Three decades of evolution in our understanding of canopy turbulence

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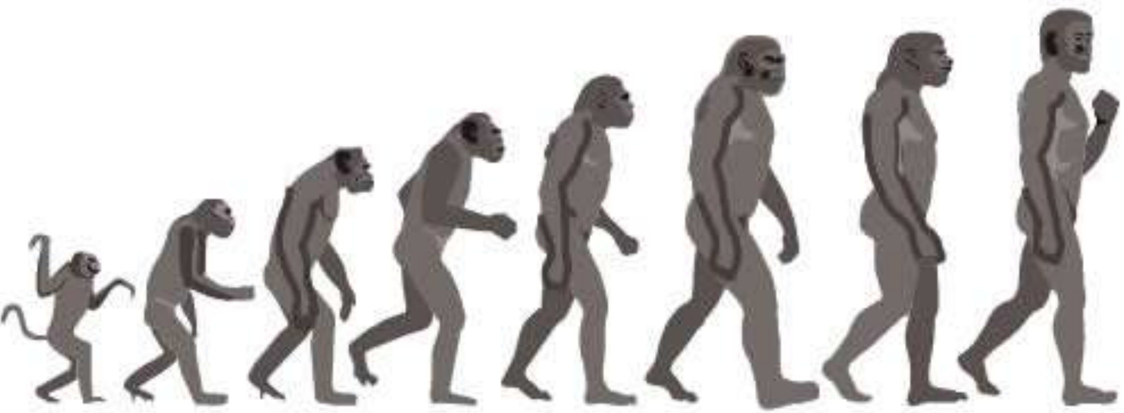
Three decades of evolution in our understanding of canopy turbulence

1. Large turbulent eddies in plant canopies

2. The effect of complex terrain-canopies on hills

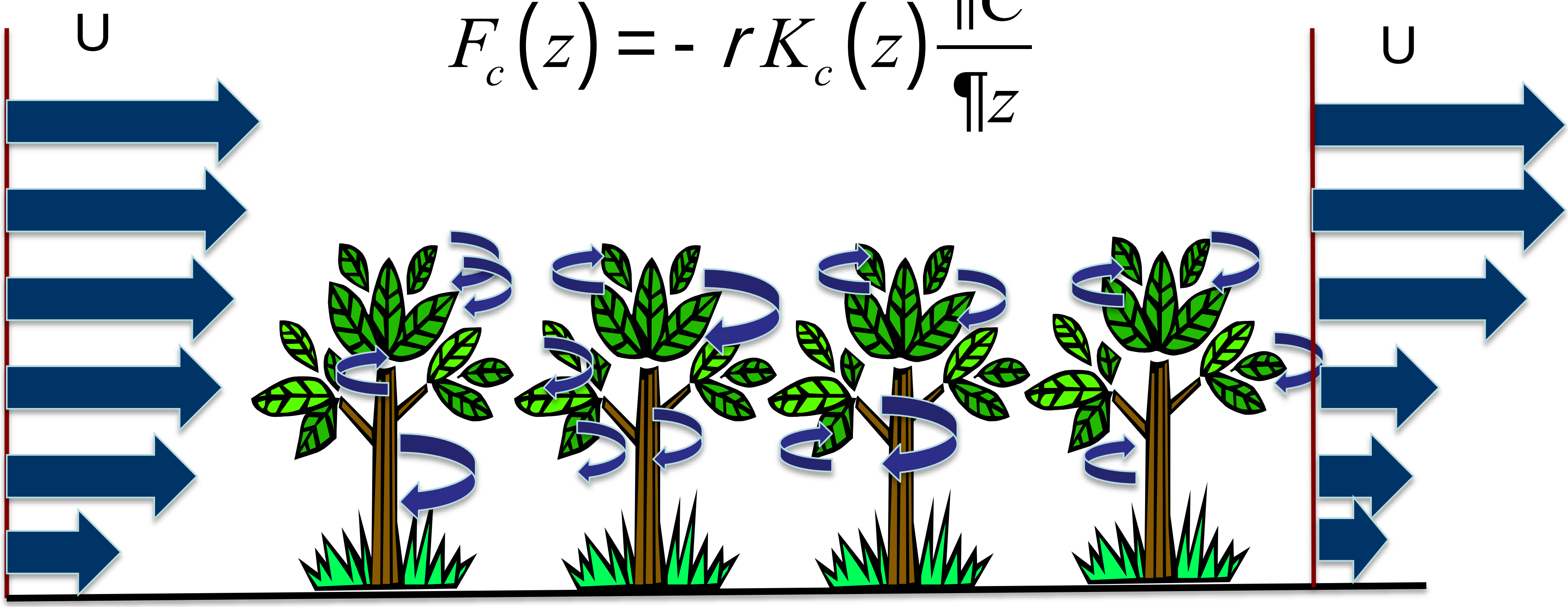
3. Diabatic effects-stable and unstable stratification



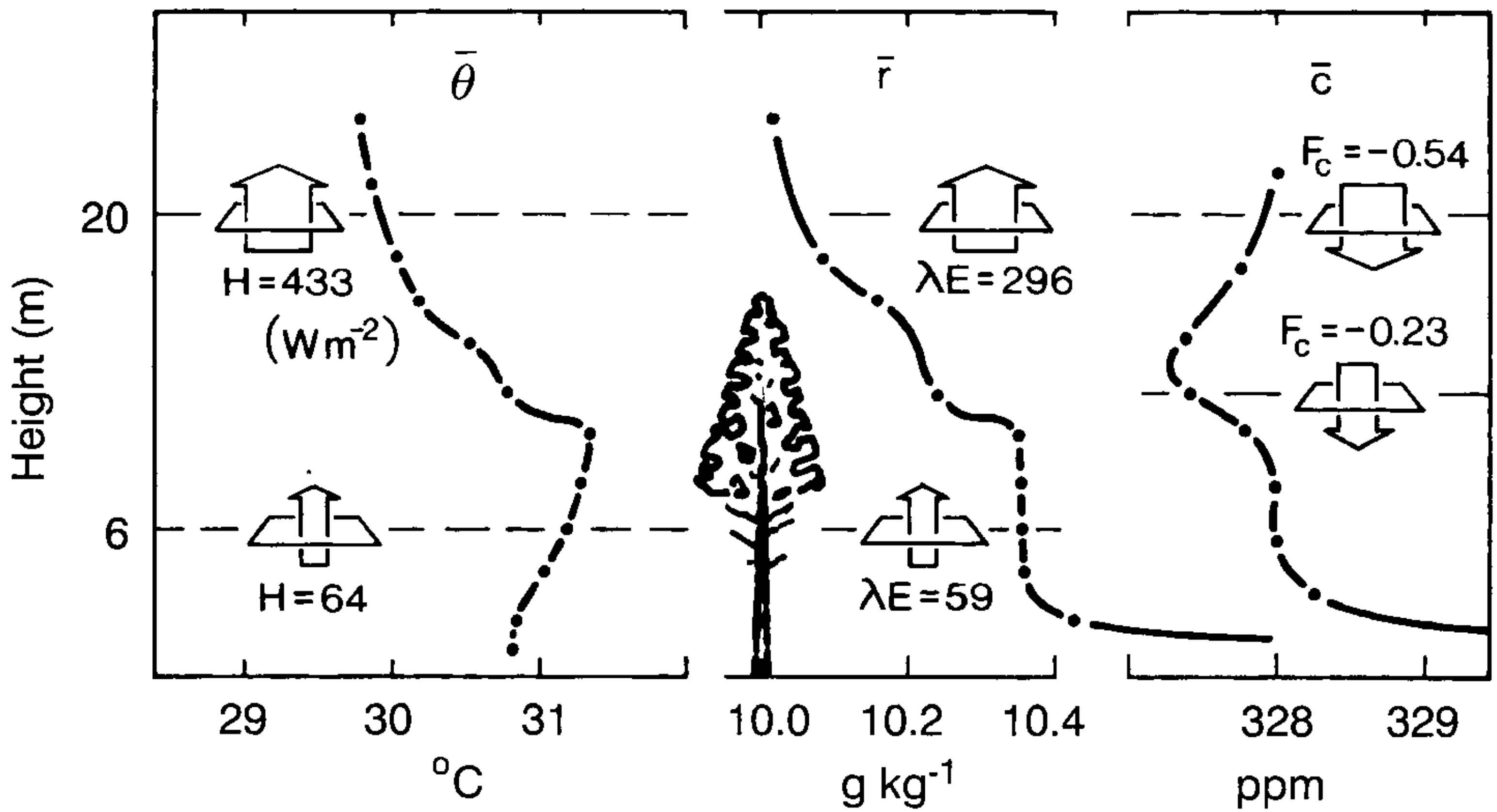
1. Large turbulent eddies in plant canopies

