Three decades of evolution in our understanding of canopy turbulence

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1. Large turbulent eddies in plant canopies
2. The effect of complex terrain-canopies on hills
3. Diabatic effects-stable and unstable stratification
1. Large turbulent eddies in plant canopies

If canopy eddies are small compared to the height of the canopy, we can calculate fluxes from mean gradients using an ‘eddy diffusivity, $K_c$

$$F_c(z) = K_c(z) \frac{C}{z}$$
If canopy eddies are not small compared to the mean concentration gradients, strange things can happen!

Simultaneous profiles and eddy fluxes measured in Uriarra Forest near Canberra show steady ‘counter-gradient’ diffusion.

Figure from Denmead and Bradley (1987)
Structure of Canopy Turbulence

Time-height traces from single towers in tall canopies give information about turbulent structure in the x-z plane.
Scalar ‘ramps’ correlated through the depth of the canopy showed wholesale ‘flushing’ of the canopy airspace by large scale gusts.

Gao, Shaw and Paw U. (1989), Camp Borden, Canada
Compositing showed that these ramps are signals of a scalar microfront compressed between downwind ejections and upwind sweeps.

Origin of the large eddies: The Mixing Layer Hypothesis

Unlike the boundary layer profile, the inflected velocity profile at canopy top is inviscidly unstable, leading to rapid growth and strong selection for a single scale, proportional to the vorticity thickness $\delta_\omega$. A cascade of instabilities beginning with a Kelvin-Helmholtz wave leads to coherent 3D eddies. This is the ‘mixing layer analogy’ (Raupach et al, 1996).

$$2L_s = \frac{U(h)}{dU(h)/dz}$$
Origin of the large eddies: The cascade of instabilities

Finnigan, Shaw and Patton, 2009
Consequences for modelling and measuring fluxes

\[ h_c = \text{canopy top} \]

\[ \frac{z}{h_c} = \frac{U(z)}{u^*} \]

Duke Forest

Moga Forest

Tumbarumba Forest

The scale that characterizes the instability at canopy top can be used to modify Monin-Obukhov similarity theory. 

Harman and Finnigan (2007)
2. The effect of Complex Terrain: Canopies on Hills

- Neutral stability
- Resolved canopy
- Surface roughness
What forces shape the flow field in a canopy on a hill?

Flow around the hill creates a pressure field.

**Above the canopy**

\[ \Delta u \propto -\Delta p \]

Max wind speed above the hill crest.

**Deep in the canopy**

\[ \Delta u \propto -\frac{\partial \Delta p}{\partial x} \]

Max \( \Delta u \) on up and downwind slopes.

Reversed flow possible deep in the canopy.

Finnigan and Belcher (2004)
Belcher et al. (2007)
Reversed flow occurs in front of the downwind trough

Example from a water flume experiment over multiple hills covered with a deep canopy

Flume and wind tunnel simulations show that separation occurs at much lower lee slopes on hills covered with tall canopies and separation regions can appear near the ground even on very gentle hills if the canopy is deep and dense enough.

Consequences for modelling and measuring fluxes: the Problem of Topographic Advection

Red, high values, blue low values, black contour marks the zero line
Consequences for modelling and measuring fluxes: the Problem of Topographic Advection

Eddy flux over the hill is strongly variable but also systematically low—some of the total flux is carried by advection.
3. Diabatic Effects: Stably stratified flow in canopies on flat ground

Within the canopy the turbulence collapse although the flow above remains turbulent.
3. Diabatic Effects: Stably stratified flow in canopies

The different mechanisms of momentum and heat transfer to the foliage ensure that the wind profile approaches zero much faster than the temperature profile approaches the leaf temperature: $L_s \sim 10 L_c$

With nighttime radiative cooling, turbulence in the canopy collapses

![Graph showing wind profile and temperature profile](image1.png)

The Richardson number captures the balance between mechanical and buoyancy influences on the turbulence. For $Ri > 0.25$, turbulence collapses

$$ Ri = \frac{g / \theta_0 \frac{d\theta}{dz}}{(dU/dz)^2} $$

![Graph showing Richardson number](image2.png)
Gravity currents in the wind tunnel

Once turbulence in the canopy has collapse, the gravity currents can extend many hill heights up and downwind from the hill crest.

$U_z/U_0$ over surface, $U_0 \sim 0.3 \text{ ms}^{-1}$
red = hot (200 Wm$^{-2}$), blue = cold

Upwind penetration of gravity current
Consequences for modelling and measuring fluxes:

Without corrections Flux Towers routinely underestimate nighttime respiration of CO2 because the flux instruments do not measure the CO2 moved sideways by the gravity current in the non-turbulent canopy flow.

Tumbarumba CO2 profiles show large concentrations near the soil but storage doesn’t balance soil respiration. Advection driven by the gravity current is the cause.
3. Diabatic Effects: Unstably stratified flow in canopies on flat ground

Near-neutral
\[ \frac{h}{L} = -0.1, \quad \frac{z_i}{L} = -2.8 \]

Strongly unstable
\[ \frac{h}{L} = -48.4, \quad \frac{z_i}{L} = -2020.8 \]

\( L = \) Monin-Obukhov length, \( h = \) canopy height, \( z_i = \) boundary layer depth
Momentum and heat flux at canopy level below updrafts and downdrafts

Unstable simulation. Black is total flux, Red is flux below updrafts, Blue is flux below downdrafts
Different eddy structures are responsible for transfer from the canopy below updrafts and downdrafts

1. x-y slice through convective PBL shows strong U and dU/dz under downdraughts
2. Below downdraughts we see ‘neutral canopy eddies driven by shear instability
3. Below updraughts we see canopy scale plumes which coalesce into the walls of PBL scale convective cells

Temperature and uw vectors triggered on T>4 at iz=10
Consequences for modelling and measuring fluxes

• The planetary boundary layer spontaneously develops large coherent structures which can extend all the way to the inversion.

• In neutral or unstable sheared conditions, the structures take the form of streamwise rolls.

• In fully convective conditions, the structures look like (hexagonal) Rayleigh Benard cells.

• The length and time scales of these structures strongly modulate fluxes to and from the canopy as they change the nature of the canopy ‘coupling’ eddies.

• However their time scales are very long (~ 1 hour) compared to surface layer eddy scales (~minutes) and this has implications for the averaging times required for flux measurement. Even in neutral flows, long averaging times may be necessary for statistical confidence.
Summary

• Over the last three-four decades, our understanding of the nature of canopy turbulence has increased enormously and with it our appreciation of how we can use eddy flux measurements to infer biome scale exchange.

• Fundamental has been a proper appreciation of the processes that produce dominant canopy ‘large’ eddies.

• Tackling flow over complex terrain revealed new physical phenomena and more lessons for flux measurements.

• As did understanding the effect of stable stratification and, now of unstable convective flow.

• The importance of field and laboratory measurements can’t be overstated: theoretical understanding has in most cases followed the appearance of results we could not explain with existing theory.

• Finally, what have I missed out: Spatial averaging; WPL corrections, and?
Dramatis Personae

- Frank Bradley \(^1\)
- Tom Denmead \(^1\)
- Roger Shaw \(^2\)
- Mike Raupach \(^1\)
- Yves Brunet \(^3\)
- Ned Patton \(^4\)
- Stephen Belcher \(^5\)
- Gaby Katul \(^6\)

- Davide Poggi \(^7\)
- Ian Harman \(^1\)
- Ray Leuning \(^1\)

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