Roughness Sub Layers

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1. Characteristics of the Roughness Sub layer

With well understood caveats, the time averaged statistics of flow in the atmospheric surface layer over homogeneous surfaces are described by Monin-Obukhov Similarity Theory (MOST). However, it has been known for decades that MOST formulae fail close to rough surfaces like urban areas or vegetation canopies or surface waves. The failure is almost always in the sense that turbulent fluxes are higher than MOST would predict from the observed mean gradients. Three kinds of dynamical process can be invoked to account for these departures:

- Distortion of the mean flow and turbulence about the roughness elements
- Near field-far field diffusive effects for scalars
- Different mechanisms of turbulence generation

We consider these in turn but first make a comment on statistics. Far from the surface we expect time-mean flow statistics to be independent of their *x-y* (horizontal) location. Near complex surfaces, the time-mean statistics become dependent on their *x-y* coordinates and we then form horizontally homogeneous statistical fields by averaging over thin horizontal slabs as well as in time.

Mean flow distortion about the roughness elements

Spatial correlations between time-mean variations around the spatial mean are termed *Dispersive Fluxes* and bear the same relationship to spatial averaging as Reynolds fluxes do to time averaging. Around smooth, regular spatial features like water waves or low topography, the dispersive fluxes can often be calculated deterministically. In such situations also, the effect of mean flow distortion on the Reynolds stresses can often be calculated accurately. These effects decay with height, affecting a layer whose depth is proportional to the horizontal scale of the surface heterogeneity. The affected layer can be thought of as a roughness sublayer but this is not what is commonly understood by the term.

When the flow is over bluff elements, the resulting chaotic time-mean streamline pattern is called *Lagrangian Turbulence* and generally augments any temporal turbulence in mixing momentum and scalars. In this case, no general relationships between the Lagrangian and Reynolds turbulence can be stated. The region of mixing enhanced by Lagrangian turbulence can be taken as one definition of the roughness sub layer.

Near field-far field diffusive effects for scalars

A Lagrangian framework for modelling dispersion is appropriate for scalar transport in and above canopies. Raupach (1989) has shown that spatial perturbations to mean scalar gradients are dominated by nearby sources as turbulent dispersion in the near field of sources or sinks is slower than in the far field. The near field is delineated by the Lagrangian Integral scale which typically extends a distance of order the canopy height from the source. Conversely, the turbulent flux and background scalar concentration is dominated by distant sources as diffusion is faster in the far field. This near field-far field dichotomy decouples the local flux from the gradient and can cause deviations from MOST flux-gradient relationships just above the canopy. Within the canopy, in extreme cases it can lead to counter-gradient fluxes. It is a process that operates even when the turbulence is homogeneous and is important whenever the Lagrangian integral scale is of significant size. The extent of near field influence, that is, the Lagrangian integral length scale is a second measure of RSL depth.

Alternative mechanisms of turbulence production

The mixing layer hypothesis (MLH) of Raupach et al (1996) proposed that the distinctive nature of turbulence over canopies or rough surfaces was the result of a generation mechanism that is fundamentally different from that operating in smooth wall boundary layers. It supposed that the inflected mean velocity profile that is ubiquitous at the rough surface-free air interface and which is *inviscidly* unstable, generated distinct energetic coherent eddies, whose scale was linked to δ_ω, the characteristic scale of the inflected profile at the level of the canopy top, $h_c : \delta_\omega = U(h_c)/U'(h_c)$. Velocity profiles without an inflection point are only unstable if viscosity or buoyancy is present.

A great deal of evidence collected over the last decade has confirmed the essentials of the MLH and established some limits to its applicability. In particular, although the horizontally averaged mean velocity profile over rough surfaces almost always displays an inflection point, the profile must be dynamically significant rather than an artefact of spatial averaging for MLH to be relevant. In this paper we develop the hypothesis that the roughness sublayer and its distinctive properties are the result of the MLH. Near field-far field effects and Lagrangian turbulence are complicating but not dominant features of the RSL while variations in the mean wind field caused by flow over smooth features like waves or gentle topography probably deserve a different title to distinguish their effects from those we are about to describe.

Key differences between the RSL and the inertial sublayer (ISL) or *Logarithmic Layer* above it, where MOST obtains, are reflected in both the mean and conditional statistics:

- Turbulence statistics in the RSL/canopy layer scale on a single length while in the ISL, statistics scale on *z-d* (where *d* is the displacement height of the logarithmic profile).
- Empirical Orthogonal Function (EOF) spectra in the RSL/canopy converge rapidly (eg. 80% of the variance is captured by the first 5 eigenmodes), suggesting that the turbulence is dominated by distinct coherent structures of a single scale, whereas convergence in the ISL is slow (eg. 80% of the variance in the first 25-50 eigenmodes), denoting a wide range of eddy scales.
- The ratios of second moments in the RSL/canopy layer are more isotropic than in the ISL and the correlation coefficient $r_{uw} = \langle \overline{u'w'} \rangle / \sigma_u \sigma_w$ is ~0.5 in the neutrally stratified RSL/canopy as compared to ~0.35 in the ISL. Putting this together with the observation that gradients are smaller in the RSL than in the ISL for the same flux suggests that RSL/canopy turbulence is in some sense more efficient at mixing.
- The turbulent Schmidt and Prandtl numbers are ~0.5 at the canopy- RSL interface compared with ~1.0 in the ISL.
- Transport of momentum and scalars in the RSL/canopy layer is dominated by the sweep quadrant whereas through the rest of the ISL, ejections dominate.