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

$$F_c(z) = -\rho K_c(z)\frac{\partial C}{\partial z}$$



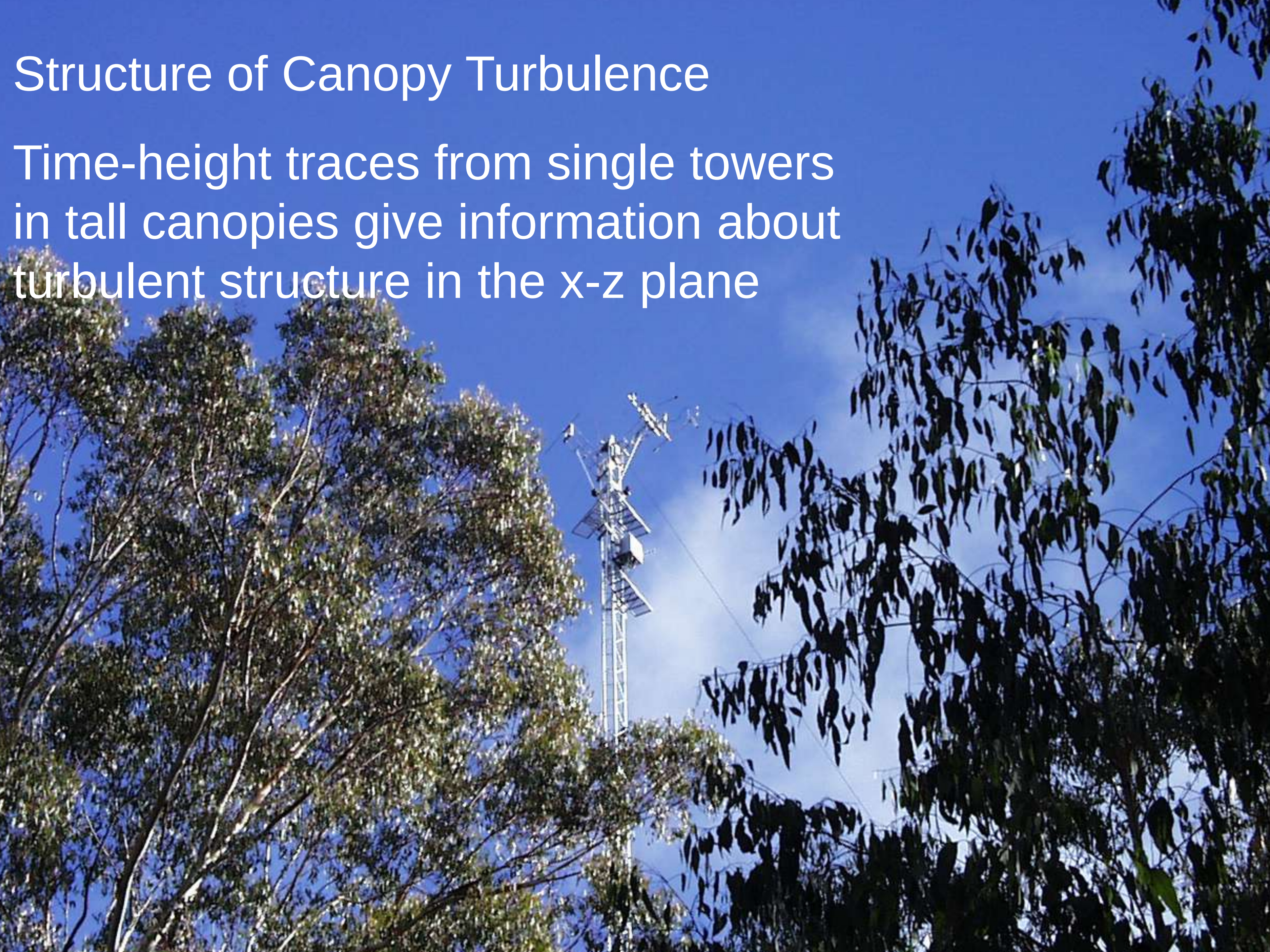
If canopy eddies are not small compared to the mean concentration gradients, strange things can happen!



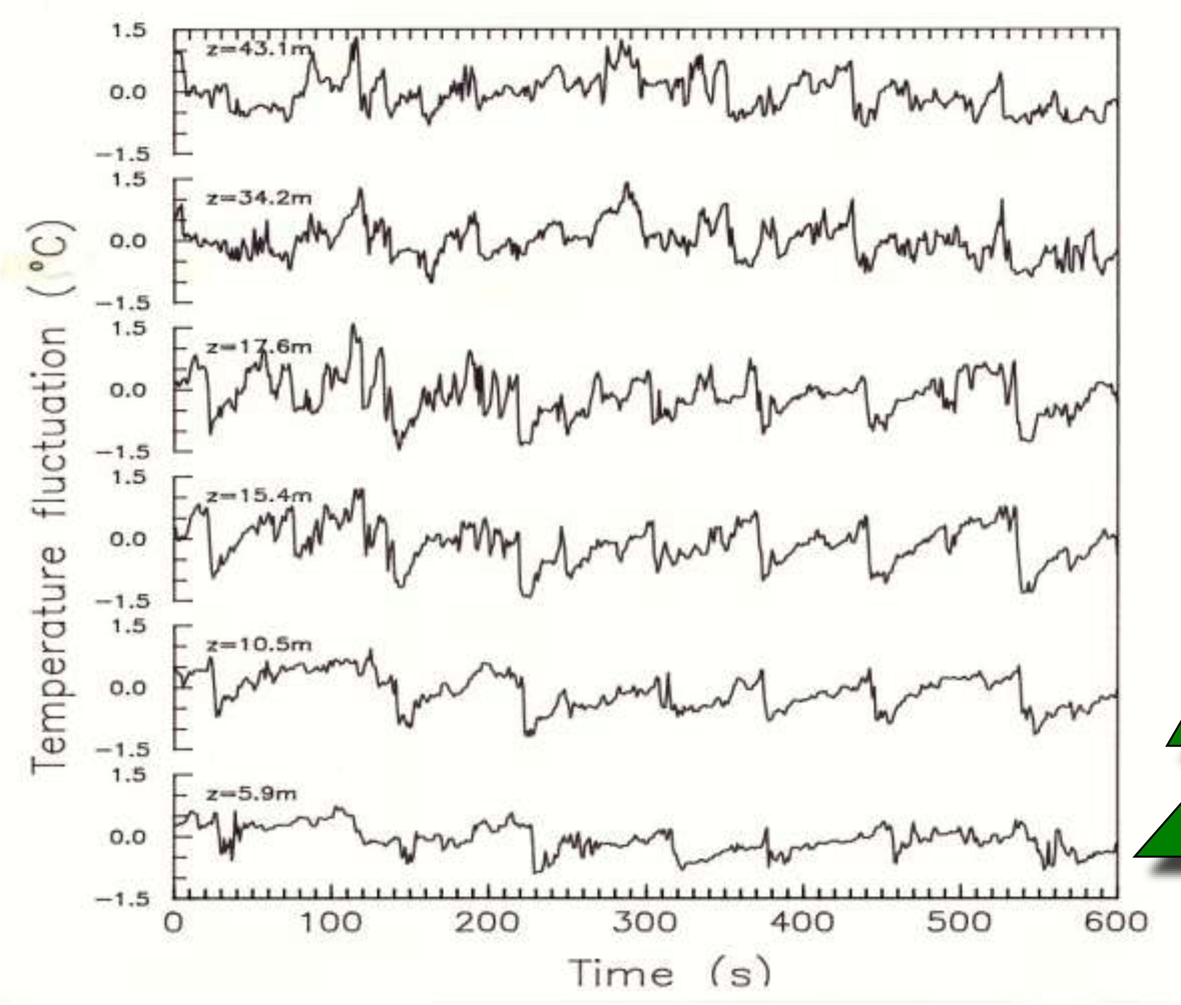
Simultaneous profiles and eddy fluxes measured in Uriarra Forest near Canberra show steady 'counter-gradient' diffusion.
Figure from Denmead and Bradley (1987)

Structure of Canopy Turbulence

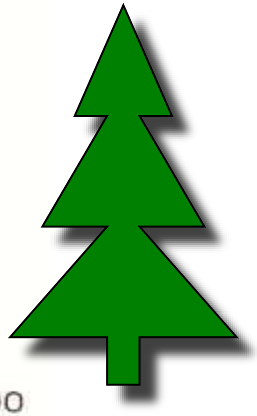
Time-height traces from single towers in tall canopies give information about turbulent structure in the x-z plane



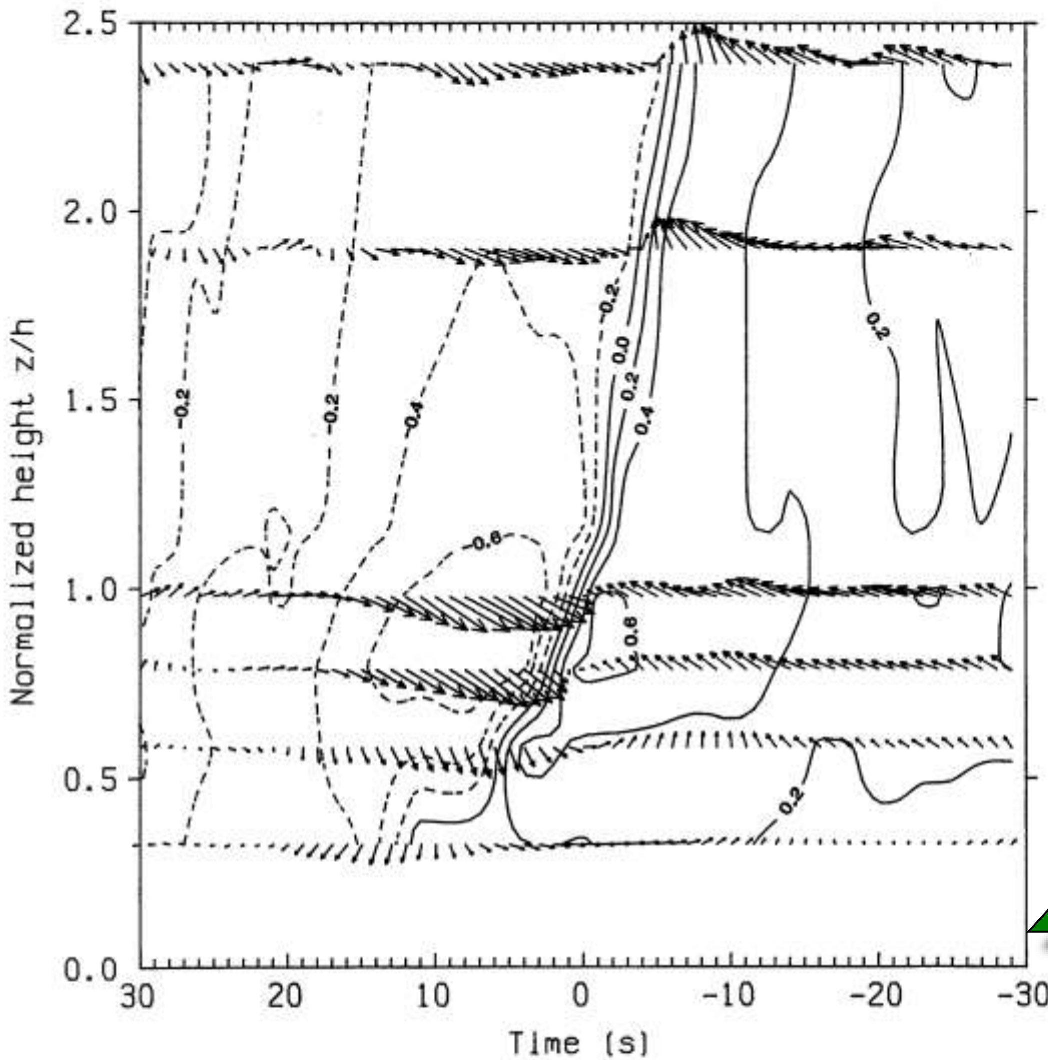
Scalar 'ramps' correlated through the depth of the canopy showed wholesale 'flushing' of the canopy airspace by large scale gusts



