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

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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

CO₂ fluctuations (ppm)

03 March 2005 21:00–22:00

CSIRO canopy turbulence
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)
  - Heights: 0.5, 4.5, 10.5, 18.5, 34.5, 42.5, 54.5, 70 m

Profiles
- temperature (Type T Thermocouples)
- wind (3D Sonics)
  - Heights: 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
Development of stability
Profiles of wind speed and temperature and their influence on hydrodynamic stability

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

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

Belcher et al. 2007. Ecol. Applications
Profiles of wind speed and temperature and their influence on hydrodynamic stability

\[ Ri = \frac{g}{T_0} \frac{\partial \theta / \partial z}{\partial U / \partial z}^2 \]
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
The Brunt–Väisälä frequency, or buoyancy frequency, is the frequency at which a vertically displaced parcel will oscillate within a statically stable environment.

\[ \mathcal{N} = \sqrt{\frac{g}{T_0}} \frac{\partial \theta}{\partial z} \]
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 $P_{BV} = \frac{2\pi}{N}$ at the interface ($98 \pm 23$ 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

\[
\langle S_s \rangle = c_d w' \chi_s' + \int_0^{h_r} c_d \frac{\partial \chi_s}{\partial t} dz + \frac{1}{L^2} \iiint_0^L \iiint_0^{h_r} \left[ uc_d \frac{\partial \chi_s}{\partial x} + vc_d \frac{\partial \chi_s}{\partial y} + wc_d \frac{\partial \chi_s}{\partial z} \right] dz dy dx
\]
Conclusions

\[
\langle S_s \rangle = c_d w' \chi_s' + \int_0^{h_r} c_d \frac{\partial \chi_s}{\partial t} \, dz + \frac{1}{L^2} \iiint_0^L \iiint_0^{h_r} \left[ u c_d \frac{\partial \chi_s}{\partial x} + v c_d \frac{\partial \chi_s}{\partial y} + w c_d \frac{\partial \chi_s}{\partial z} \right] \, dz \, dy \, dx
\]
Conclusions

\[
\langle S_s \rangle = \overline{c_d w' \chi_s'} + \int_0^{h_r} c_d \overline{\frac{\partial \chi_s}{\partial t}} \, dz + \frac{1}{L^2} \iiint_0^L L \int_0^{h_r} \left[ \overline{u c_d \frac{\partial \chi_s}{\partial x}} + \overline{v c_d \frac{\partial \chi_s}{\partial y}} + \overline{w c_d \frac{\partial \chi_s}{\partial z}} \right] \, dz \, dy \, dx
\]

\[H_A \propto \frac{\Delta \chi_s}{\Delta x}, \frac{\Delta \chi_s}{\Delta y}\]
Conclusions

\[
\langle S_s \rangle = c_d \bar{w} \bar{\chi}_s + \int_0^{h_r} c_d \frac{\partial \bar{\chi}_s}{\partial t} dz + \frac{1}{L^2} \iiint_0^L \iiint_0^L \left[ u \bar{c}_d \frac{\partial \bar{\chi}_s}{\partial x} + v \bar{c}_d \frac{\partial \bar{\chi}_s}{\partial y} + w \bar{c}_d \frac{\partial \bar{\chi}_s}{\partial z} \right] dz dy dx
\]

\[
V_A \propto \left( \bar{\chi}_{s,r} - \langle \chi \rangle \right)
\]
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 $> 0.5\text{ms}^{-1}$ but

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

\[ y = 0.87x - 0.00 \]

\[ r^2 = 0.99 \]
Terms contributing to WKE and TKE

\[
\frac{\partial \bar{e}}{\partial t} = \frac{g}{\bar{\theta}_v} \left( \frac{w'}{\bar{\theta}_v} \right) - u'w' \frac{\partial \bar{U}}{\partial z} - \frac{\partial (w'e')}{\partial z} - \frac{1}{\bar{\rho}} \frac{\partial (w'p')}{\partial z} - \varepsilon
\]
Excitation of gravity waves by KH instabilities

\[
\partial \theta / \partial z > 0
\]

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