Characteristics of canopy turbulence during the transition from convective to stable stratification

Eva van Gorsel[1], John Finnigan[1,2], Ian Harman[1,2] and Ray Leuning[1]

24/06/2009

[1] *CSIRO Marine and Atmospheric Research*

[2] *CSIRO Centre for Complex System Science*

Turbulence is a recognisable state of nature but it has no rigid definition; it is rather like certain diseases which are defined by a collection of symptoms called a syndrome. In the case of turbulence these 'symptoms' include randomness with a finite probability density function, strong vorticity, a complex highly three-dimensional velocity field, motion over a large and continuous range of length scales, and greatly increased effective values of viscosity and diffusivity. Many 'chaotic' flows, such as particular kinds of thermal convection, have some, but not all, of these 'symptoms'. **J.Hunt**

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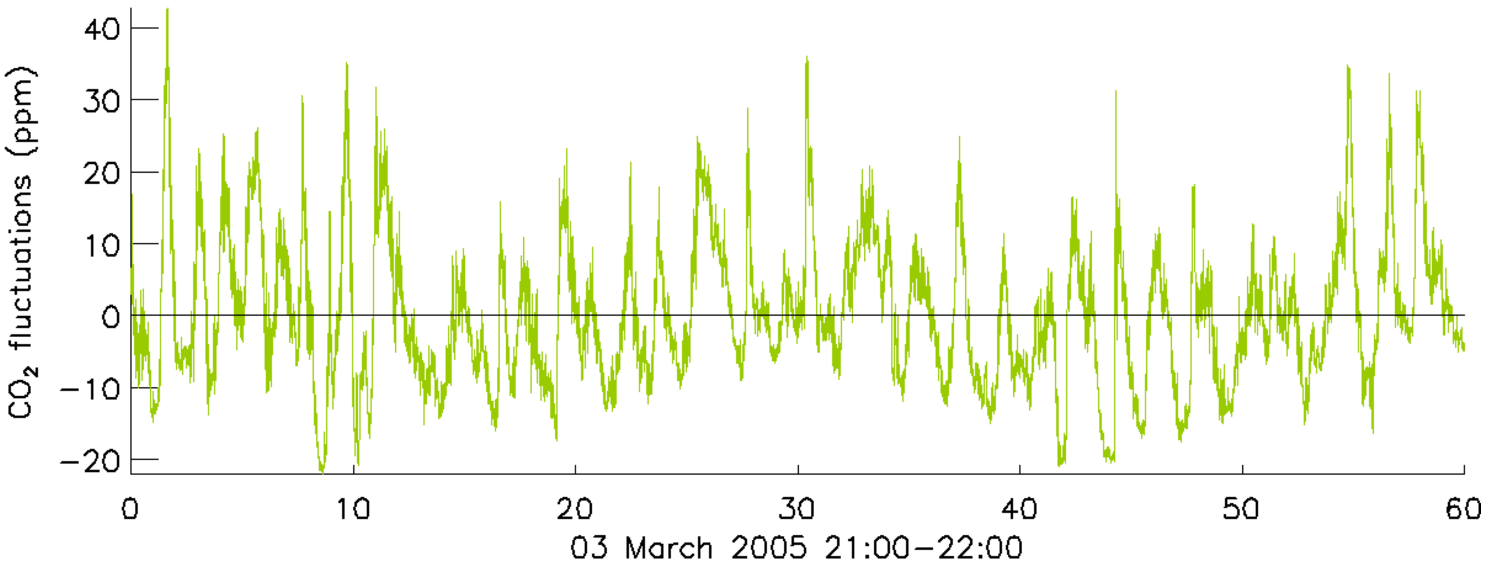
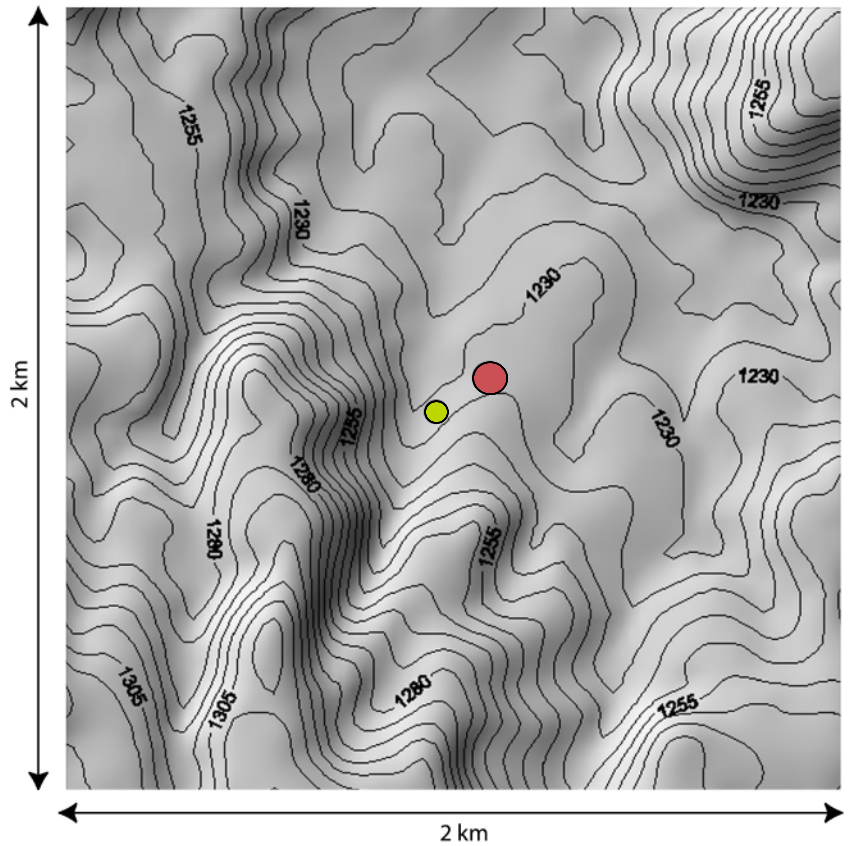
Observation



Questions that we address in this presentation

- What are the origins of these motions?
- Can they be explained with existing theory?
- What are the implications for observations of nocturnal ecosystem exchange?

