Air Flow in Forests and Complex Terrain and Nocturnal Flows

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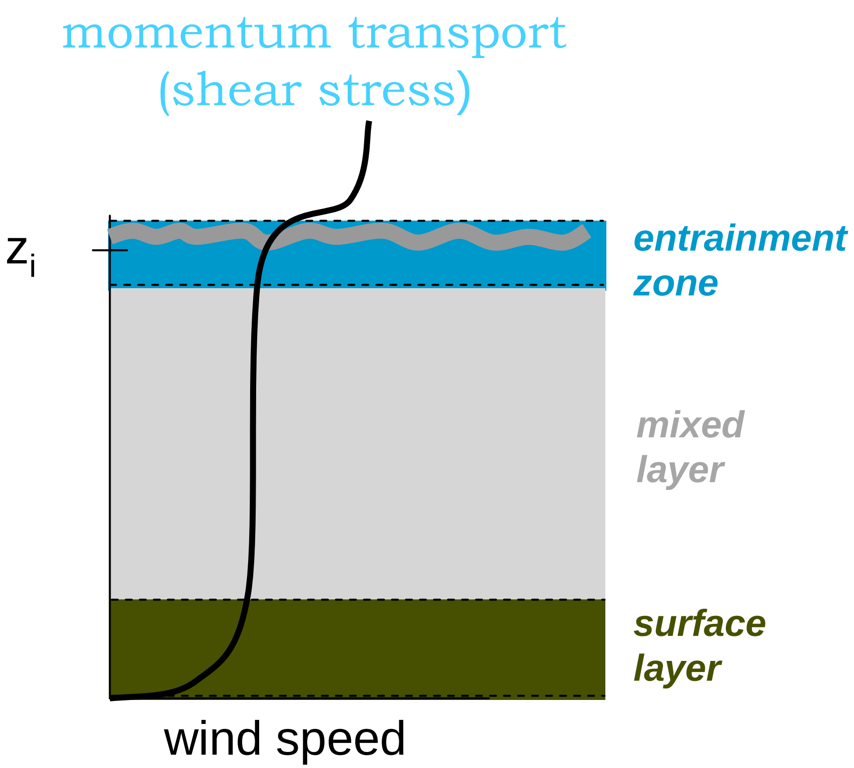
02/02/2010
CSIRO Marine and Atmospheric Research

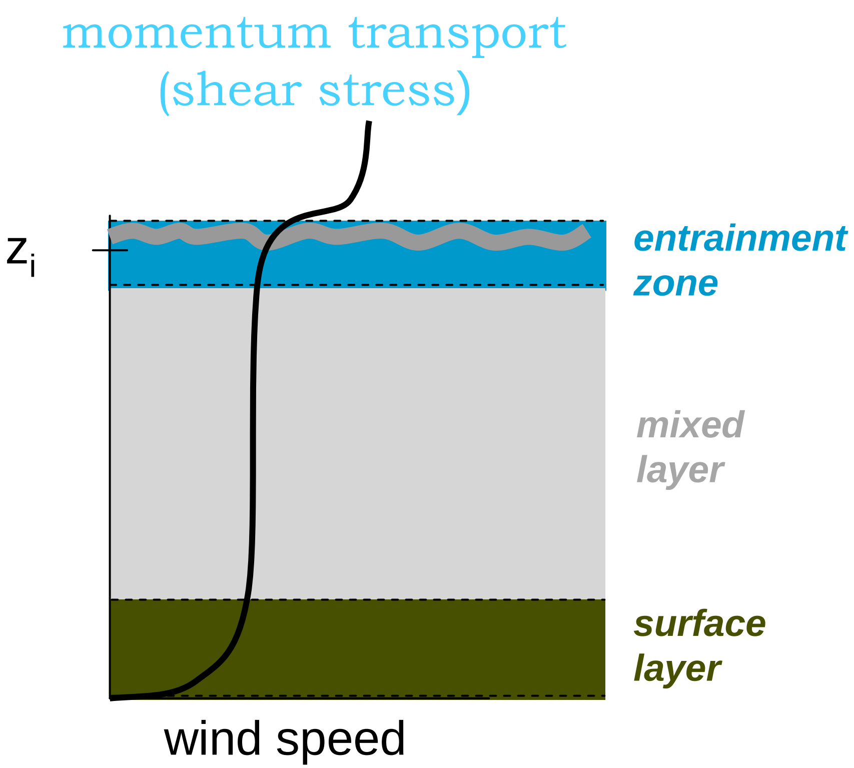
Flows through forest canopies

Atmospheric Boundary Layer (ABL)

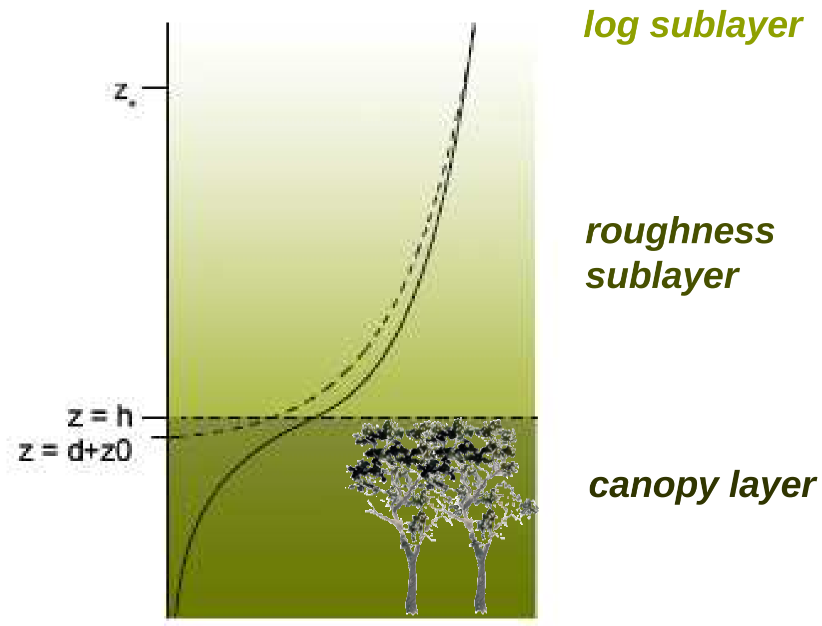


Flows through forest canopies

Atmospheric Boundary Layer (ABL)

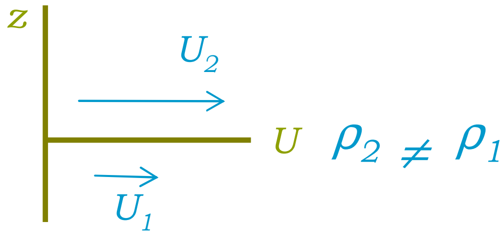


Surface Layer (SL)



