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Four things we don't know about scalar transfer from plant canopies

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In terrestrial plant canopies, turbulent exchange of water through evapotranspiration is intimately bound up with exchange of other scalars, heat and carbon dioxide in particular. Turbulent transport is rarely the process limiting exchange of these scalars between the biosphere and the atmosphere. However, in measurement programs like FLUXNET or when we parameterise surface exchange at the canopy scale in climate or weather models we must understand the mechanism of turbulent exchange in detail. In this talk we survey four current obstacles to extending our understanding of canopy turbulence from the idealised case of homogeneous flow in neutral stratification to complex flows in stable and unstable conditions.

1. Canopy eddy structure and the hydrodynamic instability
Recent analysis of canopy LES and wind tunnel simulations has revealed the 'two hairpin' structure of a characteristic canopy eddy. This structure explains a large body of results from a wide range of canopies and redefines the Roughness Sub Layer (RSL) as an asymptotic layer similar to the logarithmic and outer layers of the Planetary Boundary Layer. However, the nature of the non-linear 'mixing-layer' instability process that gives canopy/RSL eddies their coherence and enhanced transport efficiency (as compared to eddies in the logarithmic layer above) is poorly understood so we do not know how resilient this instability and the eddies that depend upon it are to large scale flow perturbations or to changes in stability.

2. Turbulent Schmidt and Prandtl Numbers
The scalar RSL can be defined as the layer across which the turbulent Schmidt (Sc) and Prandtl (Pr) numbers in neutral stratification change from their canopy top values of $\sim$0.5, typical of mixing layers, to their logarithmic layer values of $\sim$1.0, typical of boundary layers. The value of Sc or Pr is a critical parameter when adjusting Monin-Obukhov similarity theory (MOST) for the proximity of the canopy. The need for such adjustments has been recognized for several decades but they are still often ignored with serious consequences for prognostic models. However, at the present time we have only weak experimental evidence for the values of Sc and Pr in neutral conditions. More importantly, our poor understanding of the processes that set Sc and Pr and control their variation with diabatic stability is a barrier to generalizing MOST for use above tall canopies.

3. Diabatic stability and canopy flows
As radiative cooling proceeds after sundown, turbulence within dense canopies can collapse suddenly leading to decoupling of the canopy layer from the boundary layer above. Theory suggests that this process should occur because of the different transport mechanisms of scalars and momentum at leaf level. So far no definitive experimental results are available to confirm or refute this theory or to set bounds on its applicability. This has important implications for transport and canopy microclimate. In particular we need to know how the controlling time scales of this process depend upon canopy density and radiative transfer.

4. Gravity currents
Deep coherent gravity currents are often observed on long hill slopes covered with tall canopies. The process of turbulent collapse after sundown mentioned in (3) above produces a deep stable layer which is decoupled from the boundary layer above and must come into a new dynamic balance involving the hydrostatic and hydrodynamic pressure gradients and canopy drag. Scale analysis suggests that the strength of such currents depends upon hill length rather than hill slope while wind tunnel experiments reveal that they can penetrate onto flat ground far upwind of the hills on which they originate. Many field sites where flow is well behaved during the day can,

therefore, be affected by such gravity flows at night. The parameters controlling the unsteady dynamics of this situation are not known but are of critical importance to measurements of water and other trace gas exchange over the diurnal cycle.

The four topics chosen move from the fundamentals of canopy eddy structure to the impact at large scale of microscale processes. Each requires us to consider simultaneously processes from the leaf to the whole canopy scale and each will require effort from the whole community if serious progress is to be made.