and, hence, ejections dominate. Further from the wall, populations of both head-up and head-down hairpins are seen but the blocking effect of the wall ensures that head-up deflections remain of larger amplitude. In a logarithmic mean velocity profile, it is also clear that, for the same amplitude of deflection, head-down hairpins will experience stronger strain and rotation than their head-up counterparts. In a smoothly matched canopy-boundary layer profile (e.g., the base flow used in Finnigan and Belcher (2004)) this effect is amplified so that, at the canopy top, vortices deflected downward are strained and rotated much more than those deflected upward the same distance.

Evidently, there are two symmetry-breaking mechanisms at work in a wall bounded shear flow. Above a smooth solid wall the greater probability of large upward deflections exceeds the greater straining experienced by downward deflections, and head-up hairpins dominate the dynamics. At the canopy top, in contrast, the porous canopy allows downward deflections of similar amplitude to upward deflections, at least for deflection by turbulent motions whose horizontal extent is of order the canopy depth, h_C or smaller so that the greater strain downward hairpins experience ensures that sweeps dominate. As we move above the canopy top and the sizes of the eddies causing deflections become larger than h_C, the presence of the wall again becomes the dominant factor so that sweep generating head-down hairpins become less important than ejection generating head-ups. The cross-over point where sweeps cease to make a larger contribution to momentum transfer than ejections varies with the canopy structure but appears to be a function of the vorticity thickness.

The 'helical pairing' instability mode identified by Pierrehumbert and Widnall (1982), as well as linking the transverse scale of the most amplified vortex pairs to the streamwise spacing λ of the original Kelvin-Helmholtz instability, also predicts that the hairpins will be linked in pairs with the head-down hairpins lying above the head-up as shown in the composite eddy identified by λ_2 iso-surfaces in Fig. 5. As noted earlier, the dual component structure depicted in Fig. 5 was obtained by compositing velocity fields using a positive pressure pulse (p+) as a trigger. Gerz et al. (1994) obtained a similar dual-component, 'head-down over head-up' structure in a homogeneous shear flow by triggering on the scalar microfront that was assumed to be generated in the convergence zone between the ejection and sweep. However, both in our analysis and that of Gerz et al., it is possible that the coincidence of the head-up and head-down hairpins is an artefact of the conditional sampling.

We know that an isolated sweep can produce a *p*+ region because of blocking by the wall. Similarly, an ejection can produce a convergent *p*+ region as the slow moving ejected fluid blocks faster moving fluid from upstream. Hence, triggering on *p*+ may lead to unrelated sweep- and ejection-producing hairpins being made to appear related in the composite eddy. Similar problems attend the conditional trigger based on hot and cold microfronts used by Gerz et al. (1994). Currently we are investigating whether this pairing is real by employing more sophisticated dual triggers involving [p+ .AND. sweep] or [p+ .AND. ejection].

5. SUMMARY

We have proposed a model for the eddy structure of the RSL-canopy layer that explains qualitatively the unique features of this region and why it differs from the inertial sublayer above. The components of the model are firstly, the inviscid instability of the mean velocity profile at the canopy top, which in turn is a consequence of the momentum absorption over a depth h_C through the canopy rather than at a plane surface. This instability selects the scale of the most-amplified two- and three-dimensional disturbances and relates them to the vorticity thickness at canopy top.

Secondly we invoke symmetry breaking by two competing processes. Coherent ‘Stuart’ vortex tubes generated by the inviscid instability can be deflected up or down by ambient turbulent motions. Downward deflected vortex loops or hairpins experience greater rotation and straining by the mean shear and consequent amplification of the vorticity in the legs of the hairpins than upward deflections. In contrast, large upward deflections are more probable except for deflections by eddies of scale $\leq h_C$ at the canopy top. In this region the greater strain experienced by downward deflections produces head-down sweep-generating hairpins that are more energetic than ejection-generating head-ups. Far enough above the canopy, this advantage is reversed.

Laminar instability theory also predicts that hairpins with a lateral spacing similar to their streamwise spacing will be the most amplified. The result of this scale selection is eddies that are significantly more coherent and effective in transport than in the inertial sublayer above. Finally we note that this simple picture is strongly modulated by the larger scale turbulence in the boundary layer above, which can increase (or decrease) the canopy-top shear and the growth rates of instability modes in spatial patches with horizontal extents large compared to h_C (Raupach et al., 1996). This model is substantially supported by our conditional sampling and EOF analysis of the LES canopy model wind field presented above.

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