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



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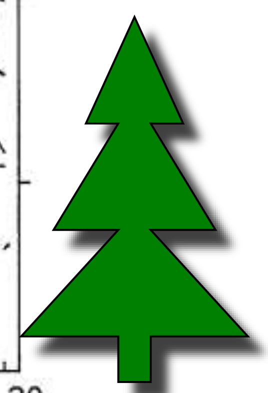
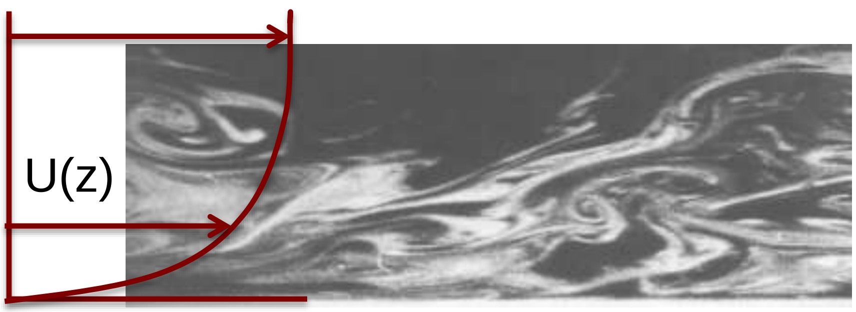
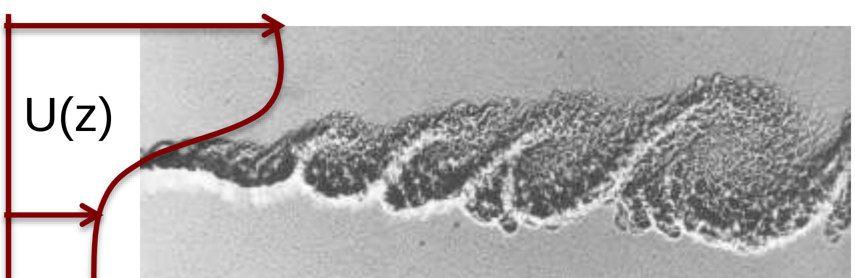


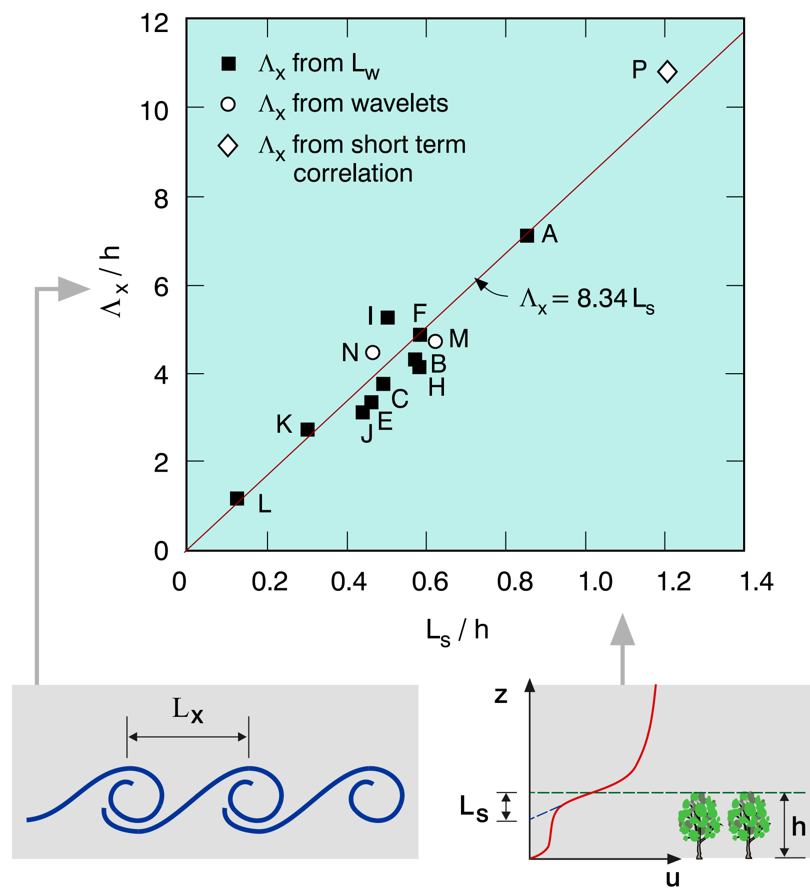
Origin of the large eddies: The Mixing Layer Hypothesis

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 δ_ω. 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).

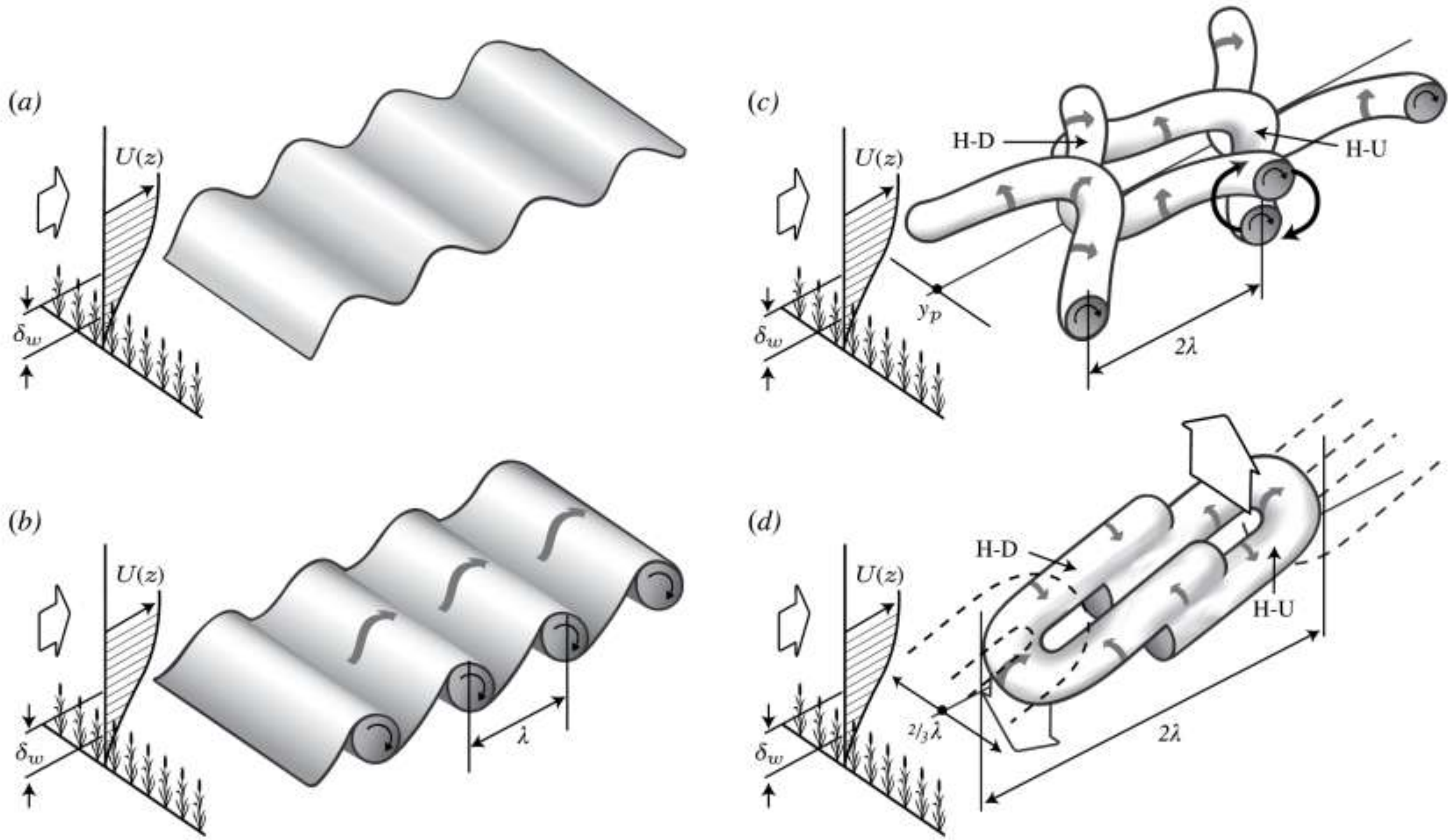
$$\delta_w \approx 2Ls = \frac{U(h)}{dU(h)/dz}$$