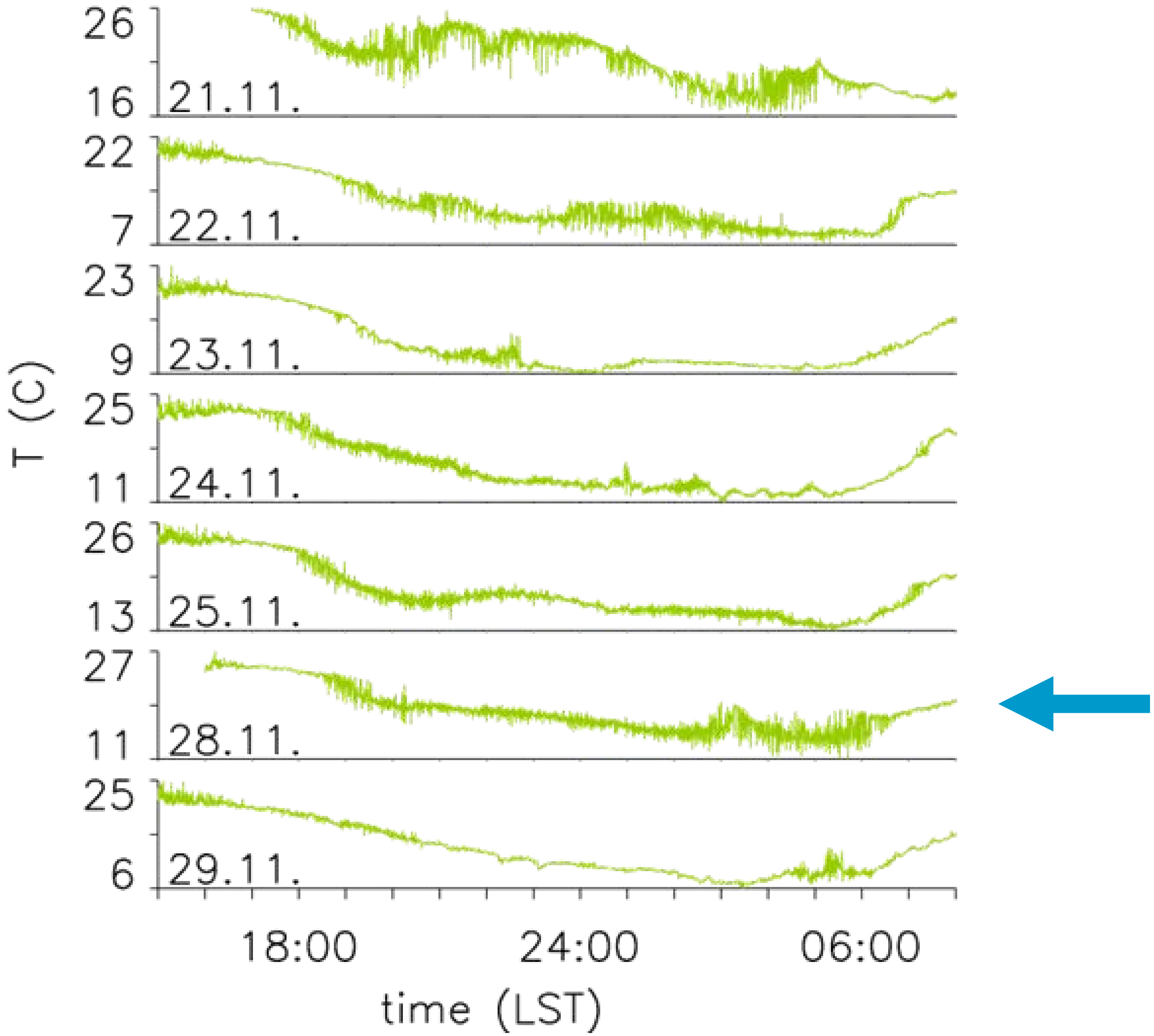
Experimental layout



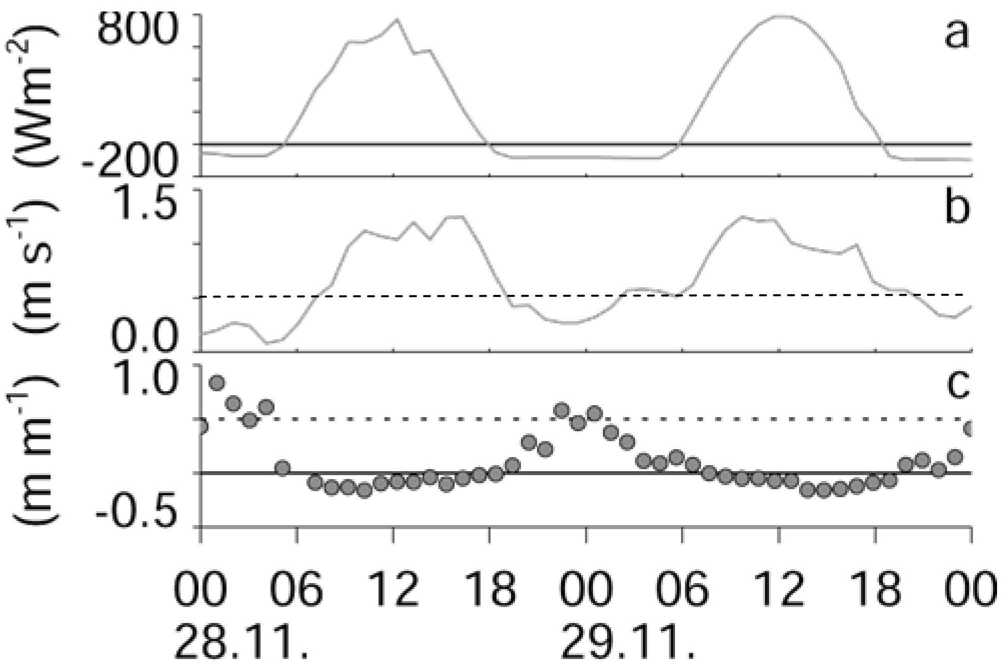
Profiles
temperature (Type T Thermocouples)
wind (2D Gill Windsonics)
0.5, 4.5, 10.5, 18.5, 34.5, 42.5, 54.5, 70 m

Profiles
temperature (Type T Thermocouples)
wind (3D Sonics)
0.8, 1.4, 2.2, 2.9, 4.4, 5.8, 10.8 m

Time series sub-canopy temperature (10 m)