I. Harman, 2007, adapted

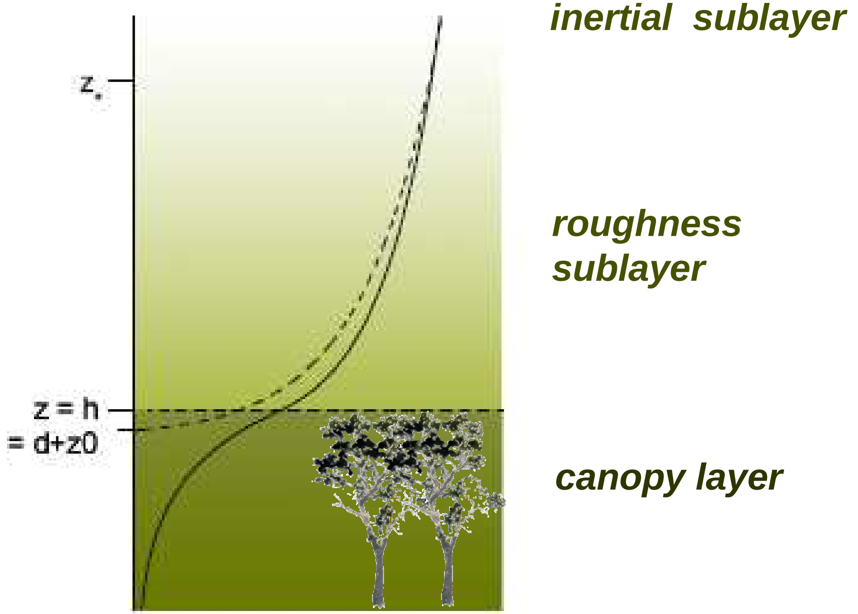
INTERMEZZO



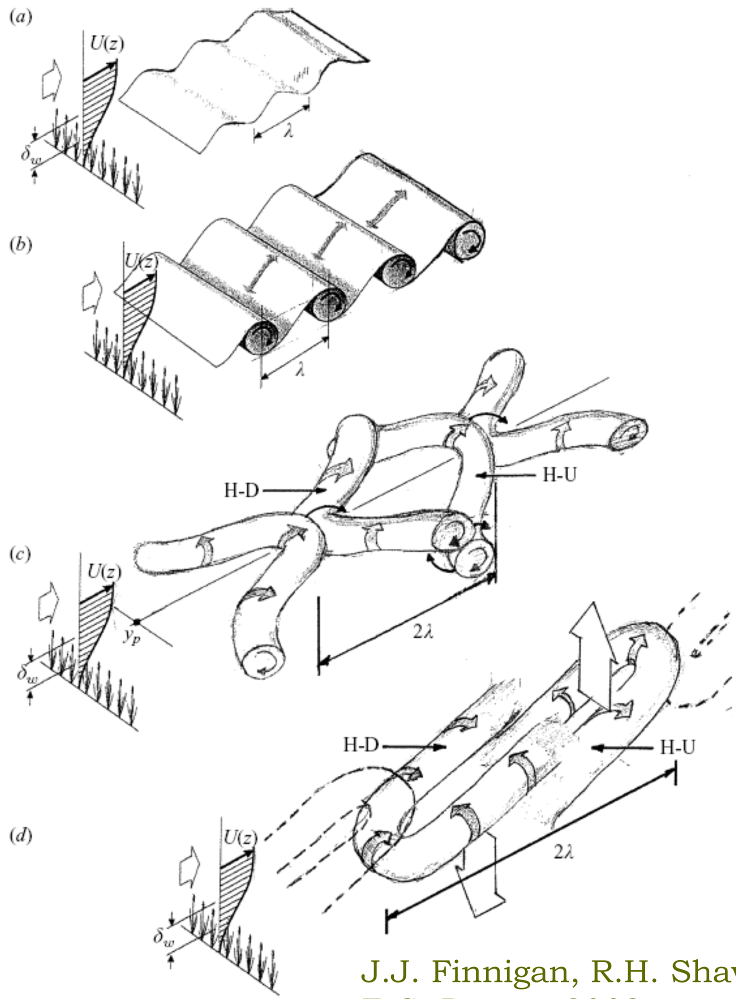
- a shear interface between 2 fluids of different density is unstable under certain conditions
- large shear amplitude -> KH waves
- even larger shear amplitude -> wave breaking, onset of turbulence
- there is a critical condition associated with flow instability

Flows through forest canopies

Surface Layer (SL)



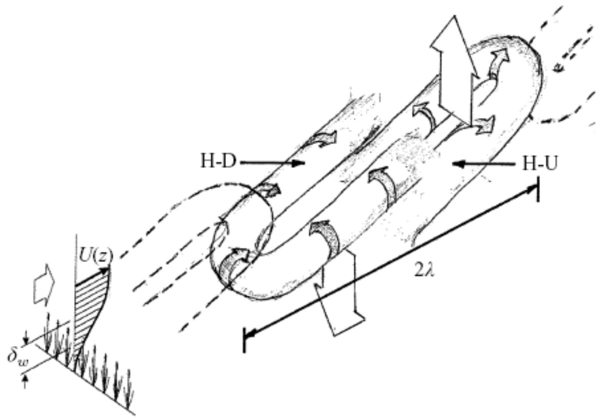
I. Harman and J.J. Finnigan, 2007, adapted



J.J. Finnigan, R.H. Shaw, and
E.G. Patton, 2009

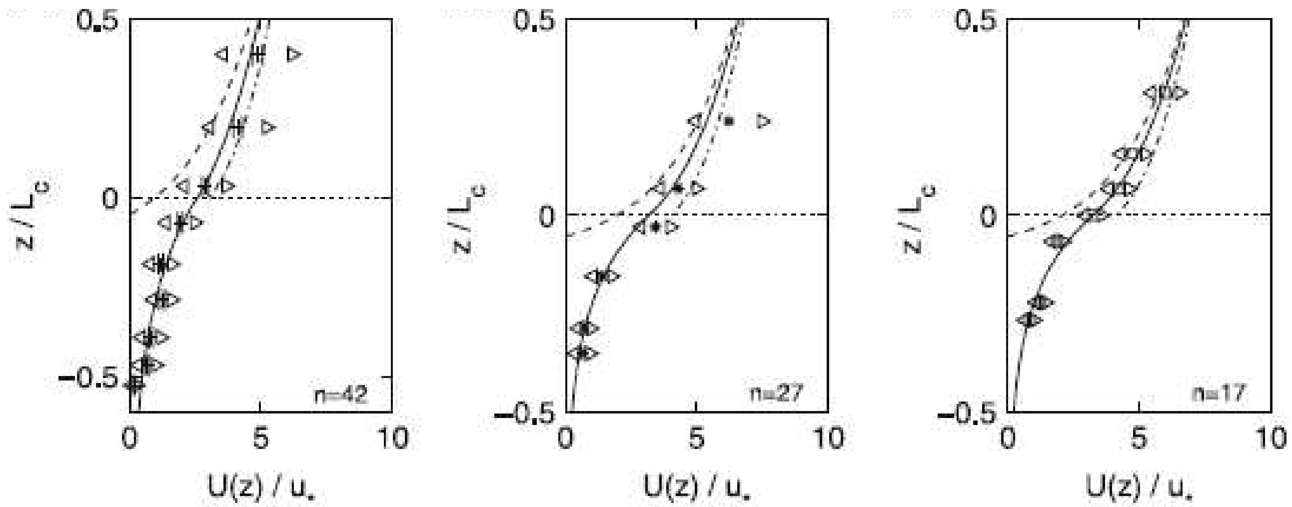
Flows through forest canopies

- canopy flow fundamentally differs from flow in the logarithmic layer: scaling of turbulence moments does not depend on distance from the ground but is dependent length and velocity scales related to canopy geometry



$$\lambda \propto \delta_w = 2 \frac{U_h}{\left.\frac{\partial U}{\partial z}\right|_h}$$