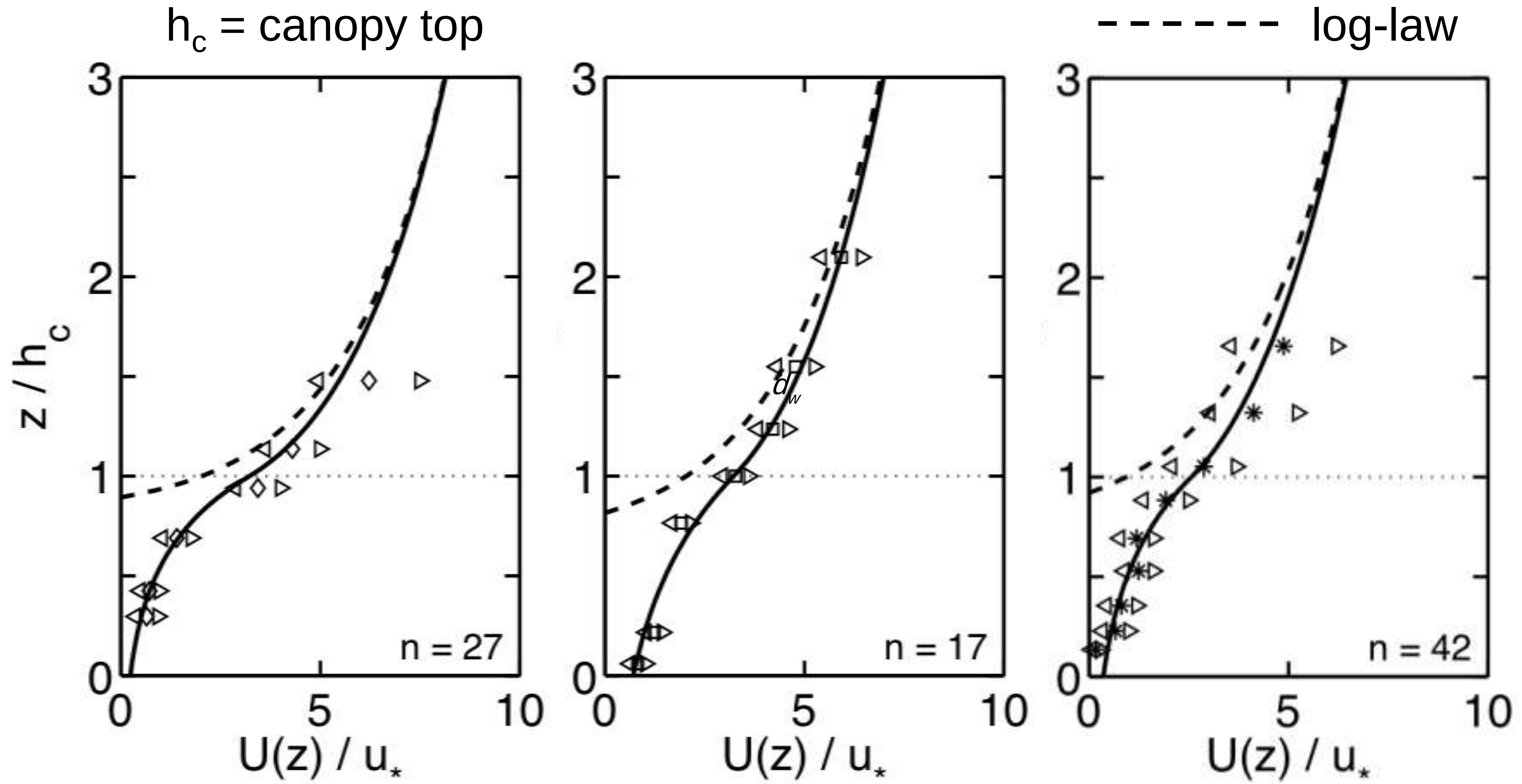


Origin of the large eddies: The cascade of instabilities



Finnigan, Shaw and Patton, 2009

Consequences for modelling and measuring fluxes

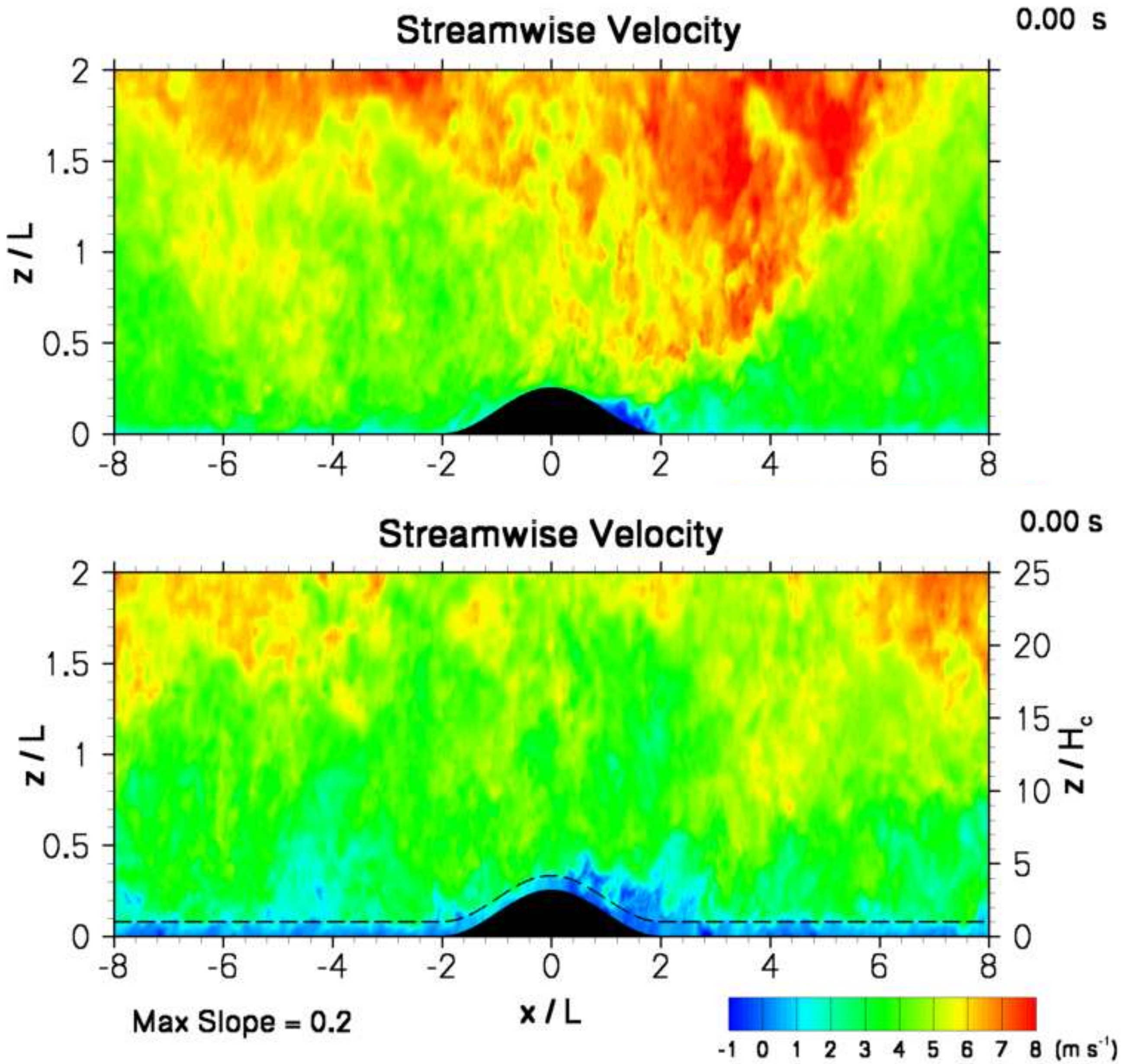


Duke Forest Moga Forest Tumbarumba Forest

d_w, 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



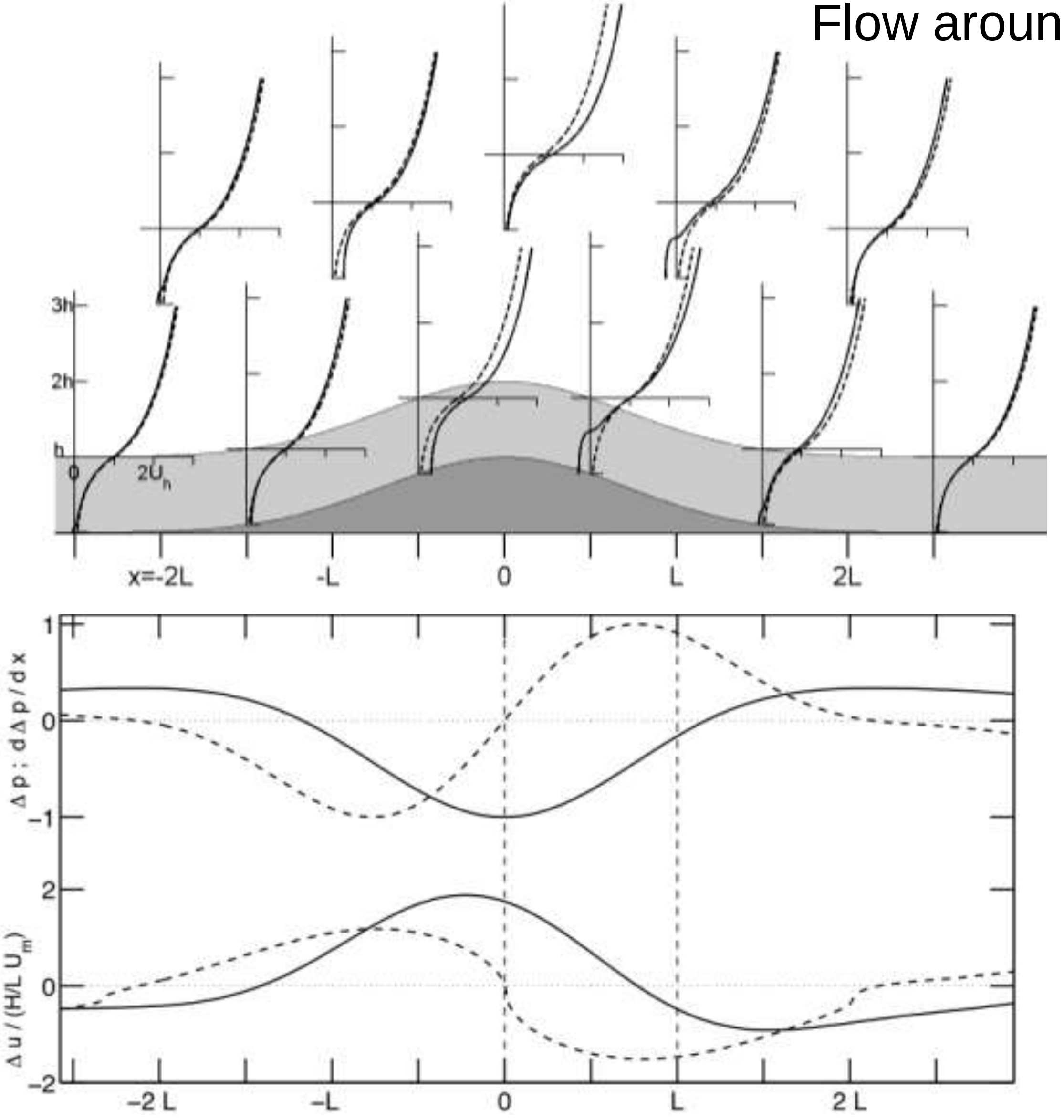
Surface roughness

Neutral stability

Resolved canopy

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