Meteorological conditions

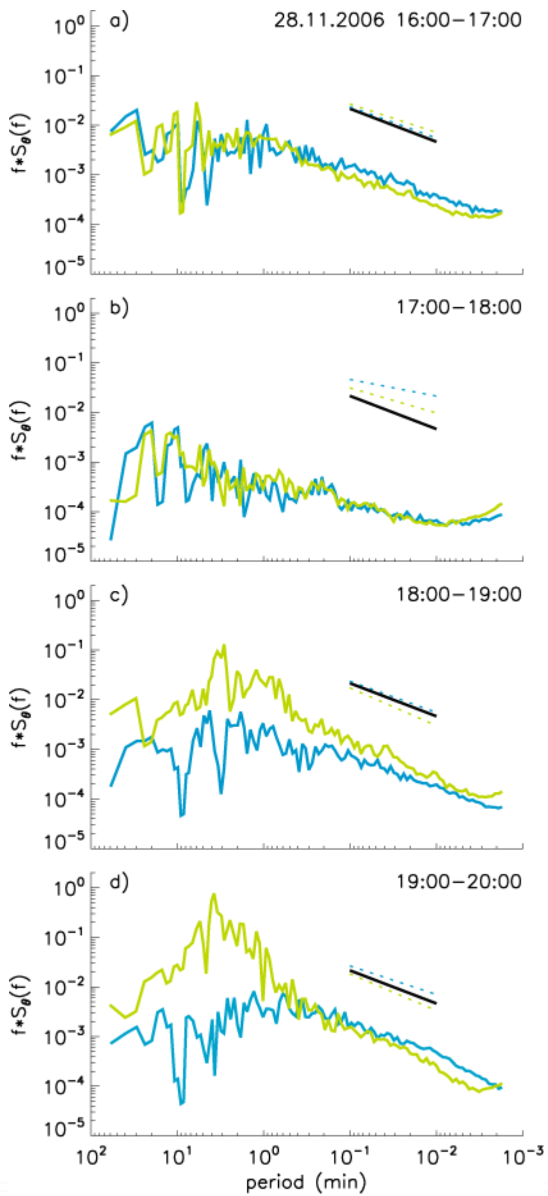


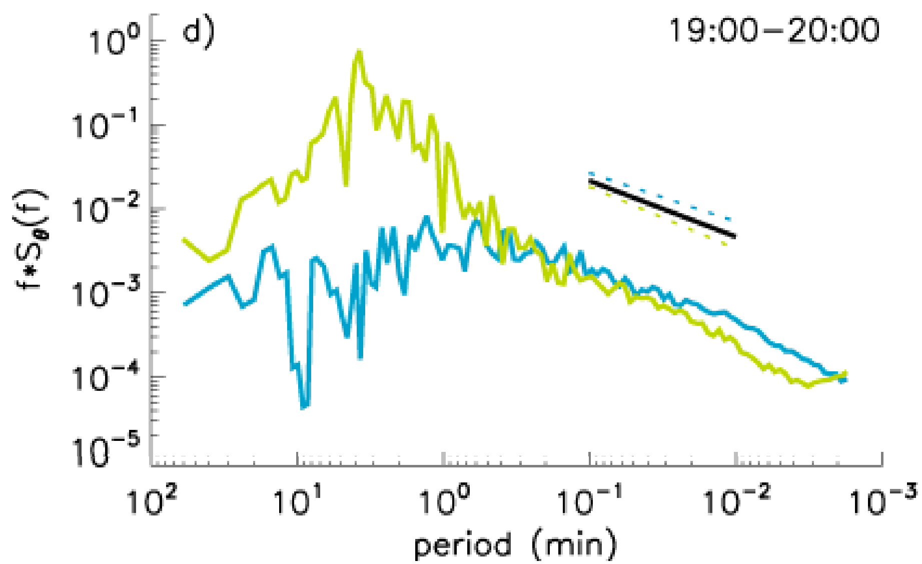
net radiation

friction velocity

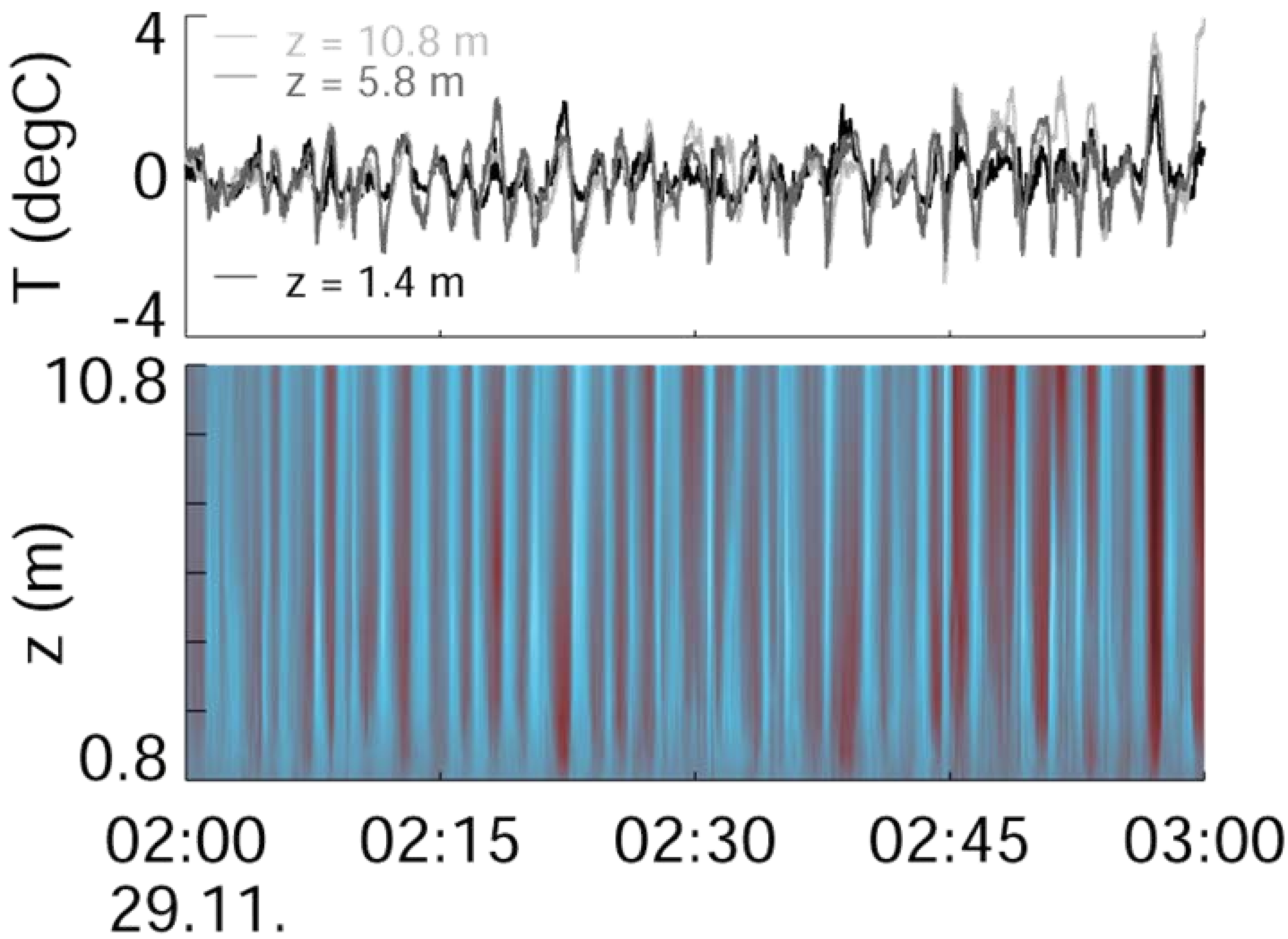
Monin-Obhukov length

Above and within canopy temperature spectra





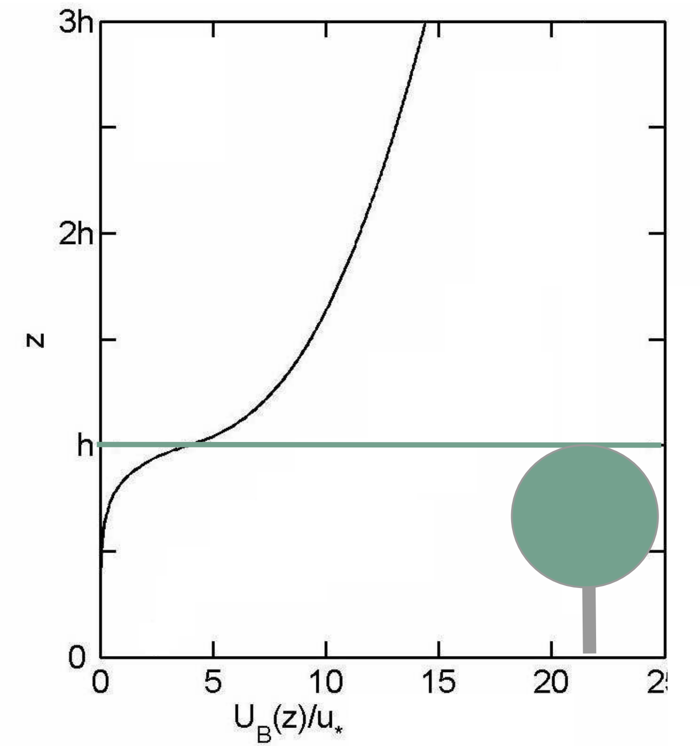
Multi level temperature time series: coherency