Flows through forest canopies



Tumbarumba Duke Forest Moga Forest

I. Harman and J.J.Finnigan, 2007

Air Flow in Complex Terrain

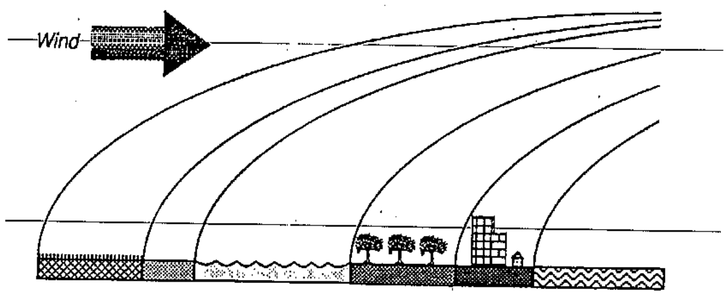
The Problem: Systematic bias can occur when measuring with single towers in complex terrain

Complex terrain generates complex flows that violate the default assumption of horizontal homogeneity.

Three particular situations are important in the context of biosphere-atmosphere exchange:

- Changing surfaces
- Topography
- Stable Stratification

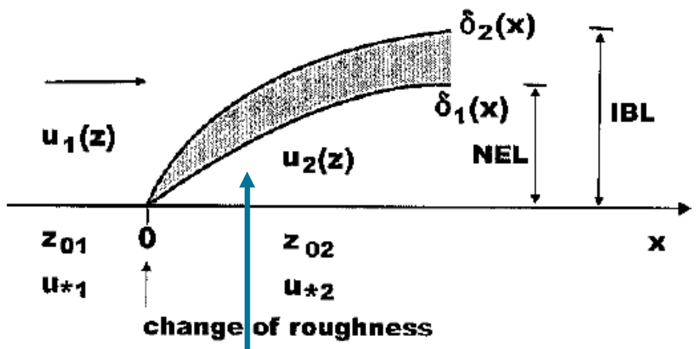
Air Flow in Complex Terrain Changing Surfaces



Internal boundary layers are significantly developed disturbance layers in the near-surface layer, which are generated by horizontal advection over discontinuities of the surface properties (roughness, thermal properties, ...)

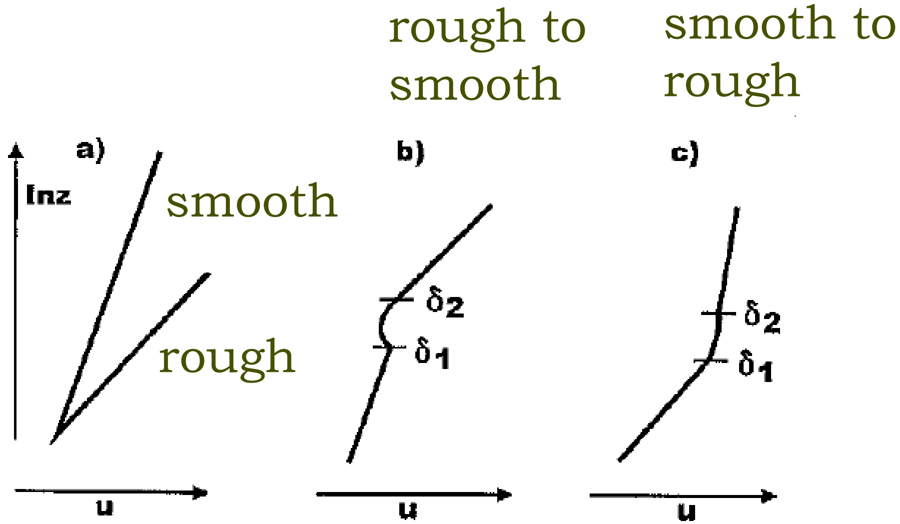
Th. Foken, 2008

Air Flow in Complex Terrain Changing Surfaces

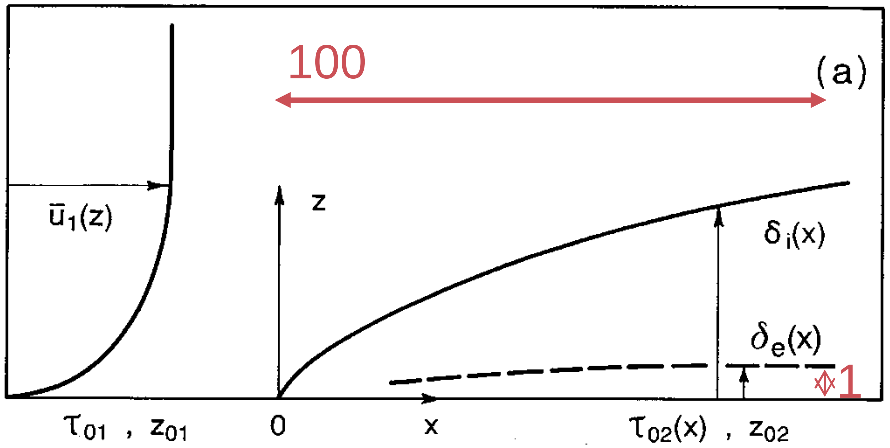


Th. Foken, 2008

New equilibrium layer is where we want to measure!



Air Flow in Complex Terrain Changing Surfaces



100:1 fetch rule of thumb
for neutral conditions

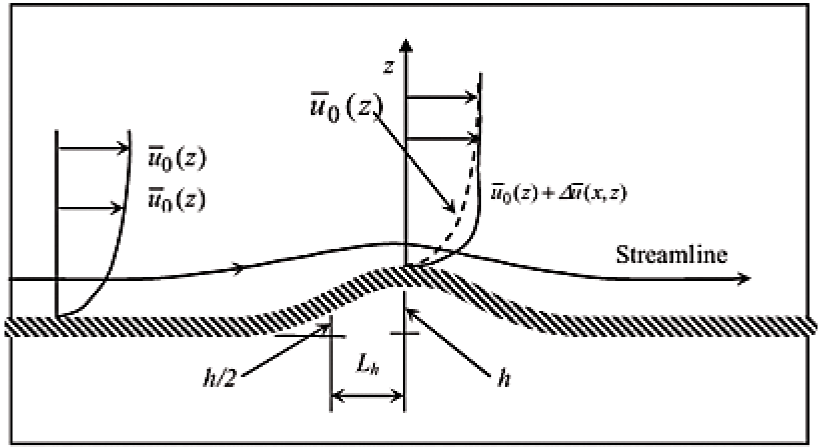
> for stable conditions

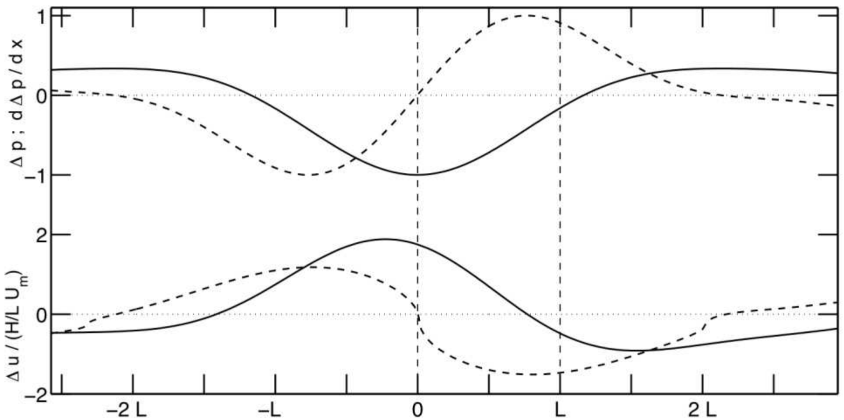
< for unstable conditions

Often the measurement height is a compromise between a representative footprint and avoiding advective effects