$$\Delta u \propto -\frac{\partial \Delta p}{\partial x}$$

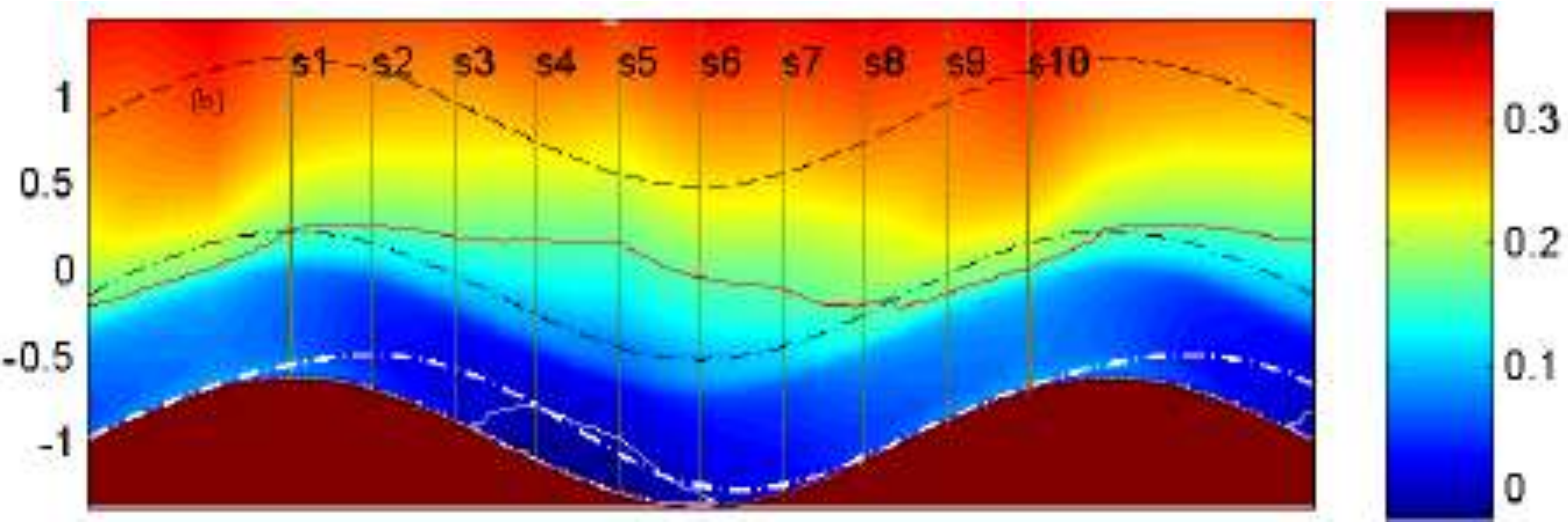
Max Δu on up and downwind slopes.

Reversed flow possible deep in the canopy.

Finnigan and Belcher (2004)
Belcher et al. (2007)

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

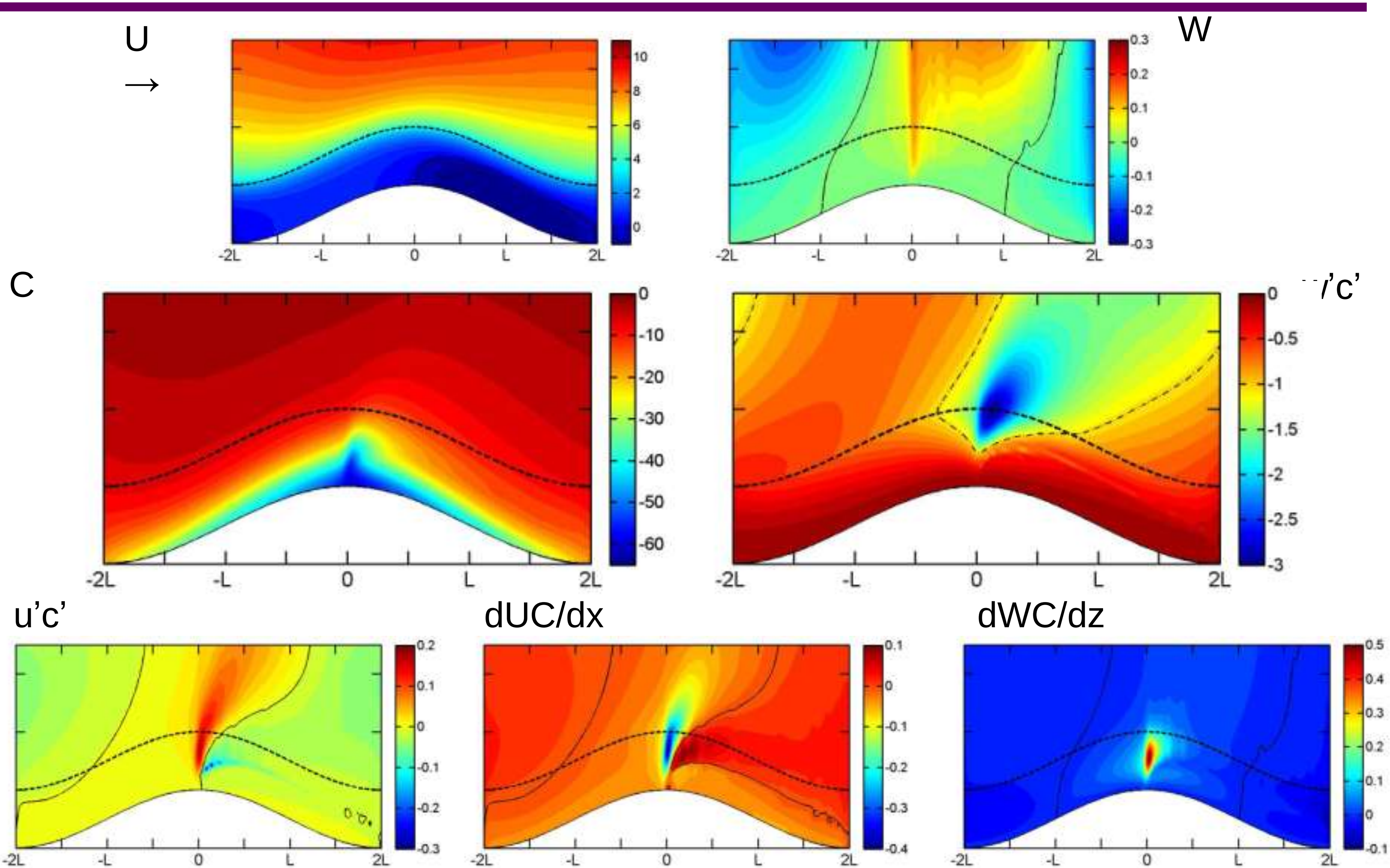
Reversed flow occurs in front of the downwind trough



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.