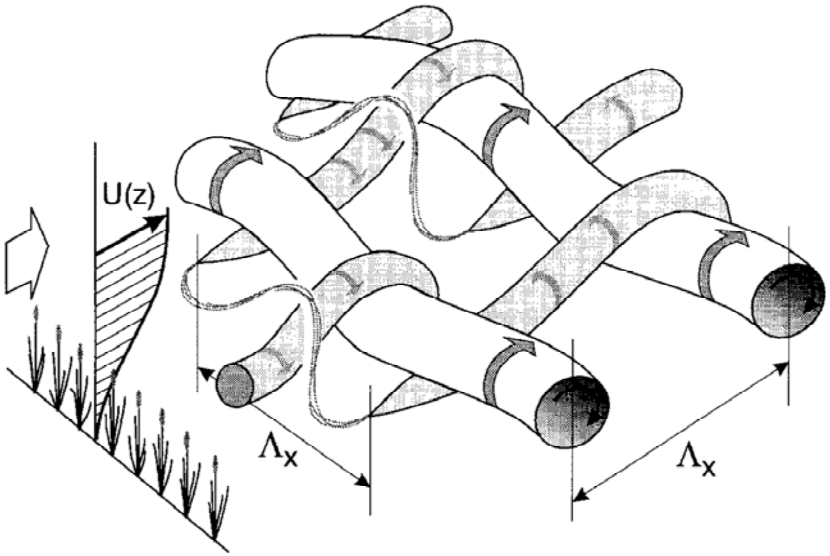


Gravity waves?

- How do canopy waves develop?
- Can we explain their amplitude and periodicity?
- Why are they observed in the canopy only and not above?

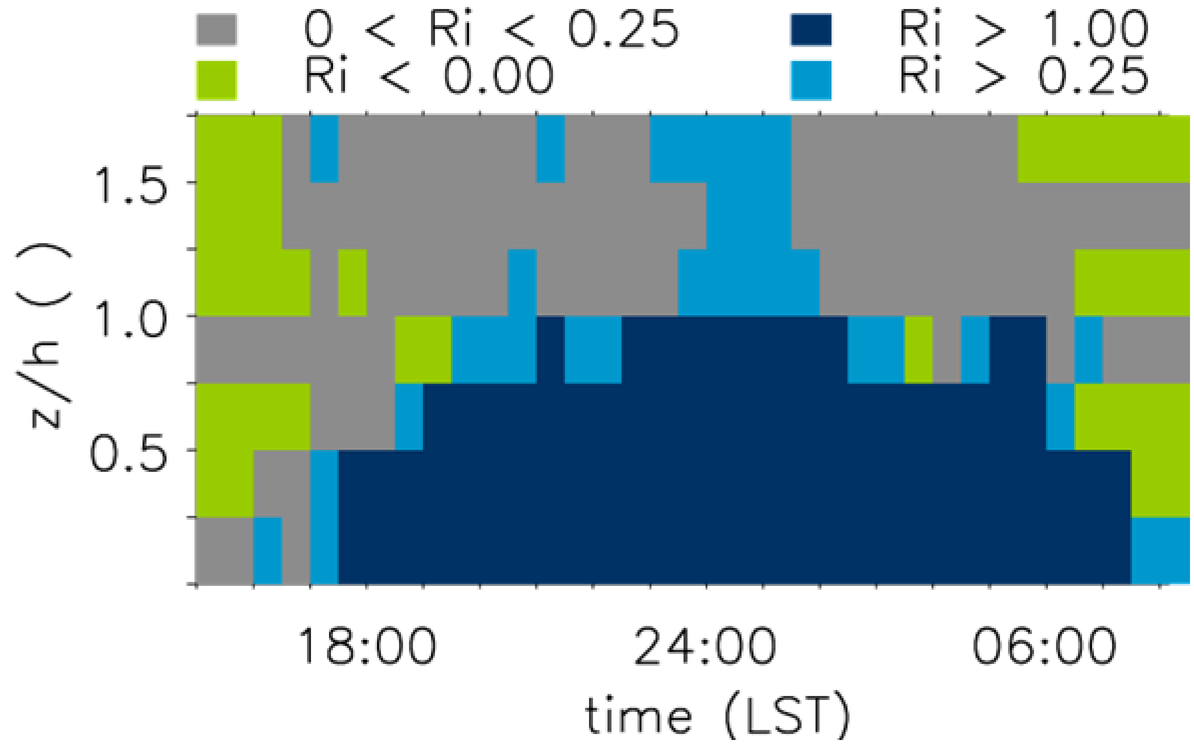
Profiles of wind speed and their influence on hydrodynamic stability



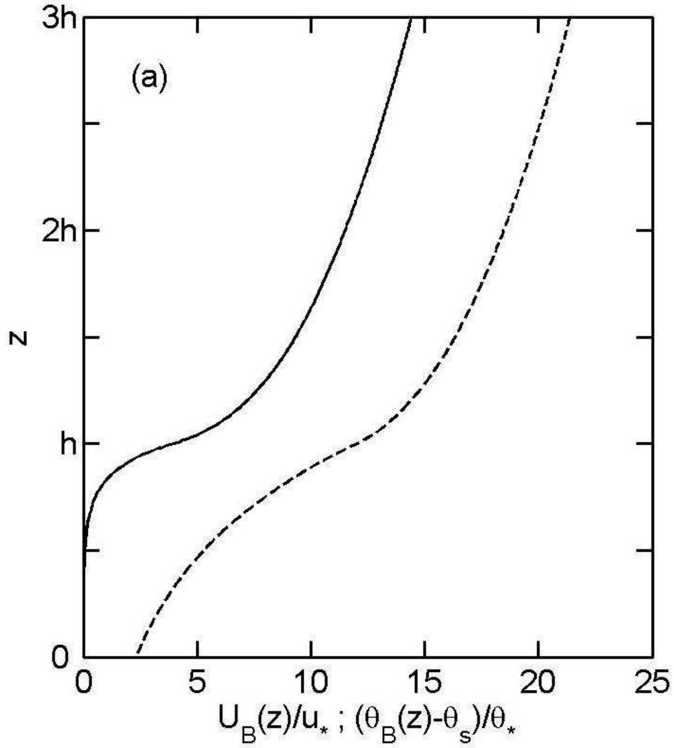


Raupach et al.1996. BLM
Finnigan 2000. Ann. Rev. Fluid Mech.

Development of stability



Profiles of wind speed and temperature and their influence on hydrodynamic stability