Air Flow in Complex Terrain Topography

C.C. Pellegrini and G. C. R. Bodstein, 2004





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

Above the canopy

$$\Delta u \propto -\Delta p$$

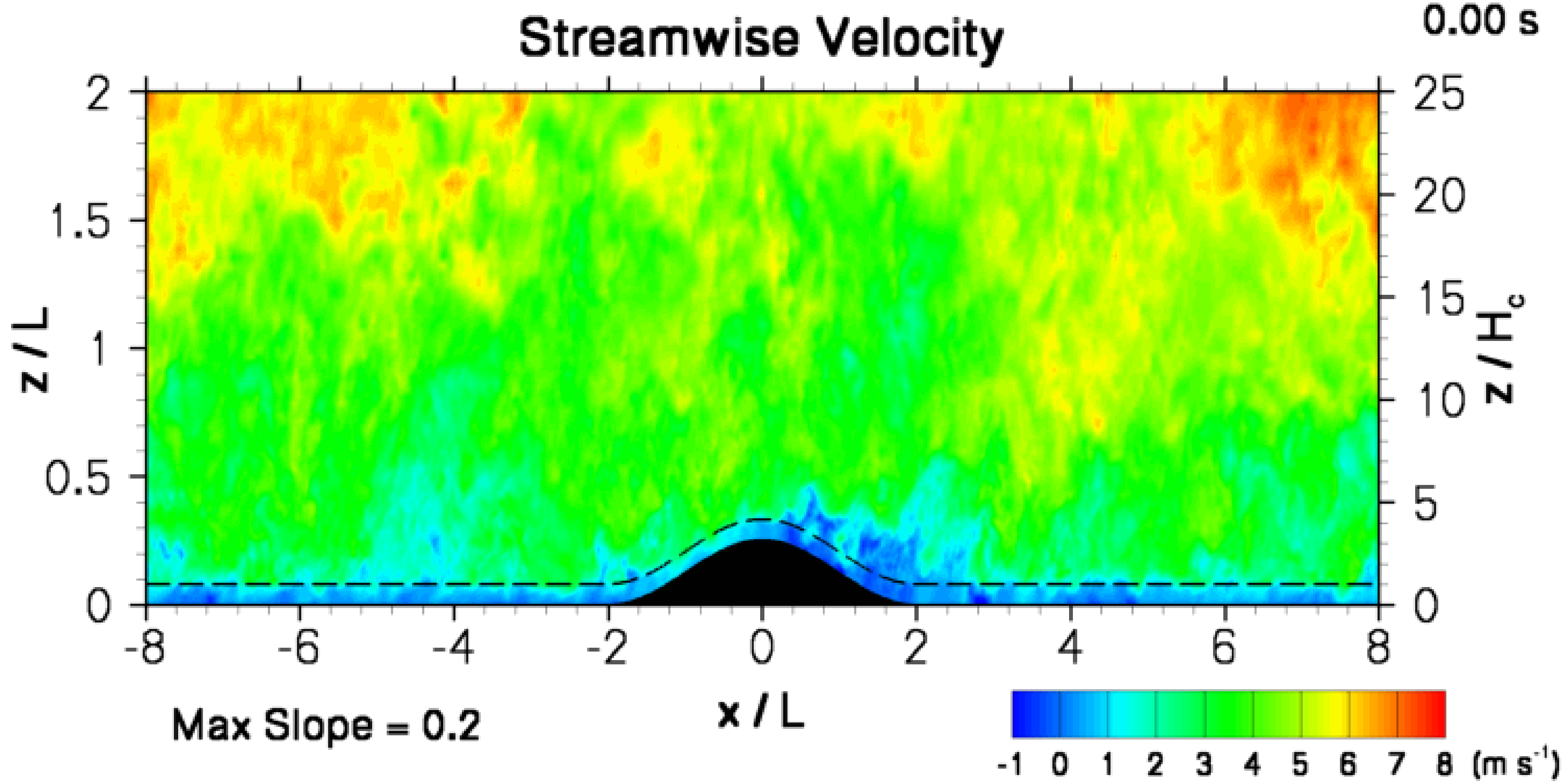
Max wind speed above the hill crest.

Deep in the canopy

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

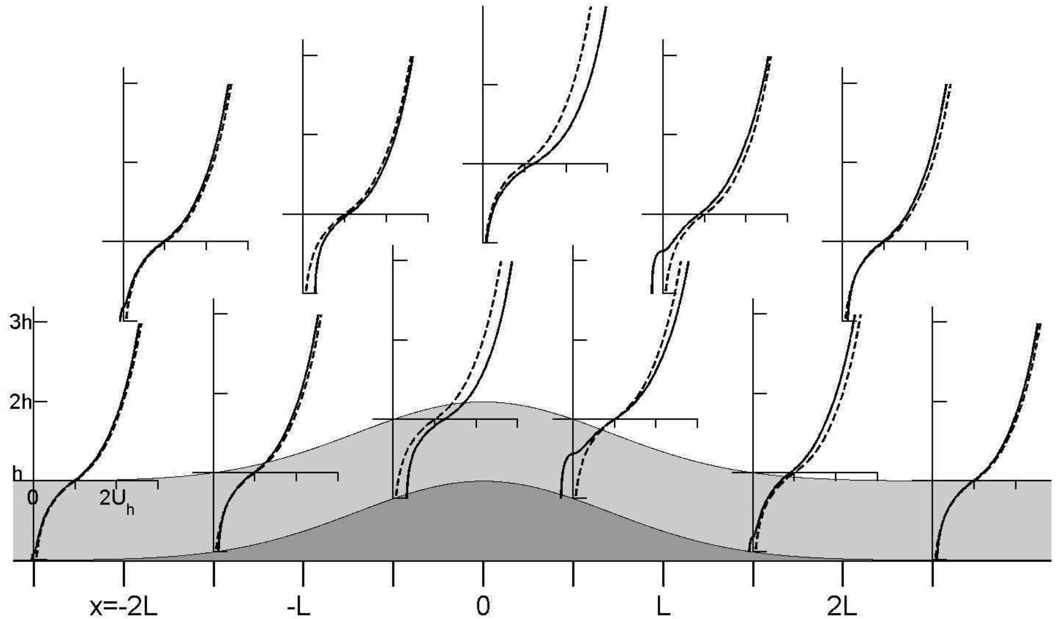
Max Δu on up and downwind slopes.

Reversed flow possible deep in the canopy.