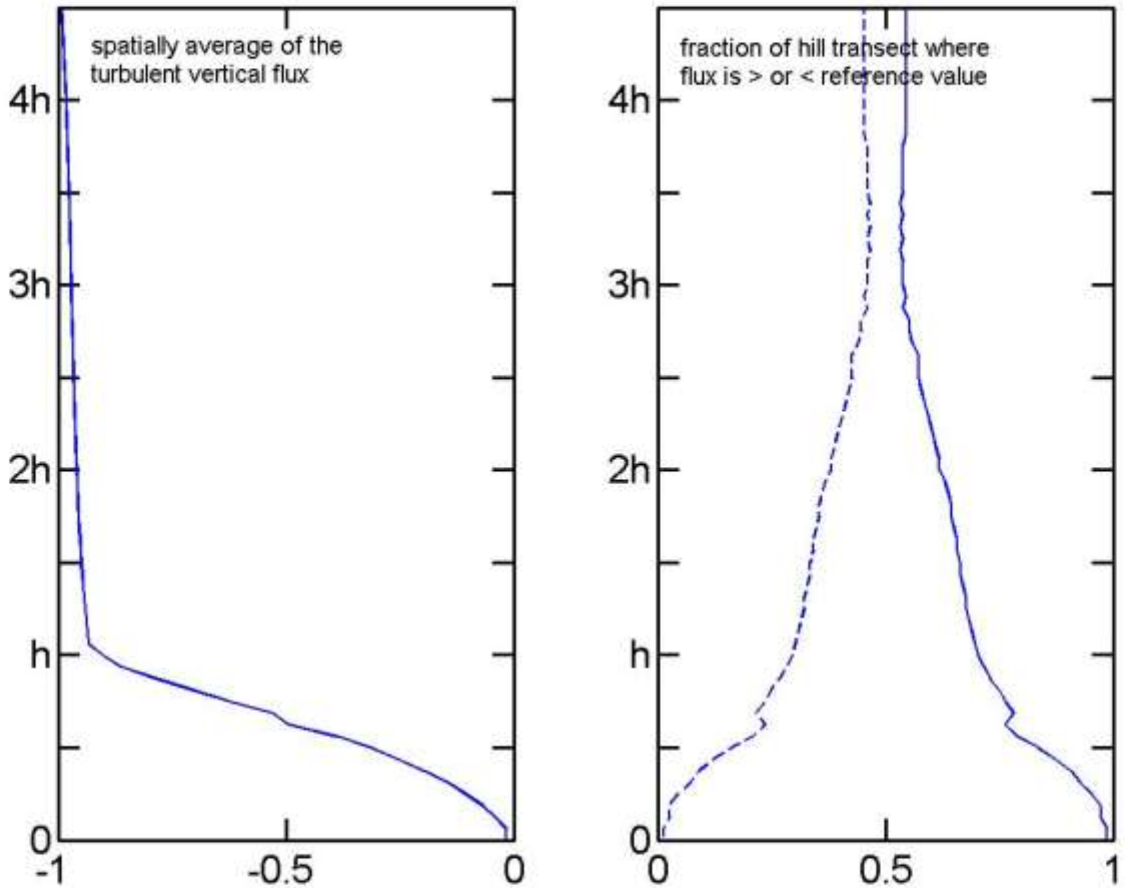
Poggi, D., Katul, G.G. and Finnigan, J.J., 2006

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



Base case:
H=20m, L=400m,
cosine hill,
hc=20m, Lc=30m,
$u^*/U_B(h_c)=0.3$,
S sink constant in h_c.
in flat conditions

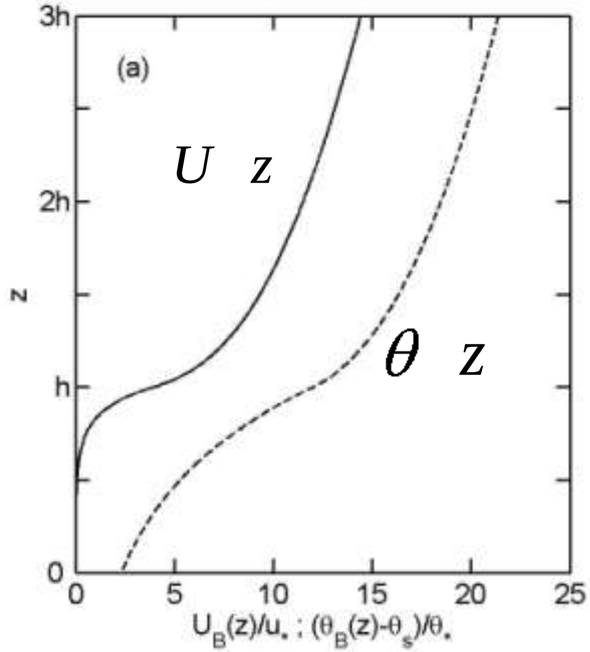
$$\left\langle \overline{w'c'} \right\rangle = -1$$

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 grou

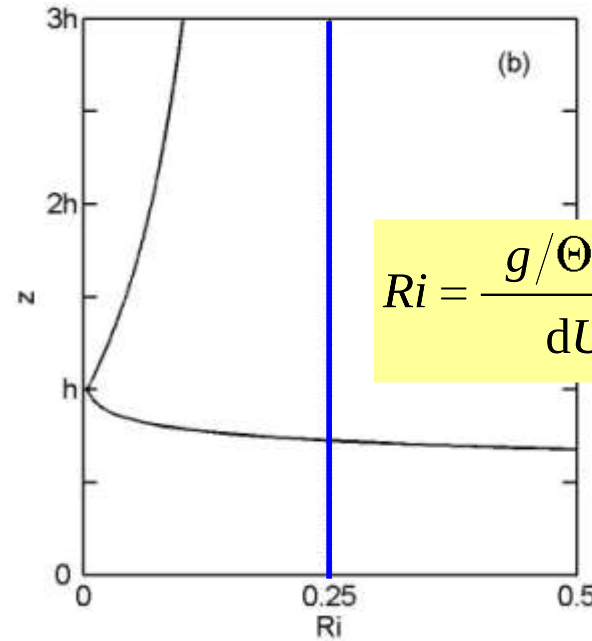
Within the canopy the turbulence collapse although the flow above remains turbulent

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

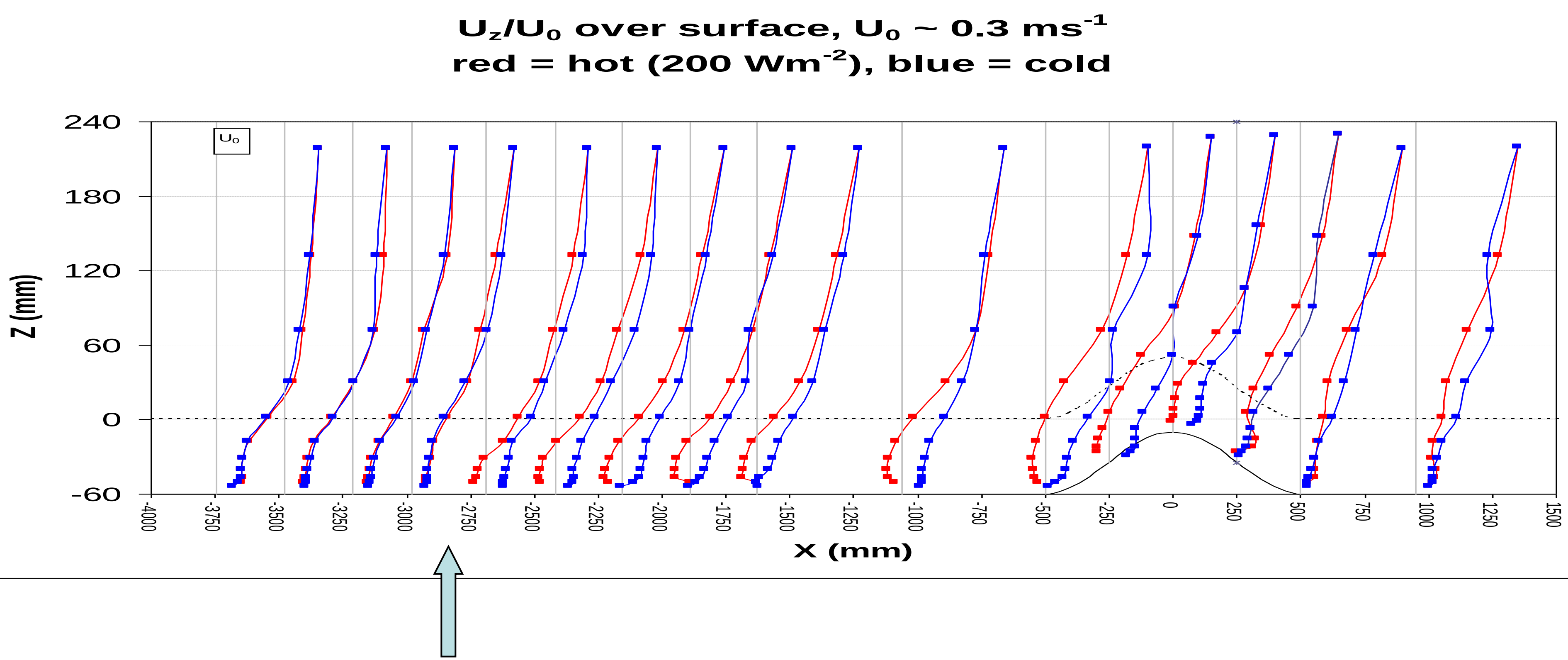


$$Ri = \frac{\left(g/\Theta_0\right)\left(\mathrm{d}\theta/\mathrm{dz}\right)}{\left(\mathrm{d}U/\mathrm{dz}\right)^2}$$

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

Gravity currents in the wind tunnel

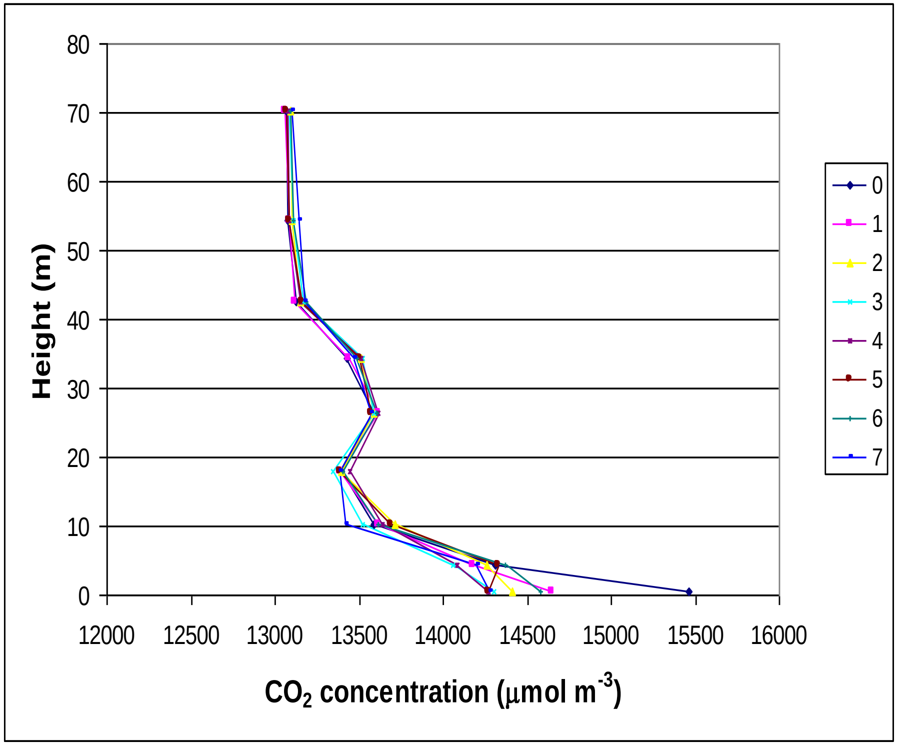
Once turbulence in the canopy has collapse, the gravity currents can extend many hill heights up and downwind from the hill crest.