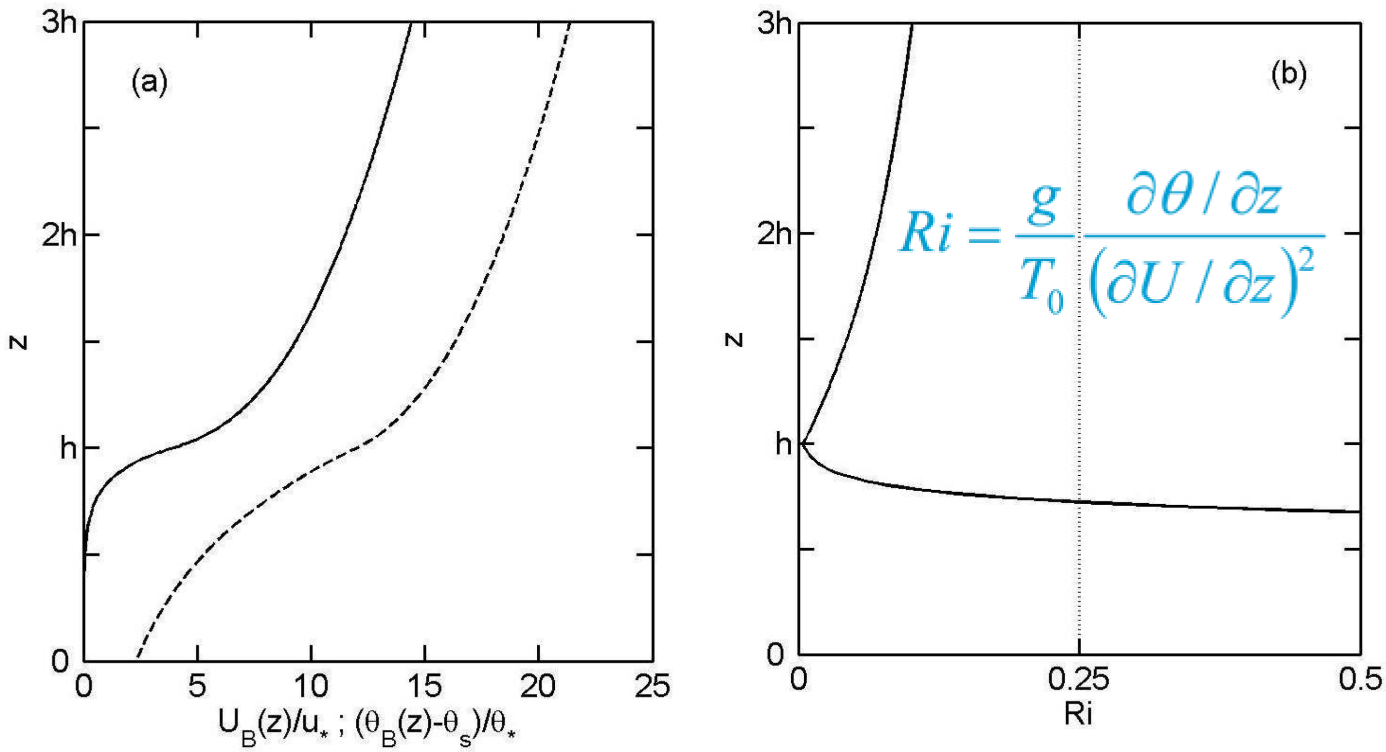


$$\cancel{U\frac{\partial C}{\partial x}} + \cancel{W\frac{\partial C}{\partial z}} = X_C + \cancel{\frac{\partial F_{cx}}{\partial x}} + \frac{\partial F_{cz}}{\partial z}$$

$$X_C = \frac{a(z)(C_x - C)}{r}$$

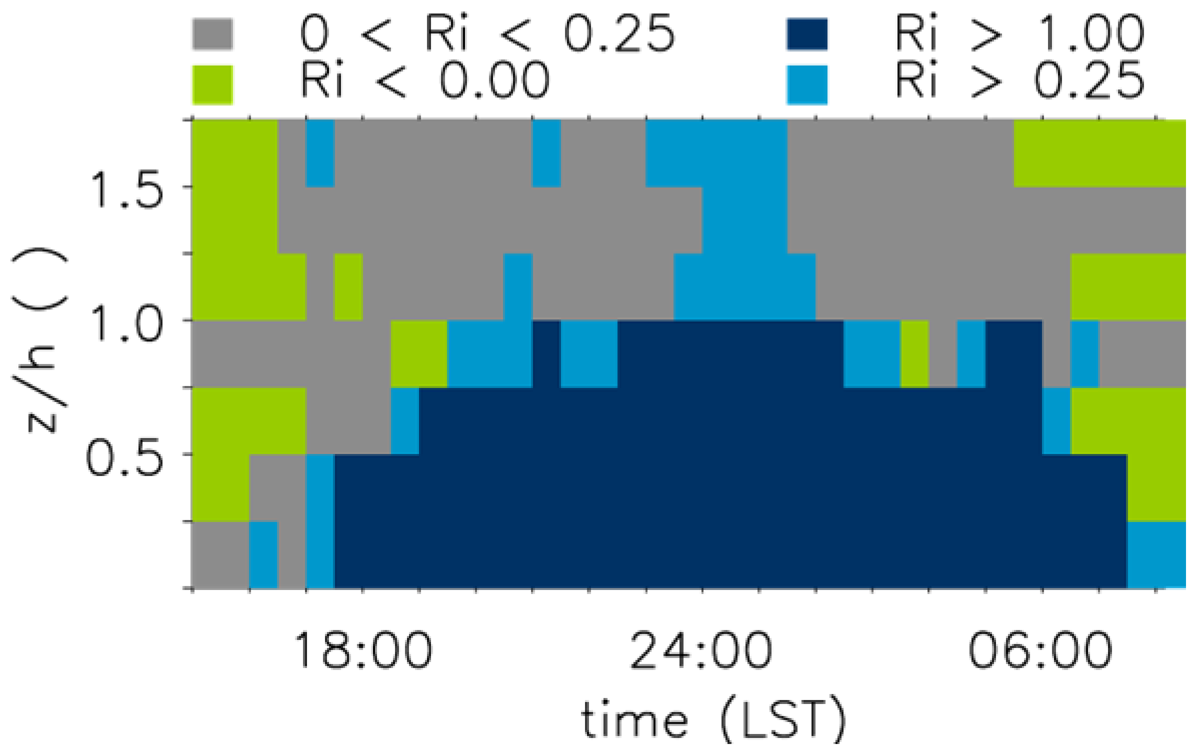
Belcher et al. 2007. Ecol.Applications

Profiles of wind speed and temperature and their influence on hydrodynamic stability

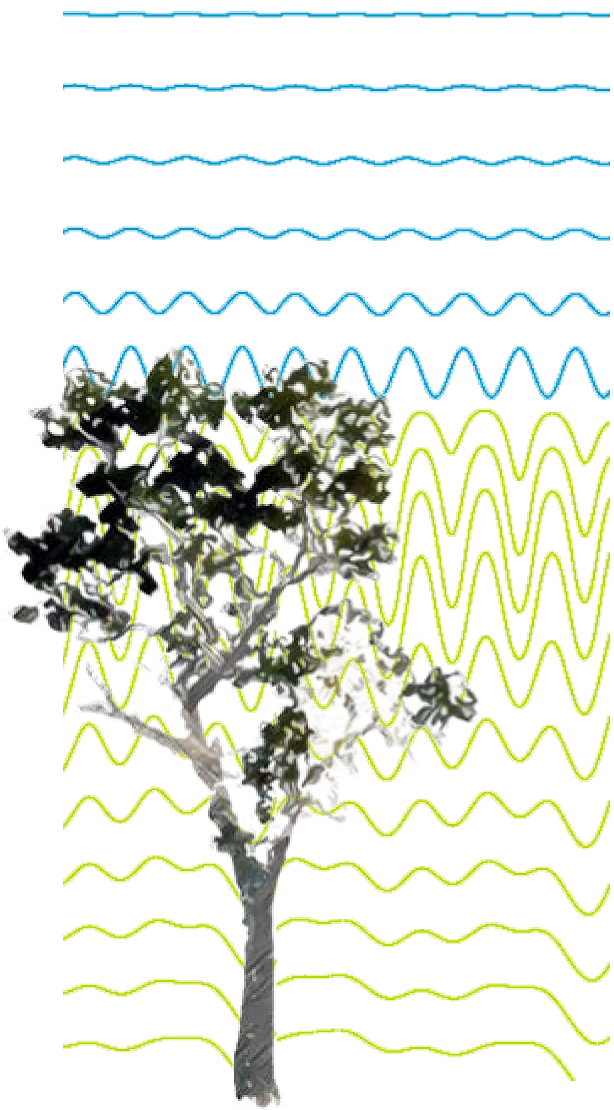


Belcher et al. 2007. Ecol.Applications

Stability distribution a result of different transport mechanisms of momentum and scalars