- Courtesy Dr Ned Patton, NCAR

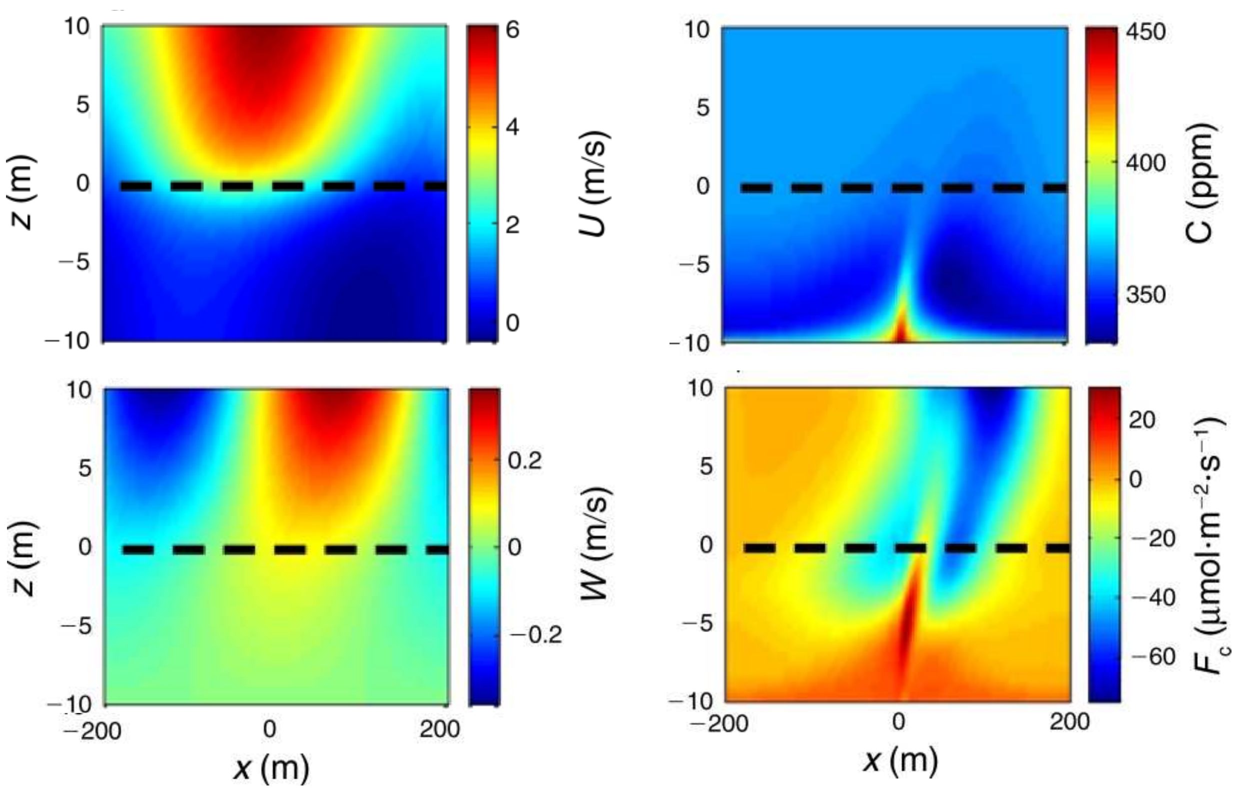
Air Flow in Complex Terrain Topography



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

This tendency for the wind to blow toward the crest of the hill on both the upwind and lee slopes within the canopy leads to a convergence of air at the crest of the hill. There is then an ejection of air out of the top of the canopy at the crest of the hill.

Air Flow in Complex Terrain Topography



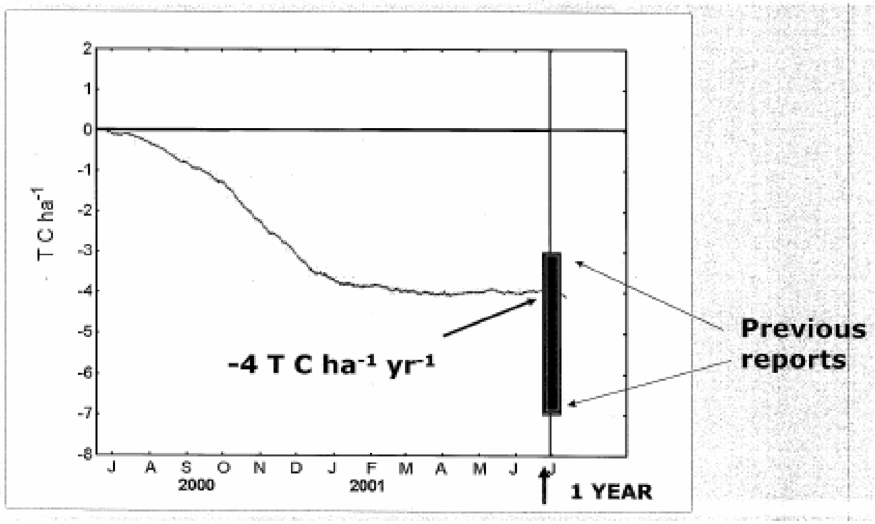
G. Katul et al. (2006)

Nocturnal Flow Overview

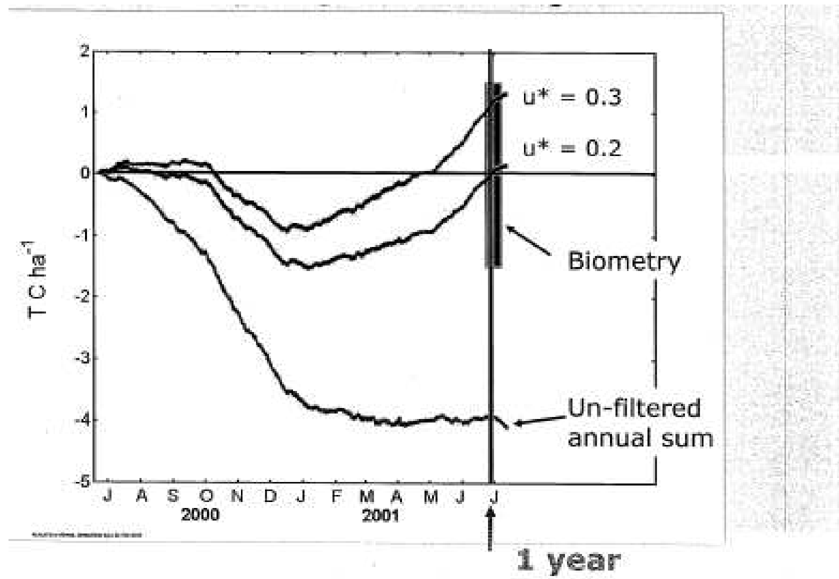
Why do we treat nocturnal flows separately?

Net daytime and nighttime fluxes of CO_2, are often of similar magnitude but opposite in sign. Hence systematic errors in one of the terms can lead to large errors in annual ecosystem carbon budget.

The **Uncorrected calculation** indicates a large carbon sink, similar to previous reports.



u* corrected tower flux agrees with Biometry – There is no evidence that the primary forest was a large Carbon sink.