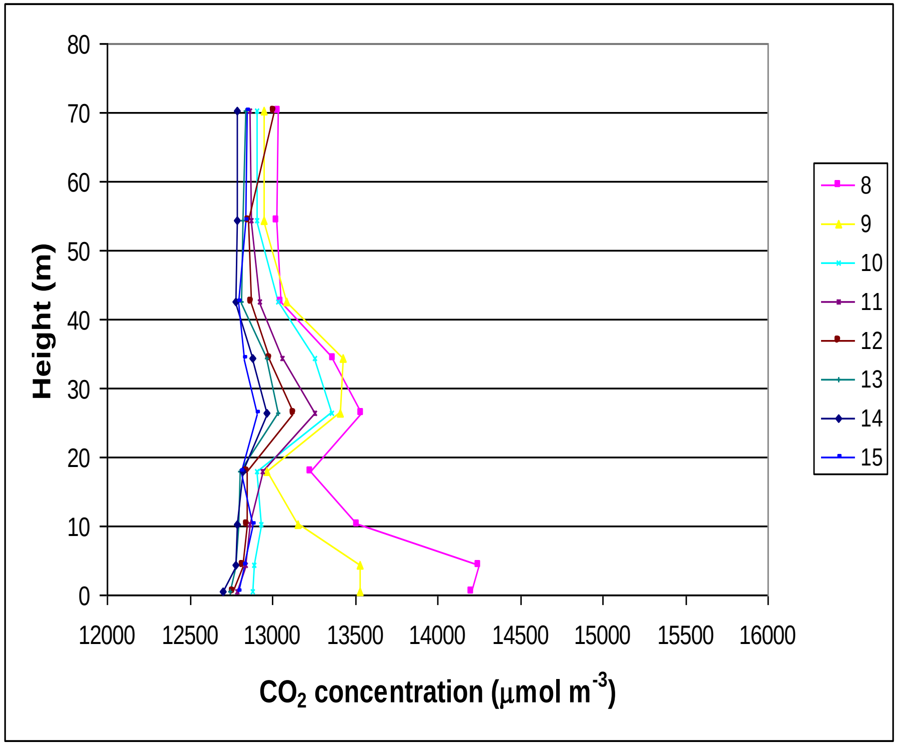


Upwind penetration of gravity current

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.



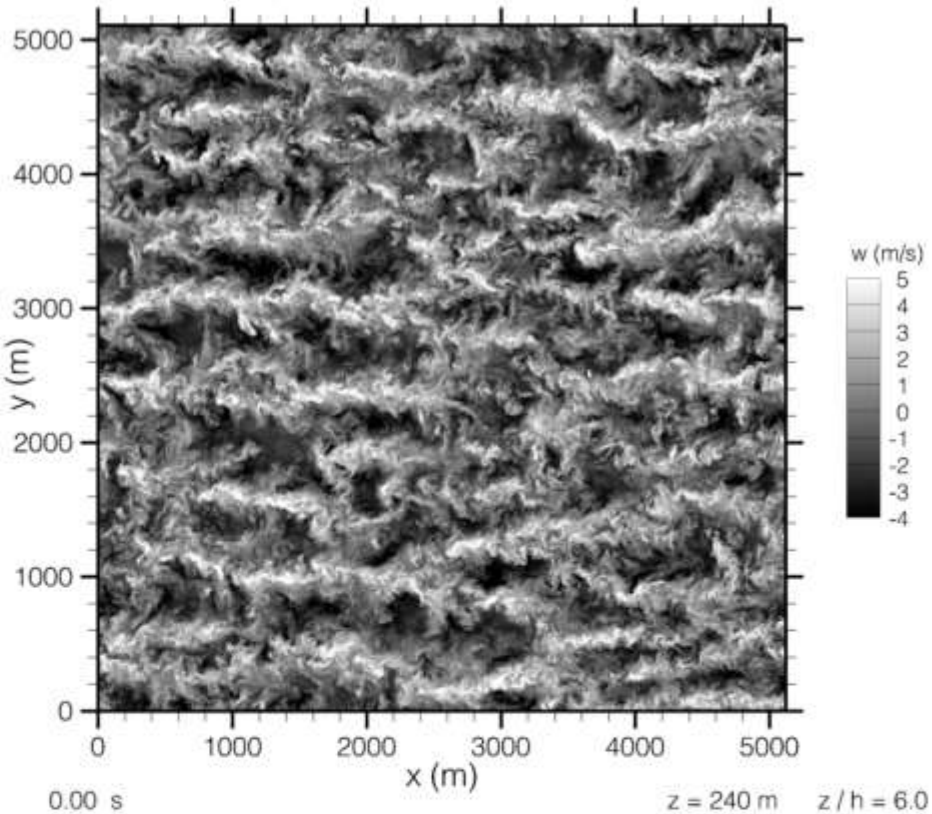


Tumbarumba CO2 profiles show large concentrations near the soil but storage doesn’t balance soil respiration. Advection driven by the gravity current is the cause