Amplitude with height



evanescent

Presence of ground: trapped →large amplitude
Role of aerodynamic drag → no complete theory of hydrodynamic stability with non-linear drag exists

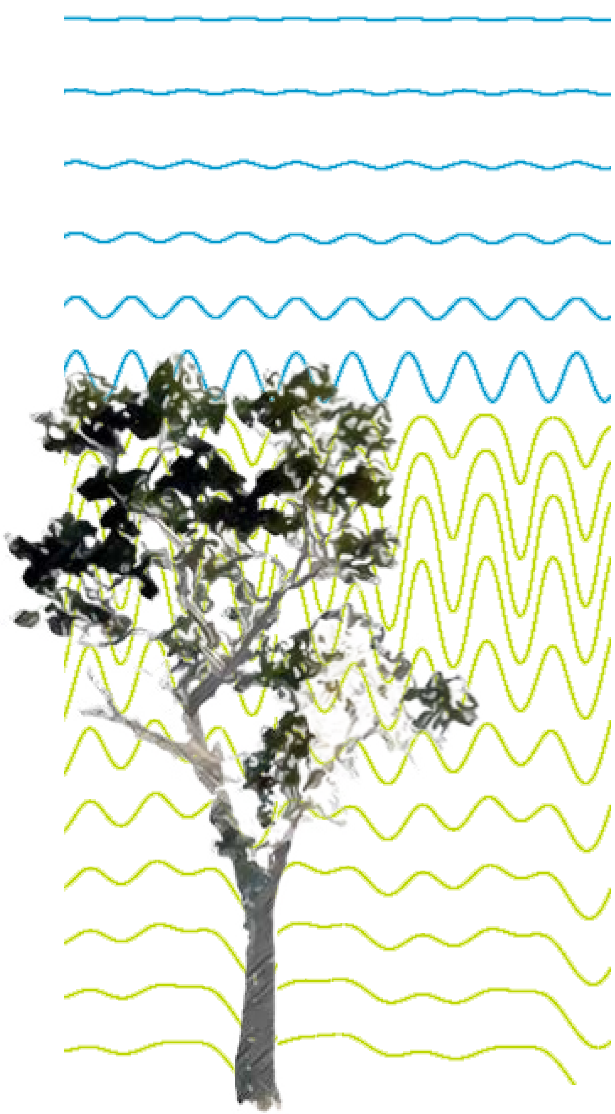
CSIRO canopy turbulence

Brunt–Väisälä frequency

The **Brunt–Väisälä frequency**, or buoyancy frequency,
is the frequency at which a vertically displaced parcel will oscillate
within a statically stable environment.

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

Periodicity



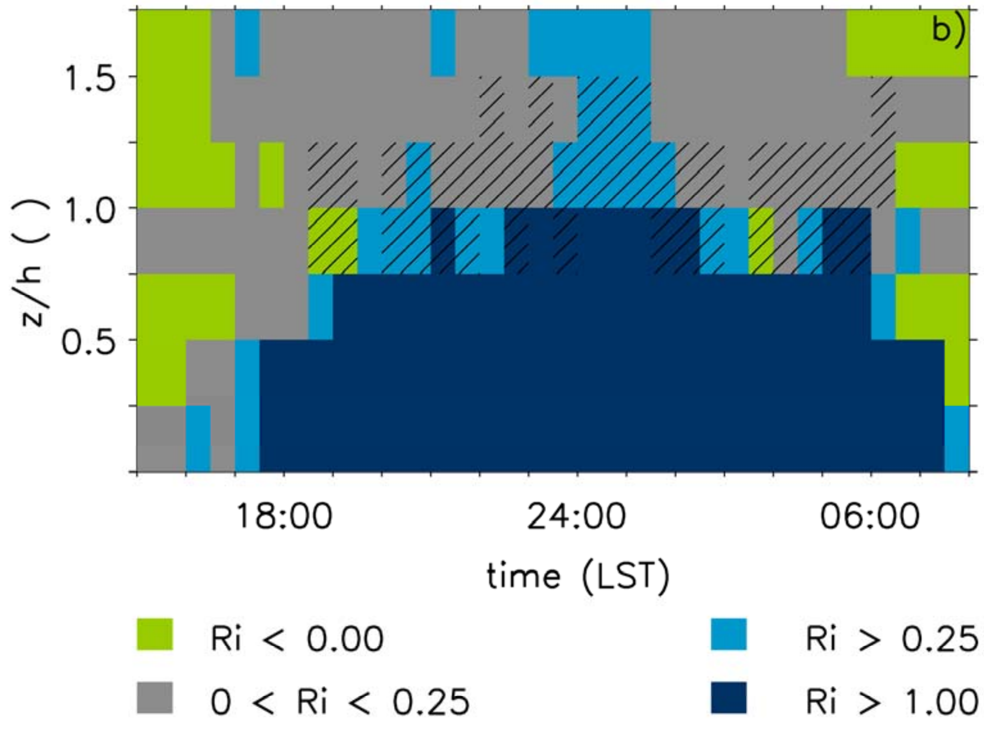
CSIRO canopy turbulence

Carruthers and Hunt (1986):
developed a linear theory at the interface between a turbulent region and a stably stratified layer.

Theory shows that in the stratified layer motions with frequency $f > N$ decay rapidly with distance z from the interface.

Observed buoyancy period $P_{BV}=2\pi/N$ at the interface (98 ± 23 s) corresponds nicely with period of observed coherent motions.

Horizontal phase speed and direction of wave propagation



Summary

Above canopy flow can support turbulence while in canopy flow is very stable and decoupled.

Due to shear instability at canopy top we find that
DESPITE SUPPRESSED TURBULENCE IN-CANOPY SCALAR FLUCTUATIONS CAN BE VERY SUBSTANTIAL

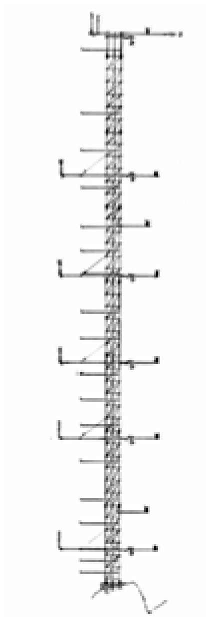
This must be considered when measuring land atmosphere exchange:

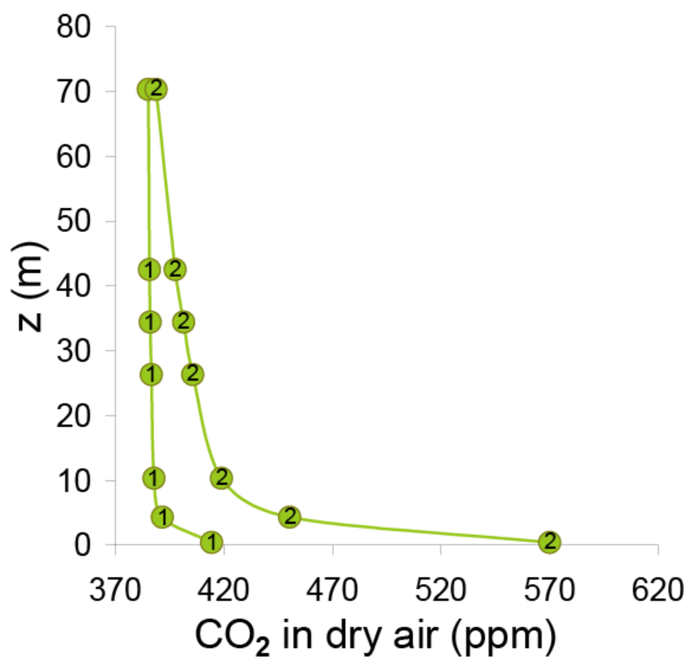
Conclusions

$$\left\langle \overline{S}_s \right\rangle = \overline{c_d}\,\overline{w'\chi_s'} + \int_0^{h_r} \overline{c_d}\,\frac{\overline{\partial \chi_s}}{\partial t}\,dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^{h_r}\left[\overline{uc_d}\,\frac{\overline{\partial \chi_s}}{\partial x} + \overline{vc_d}\,\frac{\overline{\partial \chi_s}}{\partial y} + \overline{wc_d}\,\frac{\overline{\partial \chi_s}}{\partial z}\right]dz\,dy\,dx$$