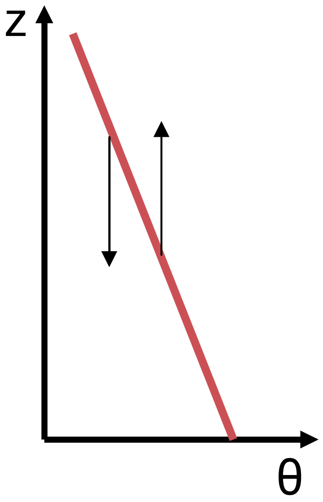
Measurements from Santarem LBA site courtesy of Prof Mike Goulden

Nocturnal Flow Overview

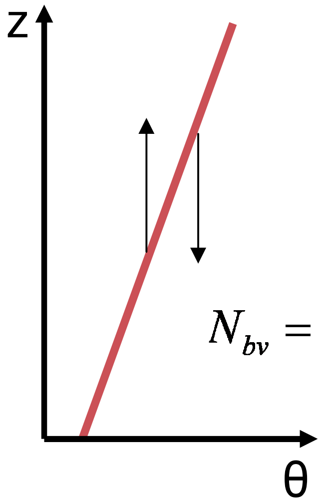
What's going on?

Mechanisms of turbulence generation/consumption:

- Shear production of turbulence $s = \left(\frac{\partial U}{\partial z}\right)^2$
- Buoyant production /consumption of turbulence $b = \frac{g}{T_0}\frac{\partial \theta}{\partial z}$



Statically unstable



Statically stable

$$N_{bv} = \sqrt{\frac{g}{T_0}\frac{\partial \theta}{\partial z}}$$

Dynamic stability:
Richardson number

$$Ri = \frac{g}{T_0}\frac{\partial \theta / \partial z}{(\partial U / \partial z)^2}$$

$Ri < 0$, unstable

$0 < Ri < 0.25$, neutral

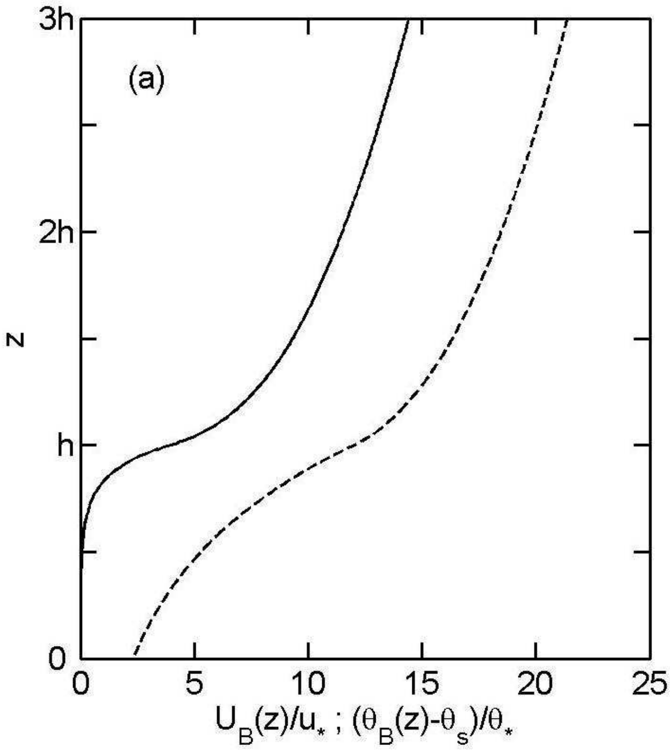
$Ri > 0.25$, turbulence can not be maintained

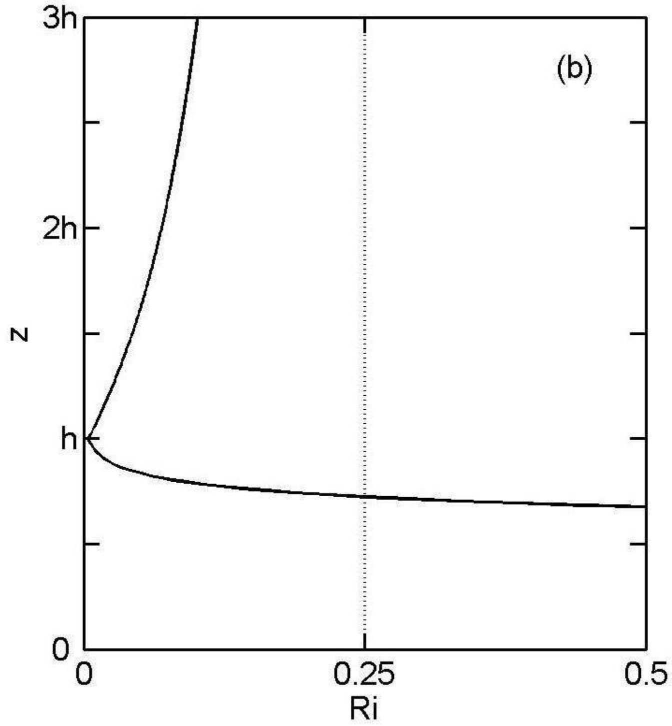
Nocturnal Flow

- Is there mixing between in-canopy and above-canopy flow? Is u* a good indicator or do we need alternatives?

- Cold air drainage: how do we know when it occurs and can we make use of this knowledge? Is u* a good indicator or do we need alternatives?

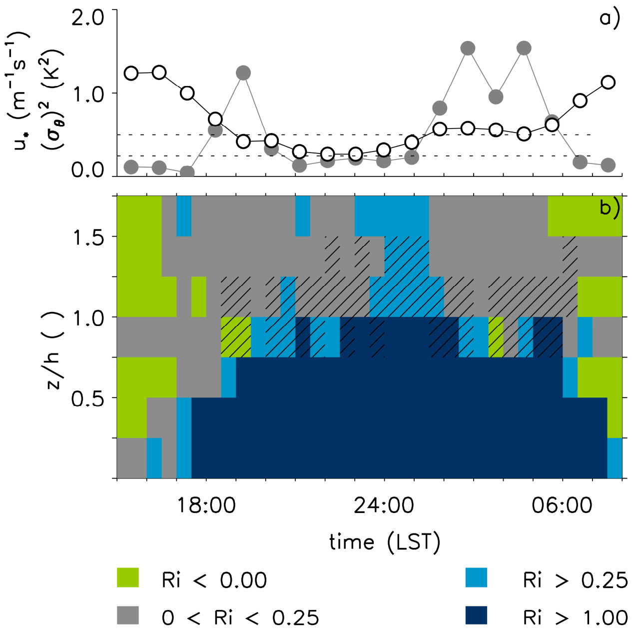
Nocturnal Flow collapse of turbulence/decoupling