3. Diabatic Effects: Unstably stratified flow in canopies on flat ground

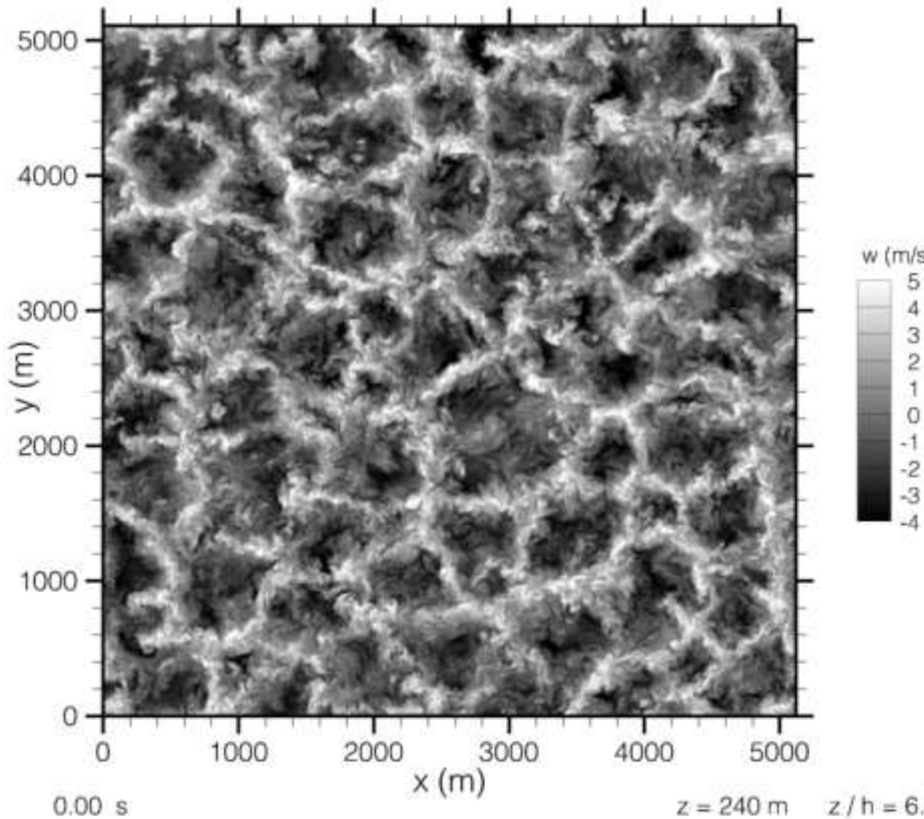
Near-neutral

$$\frac{h}{L} = -0.1 \ , \ \frac{z_i}{L} = -2.8$$



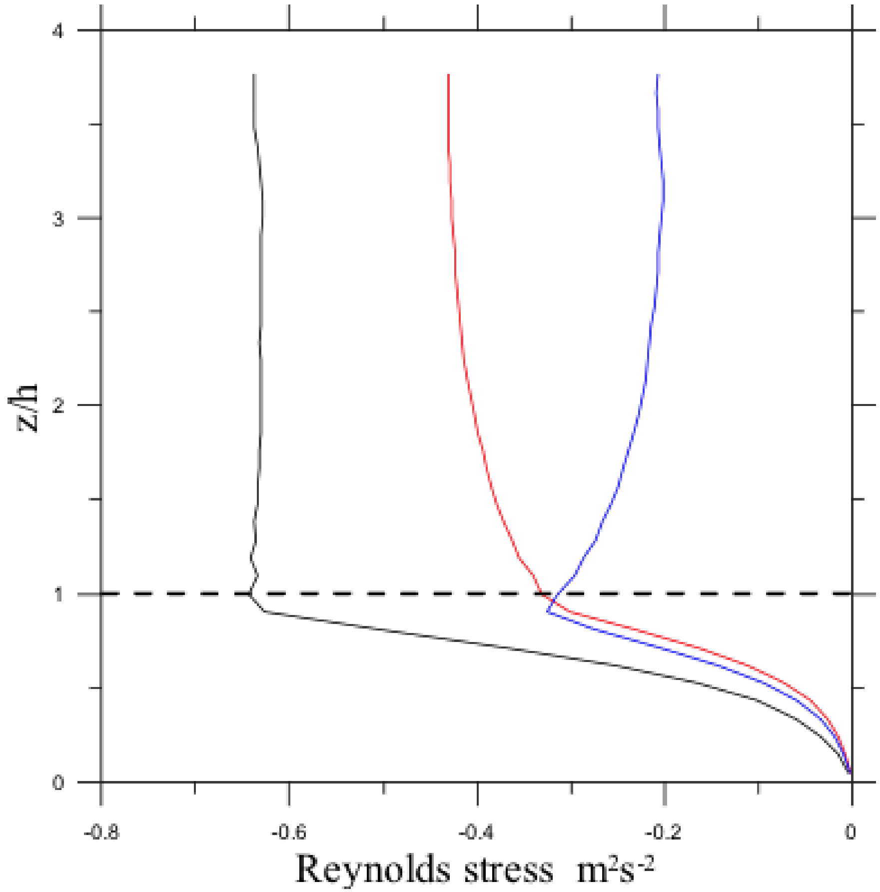
Strongly unstable

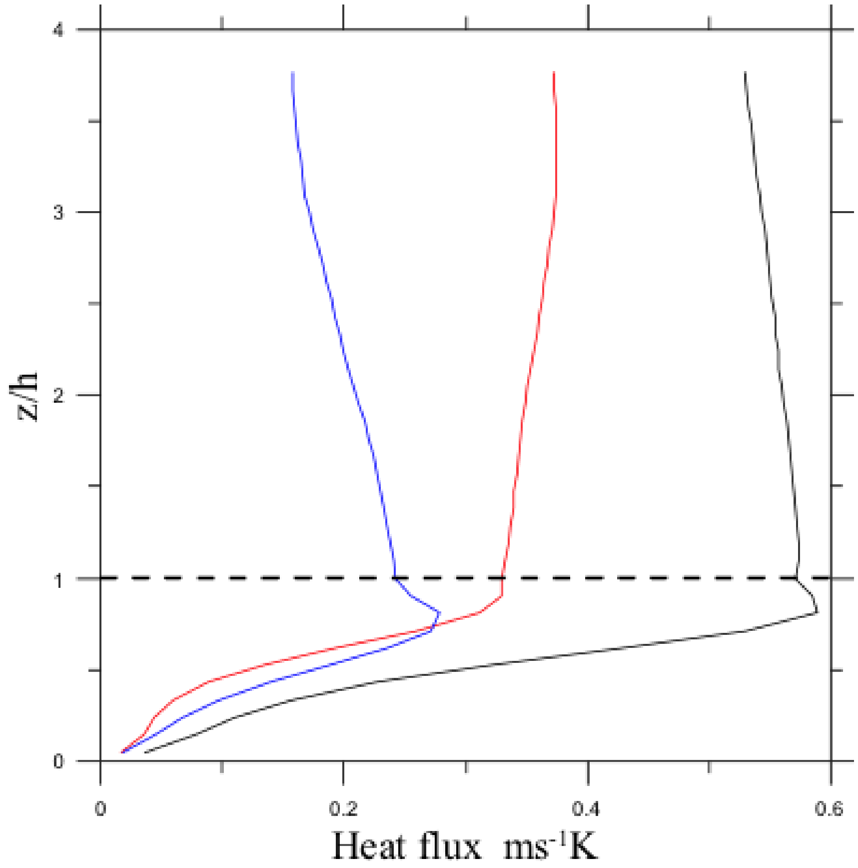
$$\frac{h}{L} = -48.4 \ , \ \frac{z_i}{L} = -2020.8$$



$L =$ Monin-Obukhov length , $h =$ canopy height , $z_i =$ boundary layer depth

Momentum and heat flux at canopy level below updrafts and downdrafts

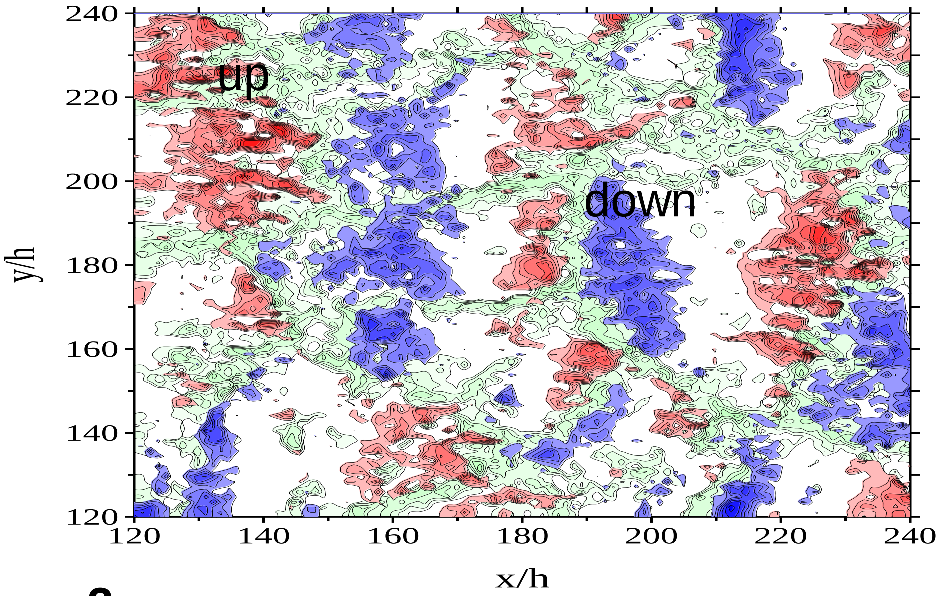




Unstable simulation. Black is total flux, Red is flux below updrafts, Blue is flux below downdrafts

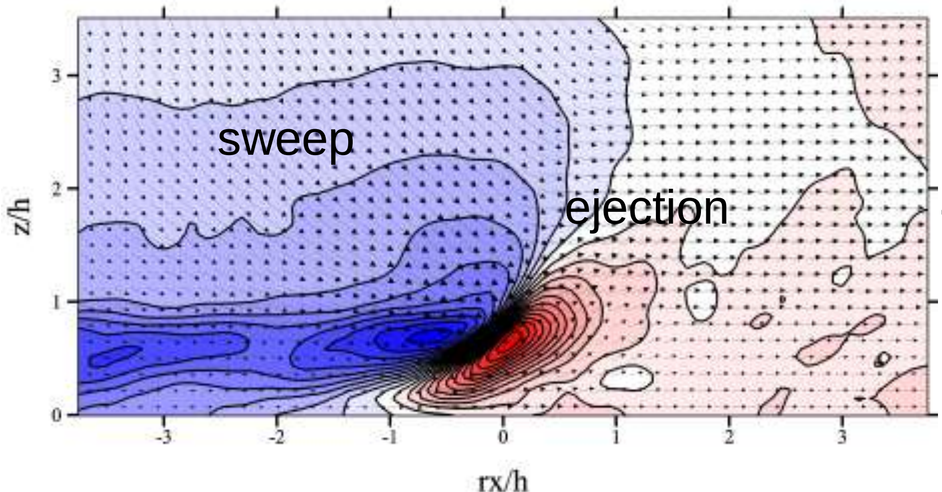
Different eddy structures are responsible for transfer from the canopy below updrafts and downdrafts

1



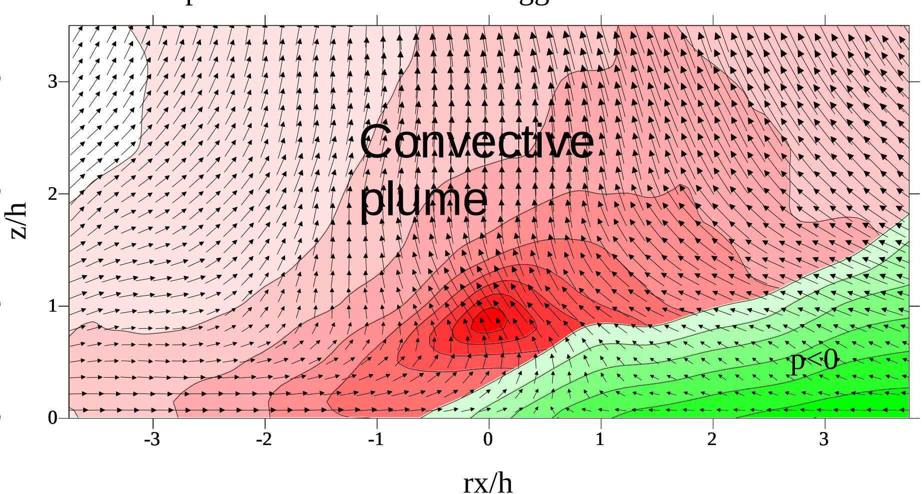
1. x-y slice through convective PBL shows strong U and dU/dz under downdraughts
2. Below downdraughts we see 'neutral canopy eddies driven by shear instability
3. Below updraughts we see canopy scale plumes which coelesce into the walls of PBL scale convective cells

2



3

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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