Conclusions

$$\langle \overline{S}_s \rangle = \overline{c_d}\,\overline{w'\chi_s'} + \int_0^{h_r} \overline{c_d}\,\frac{\overline{\partial \chi_s}}{\partial t}\,dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^{h_r}\left[\overline{uc_d}\,\frac{\partial\overline{\chi_s}}{\partial x} + \overline{vc_d}\,\frac{\partial\overline{\chi_s}}{\partial y} + \overline{wc_d}\,\frac{\partial\overline{\chi_s}}{\partial z}\right]dzdydx$$





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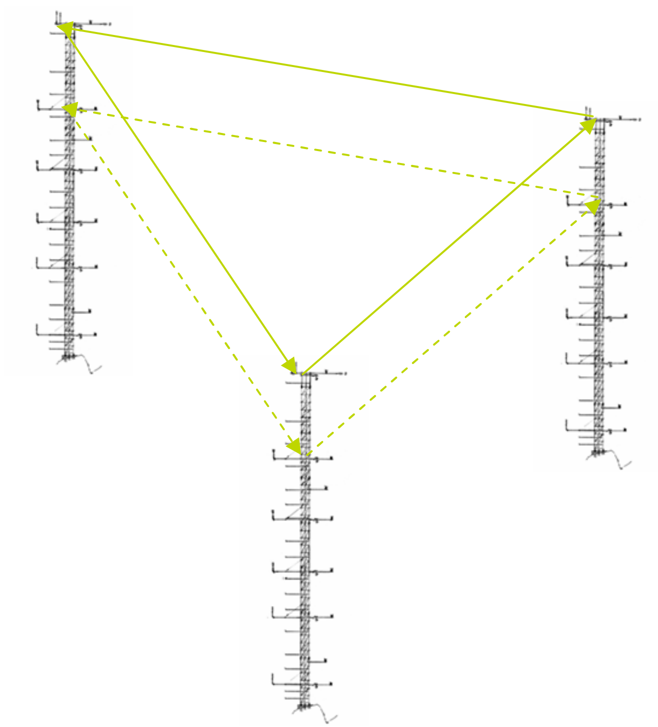
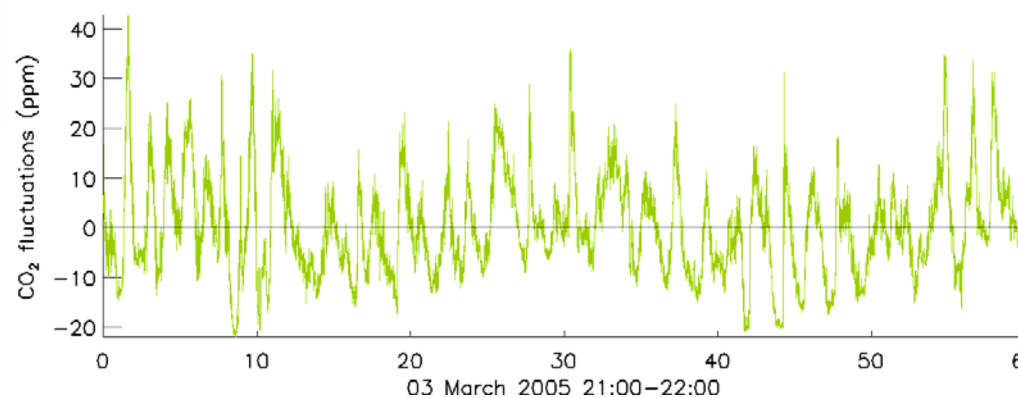


$$H_A \propto \frac{\Delta \chi_s}{\Delta x}, \frac{\Delta \chi_s}{\Delta y}$$



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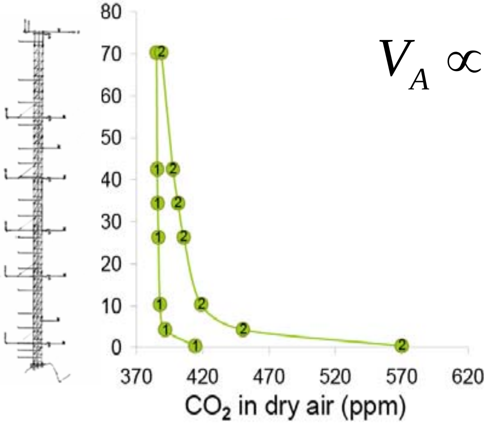


$$V_A \propto \left(\overline{\chi}_{s,r} - \langle \chi \rangle\right)$$

Conclusions

Scalar fluctuations lead to increased random errors.

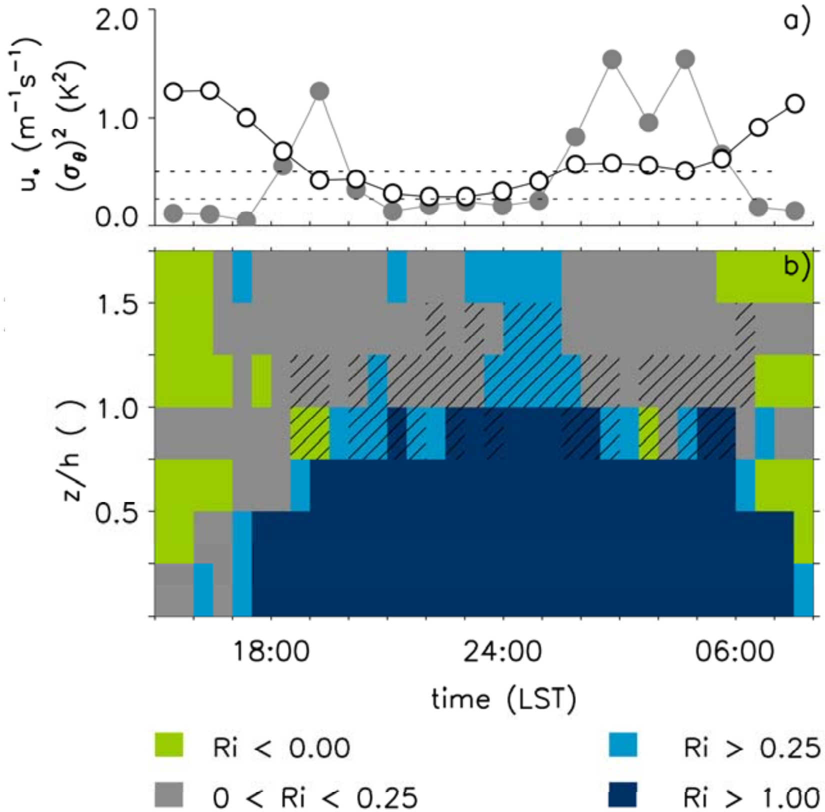
Improvements (experimental):