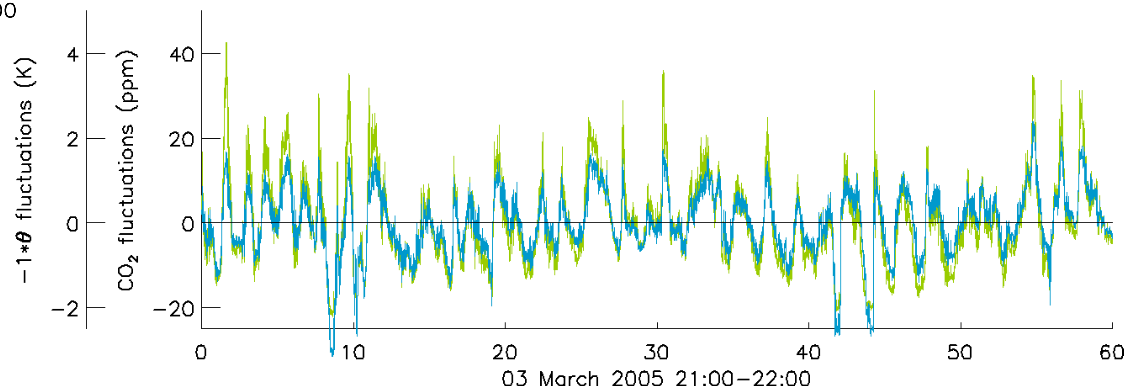
Belcher et al. 2007. Ecol.Applications

Nocturnal Flow collapse of turbulence/decoupling



van Gorsel et al.2006

$$N_{bv} = \sqrt{\frac{g}{T_0}\frac{\partial \theta}{\partial z}}$$



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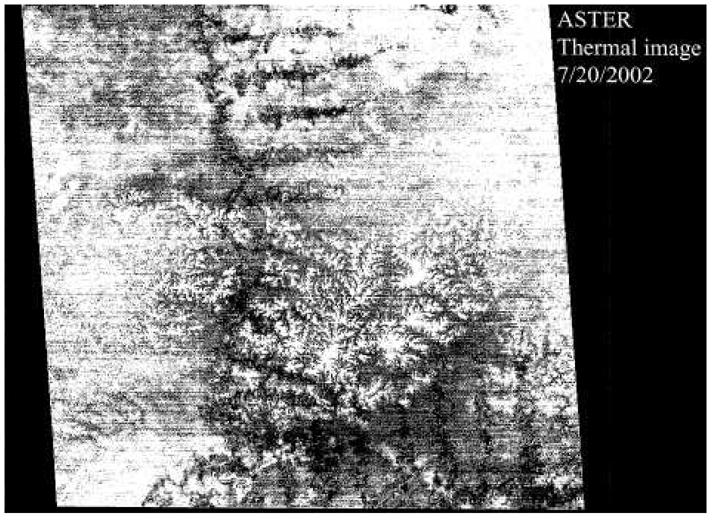
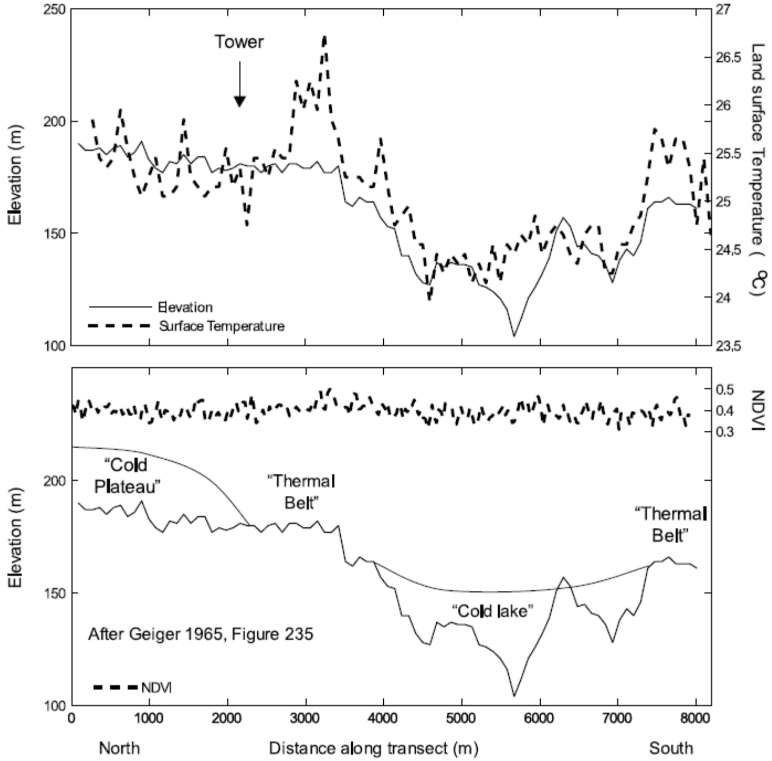
Nocturnal Flow Cold air drainage

M. Goulden et al., 2006





Santarem LBA site. Valleys in topographic map coincide with cold areas in ASTER thermal image suggesting cold air drainage. Similar corroborating evidence exists from many sites.

Nocturnal Flow Cold air drainage: when does it occur?

Governing equation of the longitudinal velocity component :

$$\frac{D\bar{u}}{Dt} = 0 = -\frac{\partial \bar{p}}{\partial x} + \frac{g}{T_0}(\Delta\bar{\theta} sin\alpha) + f\bar{v} - \frac{\partial \tau}{\partial z} - \frac{|\bar{u}|\bar{u}}{L_c}$$

i ii iii iv v

i. hydrodynamic pressure gradient Pd
ii. Hydrostatic pressure gradient Ph
iii. Coriolis force
iv. Turbulent stress Fs
v. Canopy drag force Fd

0 = -Pd +Ph –Fs-Fd

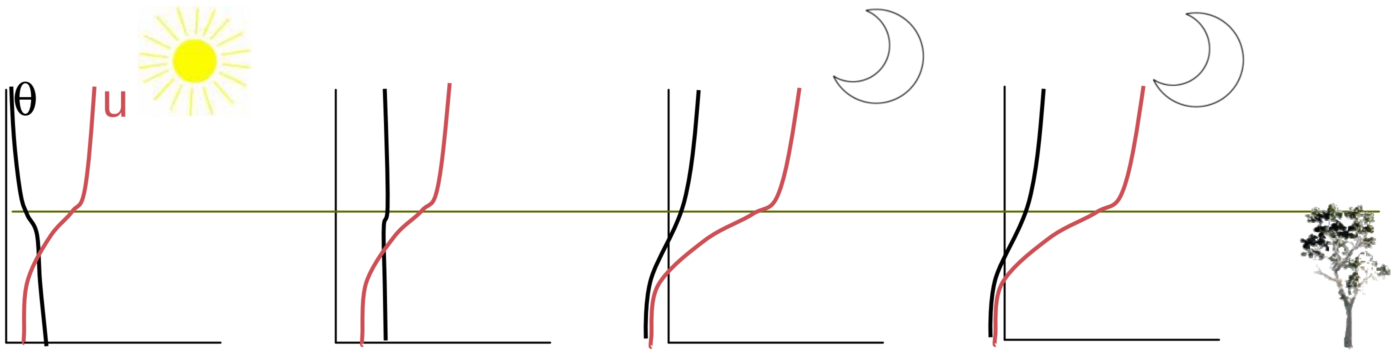
Nocturnal Flow

Cold air drainage: when does it occur? $0 = -Pd + Ph - Fs - Fd$

- How do wind and temperature profile develop through the day?
- What terms in the governing equation of the longitudinal velocity are important?
- What terms in the mass balance are important and need to be considered?