2. Turbulence Structure in the Roughness Sub layer

A model of the turbulent eddy structure over smooth walls in boundary layers and channel flows has been developed by Adrian and various collaborators using sophisticated conditional sampling techniques. Flow in an ISL above a rough wall is very similar (although not identical) to that over a smooth wall and we will assume that Adrian's model is relevant there also. His model envisages the synergistic development of trains of 'head-up' (HU) hairpin or horseshoe vortices aligned around cores that consist of a low-speed flow region, elongated in the streamwise direction. The sense of rotation of the HU hairpins is as if the spanwise vortex lines of the mean flow have been deflected upwards and then stretched and rotated by the mean shear. As a result, an ejection is generated between the legs of each HU hairpin and these ejections merge in the low speed core. Sweeps are weak or non existent.

We have applied analogous conditional sampling approaches as well as EOF analysis to field data, wind tunnel simulations and LES models of uniform canopy flow. By interpreting our results in the light of the MLH theory we have arrived at a consistent picture of RSL turbulent structure that accounts for its differences from that in the ISL. The model has the following elements (Shaw et al., 2006):

- The hydrodynamic instability of the inflected velocity profile at canopy top produces Kelvin-Helmholtz waves with regions of spanwise vorticity of alternating sign and streamwise spacing proportional to δ_ω.
- This perturbed vorticity field is itself unstable and the vorticity clumps into coherent spanwise *Stuart* vortices that retain the streamwise spacing of the Kelvin-Helmholtz waves.
- These Stuart vortices can be distorted by ambient turbulent eddies to form head up hairpins (deflection away from the wall) or head down (HD) hairpins (deflection towards the wall). The porous canopy layer allows strong deflections towards the wall that would be blocked near a solid surface.
- Secondary instabilities of this train of vortices provide strong selection for the spanwise scale of the hairpins. They also suggest that HU and HD hairpins will be formed in pairs, a prediction confirmed by our measurements. Similarly, the canopy depth h_c limits the horizontal scale of strong gusts directed towards the wall: they cannot have horizontal extent much larger than h_c.
- The strain and rotation experienced by a HD hairpin in a logarithmic mean velocity profile or a log-exponential profile, such as we find near the canopy top, is larger than that experienced by a HU so that with equal populations of HU and HD hairpins, HD's will be more energetic. HD hairpins generate sweeps between their legs so that near the canopy top sweeps dominate ejections.
- Further from the canopy and underlying surface, larger scale gusts can deflect the vortices but the blocking effect of the ground is now dominant so that strong upward deflections that produce HU hairpins and ejections dominate downward gusts that lead to sweeps.
- We have found empirically that the two hairpin types come in pairs with sweep-producing HD's overlying ejection-producing HU's. The strong convergence between the hairpins that this produces results in intense scalar microfronts.

3. A simple model of the Roughness Sub layer

The fundamental role played by the inviscid instability in generating this distinct turbulent structure has prompted the construction of a simple RSL model based upon its key scale, δ_ω (Harman and Finnigan, 2006). This model views the RSL as a region influenced by the particular turbulence generated by the MLH. This influence decays exponentially above the canopy with an *e*-folding distance proportional to δ_ω. Hence, unlike earlier models, we do not assume a precise depth for the RSL. The effects of the MLH turbulence are represented by a function $\hat{\phi}(z/\delta_\omega)$ that is analogous to the MOST $\phi(z/L_{mo})$ functions (where L_{mo} is the Obukhov length) and combines multiplicatively with them.

By matching a simple, one-parameter model of the canopy flow with the ISL, where $\phi(z/L_{mo})$ functions represent the effects of stability, through an RSL where both $\hat{\phi}(z/\delta_\omega)$ and $\phi(z/L_{mo})$ affect the flux-gradient relationships, we find that the fundamental parameters of the log law, displacement height *d* and roughness length z_0, become strong functions of stability. When we consider the effect of this dependence on the parameterisation of momentum transfer to the surface in climate, mesoscale and boundary layer models, we find that that the effects are profound. The model has been applied to a range of forest canopy data varying in height, foliage density and heterogeneity and represents observations remarkably well.

4. Extension to scalars

The simple canopy model used in the RSL model discussed above predicts an exponential decay of mean velocity into the canopy. For simple concentration boundary conditions on the foliage, the scalar analogue of this also predicts an exponential decay of mean scalar but with an exponent that is smaller than that for velocity by the factor $(r\,\mathrm{Sc}_t)$. Sc_t (Pr_t) is the turbulent Schmidt (Prandtl) number and In the upper canopy/RSL, Sc_t and Pr_t are ~0.5 compared to ~1.0 in the ISL. The Stanton number is the ratio of the efficiency of scalar to momentum transport across canopy elements and $r \sim 0.1$ so the factor $r\,\mathrm{Sc}_t \sim 0.05$. There are two immediate consequences of this.

First, scalar gradients are much weaker than velocity gradients in the RSL with consequences for measurements of flux-gradient relationships and extrapolation of measurements in the RSL to the ISL and upper planetary boundary layer. Second, the difference in the intrinsic gradients of temperature and windspeed in the canopy ensures that for even moderate stability above the canopy, the local gradient Richardson Number within the canopy is large so that turbulence is strongly suppressed. This phenomenon effectively decouples the canopy flow from that above on stable nights and allows the generation of strong gravity currents even on very gentle slopes, if a canopy is present.

5. References

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