The Structure of Canopy Turbulence and their Implications to Scalar Dispersion

By

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Abstract: The canonical form of atmospheric flows near the land surface, in the absence of a canopy, resembles a rough-wall boundary layer and has been extensively studied for more than half a century. However, in the presence of an extensive and dense canopy, the flow within and just above the foliage resembles a perturbed mixing layer – a hypothesis proposed about 2 decades ago and appears supported by several field experiments. However, to date, no analogous formulation exists for intermediate canopy densities. Using detailed laser Doppler velocity measurements conducted in an open channel over a wide range of canopy densities, a phenomenological model that describes the structure of turbulence within the canopy sublayer (CSL) is developed. The model decomposes the space within the CSL into three distinct zones: the deep zone in which the flow is shown to be dominated by vortices connected with von Kármán vortex streets, but periodically interrupted by strong sweep events whose features are influenced by canopy density. The second zone, which is near the canopy top, is better represented by a superposition of attached eddies and Kelvin–Helmholtz waves produced by inflectional instability in the mean longitudinal velocity profile. Here, the relative importance of the mixing layer and attached eddies are shown to vary with canopy density through a coefficient α. The relative enhancement of turbulent diffusivity over its surface-layer value near the canopy top depends on the magnitude of α. In the uppermost zone, the flow follows the classical surface-layer similarity theory.

Another important attribute of turbulent flows inside canopies is wake production and short-circuiting of the energy cascade. How these processes affect passive scalar concentration variability in general and their spectral properties in particular remains largely unexplored. Progress on this problem is frustrated by the shortage of high resolution spatial concentration measurements, and by the lack of simplified analytical models that connect spectral modulations in the turbulent kinetic energy (TKE) cascade to scalar spectra. Here, we report the first planar two-dimensional scalar concentration spectra ϕ_{cc} inside tall dense canopies derived from flow visualization experiments. We found that in the spectral region experiencing wake production, the ϕ_{cc} exhibits directional scaling power laws. In the longitudinal direction (x), or the direction experiencing the largest drag force, the $\phi_{cc}(k_x)$ was steeper than $k_x^{-5/3}$ and followed an approximate $k_x^{-7/3}$ at wavenumbers larger than the injection scale of wake energy, where k_x is the longitudinal wavenumber. In the lateral direction (y), the spectra scaled as

$k_y^{-5/3}$ up to the injection scale, and then decayed at an approximate $k_y^{-7/3}$ power law. This departure from the classical inertial subrange scaling was reproduced using a newly proposed analytical solution to a simplified scalar spectral budget equation. Near the velocity viscous dissipation range, the scalar spectra appear to approach an approximate k^{-3}, a tantalizing result consistent with dimensional analysis used in the inertial-diffusive range.

We then explore the consequences of these key CSL attributes on scalar transport in the context of three-dimensional Lagrangian Dispersion Models (LDM). The CSL is known to be inhomogeneous, non-Gaussian, and highly dissipative, thereby posing unique challenges to classical LDM approaches that usually satisfy the well-mixed condition and account for turbulence inhomogeneity but not for its non-Gaussian statistics and enhanced dissipation. While numerous studies evaluated the importance of the former (with mixed results), few studies to date considered the latter. We present new data and explore: (1) the skill of LDM in reproducing mean scalar concentration distributions within dense and rigid canopies for source releases near the canopy top and near the ground, and (2) the extent to which these estimates are sensitive to the formulation of the mean turbulent kinetic energy dissipation rate (ε) profile. Toward this end, Laser Induced Florescence (LIF) and Laser Doppler Anemometry (LDA) were also used to measure scalar concentration and Eulerian flow statistics within a dense model canopy in a rectangular flume. It is shown that LDM concentration predictions are sensitive to how ε is estimated. Good agreement between measured and modelled mean concentration distributions were obtained when ε was estimated from the mean squared longitudinal velocity gradients and isotropic turbulence principles. However, when ε was estimated from the widely used scaling arguments that employ a constant Lagrangian time scale and a specified vertical velocity variance σ_w^2 profile, the predicted concentrations diverged significantly from the LIF measurements.

We conclude this talk with preliminary results on how hilly terrain modulates this emerging picture of the CSL structure with particular attention on the ejection-sweep cycle, which is the main coherent motion responsible for much of the turbulent transport. In this preliminary investigation, we report on two new flume experiments that explore the higher order turbulence statistics above a train of gentle hills. The first set of experiments was conducted over a bare surface while the second set of experiments was conducted over a modeled vegetated surface composed of densely arrayed rods. Using this data, the connections between the ejection-sweep cycle and the higher order turbulence statistics across various positions above the hill surface were investigated. The data suggests that in the inner layer, the higher-order turbulence statistics appear to be much more impacted by their relaxation history towards equilibrium rather than the advection-distortion history from the mean flow. Hence, we showed that it is possible to explore how various boundary conditions, including canopy and topography, alter the properties of the ejection-sweep cycle by quantifying their impact on the gradients of the second moments only.