Nocturnal Flow

Cold air drainage: when does it occur? $0 = -P_d + P_h - F_s - F_d$



$$F_c = \overline{c_d}\,\overline{w'\chi_c'}$$

$$F_c = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^h \overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}\,dz$$

$$F_c = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^h \overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}\,dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{uc_d}\,\overline{\frac{\partial \chi_c}{\partial x}} + \overline{vc_d}\,\overline{\frac{\partial \chi_c}{\partial y}} + \overline{wc_d}\,\overline{\frac{\partial \chi_c}{\partial z}}\right] dx\,dy\,dz$$

Nocturnal Flow

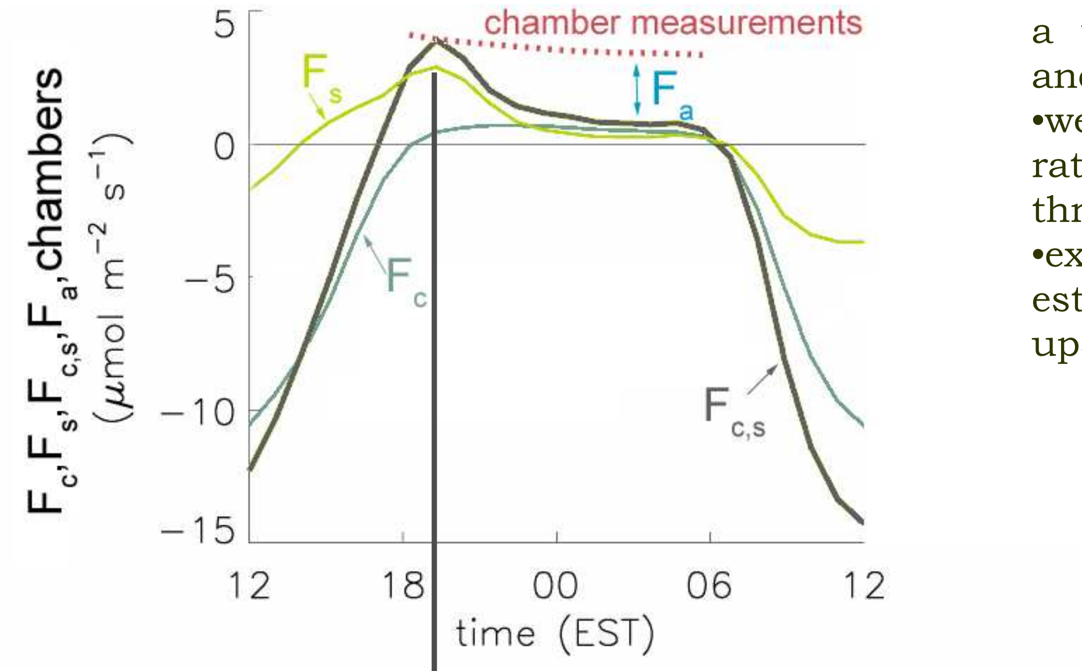
- Radiative cooling leads to collapse of the canopy turbulence after sundown. Once turbulent mixing has stopped, the canopy air layer cools faster

- The canopy flow decouples from the flow above and becomes a competition between the hydrodynamic and hydrostatic pressure gradients with the resultant flow opposed by the drag of the foliage

- As cooling continues, the hydrostatic forcing wins and begins to drive the airflow downhill, carrying CO2-rich air sideways past the tower (Watanabe: 4h)

- Can the hiatus between the decoupling of the turbulence and the onset of the gravity be exploited to get a physically more sounder method of measuring nighttime respiration?

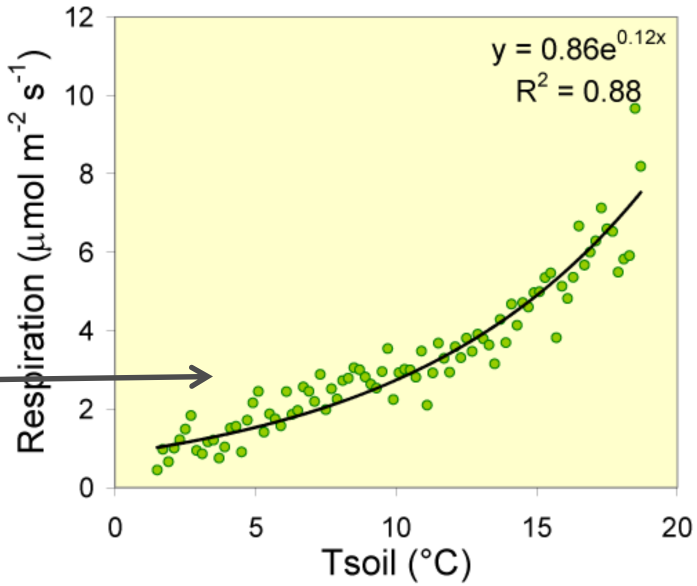
Nocturnal Flow alternative to u*-filtering



Tested on 25 tower flux sites covering a wide range of vegetation, climate and topographic conditions:

•we found higher nocturnal respiration rates than estimated with u*-threshold filter

•excellent agreement with independent estimates such as ones derived from upscaled chamber measurement



van Gorsel et al., 2009

Nocturnal Flow summary

- Complex terrain generates complex flows – advection terms must be considered.
- Rules exist for the minimum fetch needed for adjustment.
- Flow through tall canopies on hills is complicated due to multiple physical processes.
- Many (most?) flux sites cannot close carbon balance at night – u* filters and biological models are commonly used instead.
- Intrinsic dynamics of canopies promote gravity currents –and advection of CO2 sideways away from tower. Delay to onset of gravity current can be exploited.

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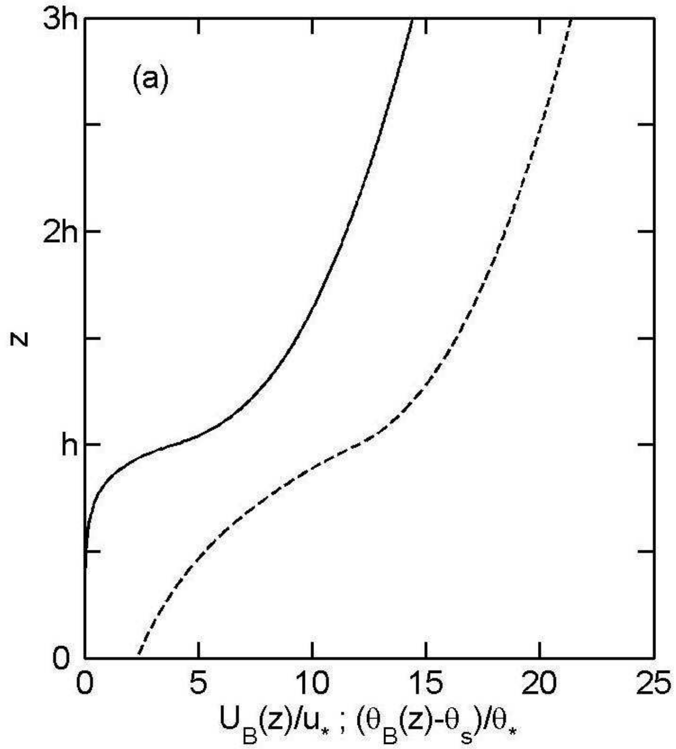
THANK YOU

advection diffusion equation



$$U\frac{\partial C}{\partial x}+W\frac{\partial C}{\partial z}=\mathrm{X}_C+\frac{\partial F_{cx}}{\partial x}+\frac{\partial F_{cz}}{\partial z}$$

$$\mathrm{X}_C=\frac{a(z)(C_x-C)}{r}$$

Belcher et al. 2007. Ecol.Applications