- Careful experimental design
- Faster instruments (and subsequent filtering)
- Novel techniques

Improvements (theory):

- Include drag, static stability, presence of ground into linear stability analysis

Conclusions



Above canopy u* is > 0.5ms^{-1} but the flow within the canopy

- remains decoupled from the flow above
- is subject to large amplitude waves

CSIRO Marine and Atmospheric Research
Eva van Gorsel

www.csiro.au

Thank you

Contact Us
Phone: 0437 574 389 **or** +61 2 6246 5611
Email: eva.vangorsel@csiro.au **Web:** www.cmar.csiro.au

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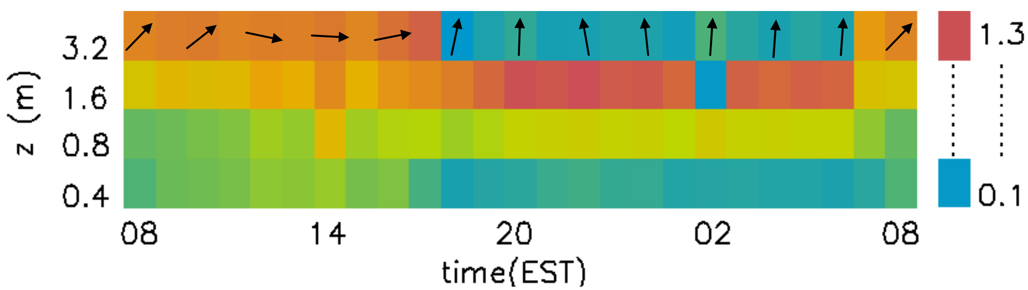
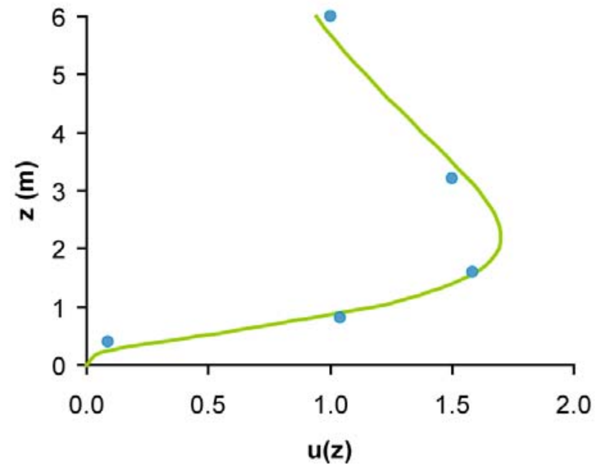
Development of drainage flows

Under stable conditions when turbulence has collapsed drainage flows develop when the hydrostatic pressure gradient outbalances the sum of hydrodynamic pressure gradient and canopy drag

Tumbarumba 06-13.03.2005

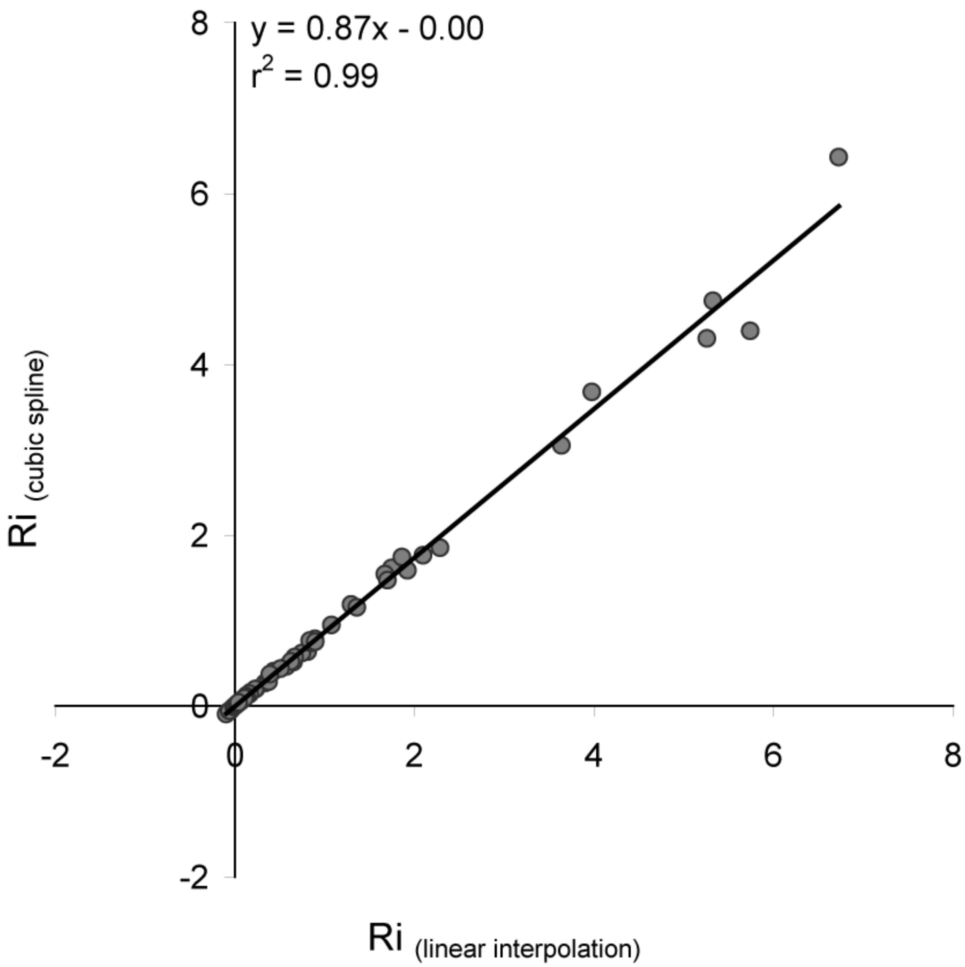




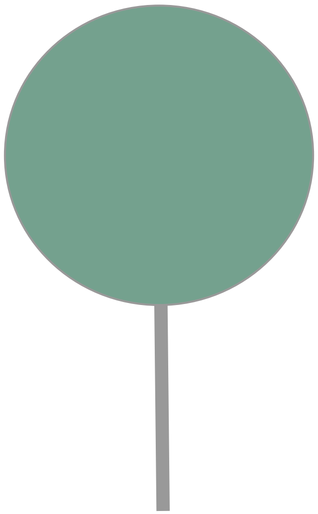
wind velocities *u(z)* normalized with *u(6m)*

and wind direction. Slope wind direction is ↑

Error in Ri due to interpolation



Terms contributing to WKE and TKE



$$\frac{\partial \overline{e}}{\partial t} = \frac{g}{\overline{\theta}_v}\left(\overline{w'\theta_v'}\right) - \overline{u'w'}\frac{\partial \overline{U}}{\partial z} - \frac{\partial\left(\overline{w'e'}\right)}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

$$\frac{\partial \overline{e}}{\partial t} = \frac{g}{\overline{\theta}_v}\left(\overline{w'\theta_v'}\right) - \overline{u'w'}\frac{\partial \overline{U}}{\partial z} - \frac{\partial\left(\overline{w'e'}\right)}{\partial z} - \frac{1}{\overline{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

Excitation of gravity waves by KH instabilities

$$\partial\theta / \partial z > 0$$

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