Lecture, 21 Wind and Turbulence, Canopy Air Space, Part II

- Momentum Transfer
  - Conditional Sampling
- Turbulence Spectra in Forests
- Coherent Structures
- K-Theory and Mixing Layer Theory

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So far we have treated the canopy as a big leaf, or elevated plane of momentum transfer. Here we will discuss how the canopy extracts momentum from the wind, and the scales of turbulence

Flux Divergence of Momentum Transfer is a function of the drag coefficient, $\mathbf{C_d}$, leaf area density,**a**, and wind velocity, **u**

$$\frac{\partial \tau(z)}{\partial z} = \frac{\partial \overline{w'u'(z)}}{\partial z} = -\rho C_d a \,|\,\overline{u}\,|\,\overline{U}$$

The Attenuation of Momentum is related to the integral of the Flux Divergence

$$\tau(z) = \tau(h) - \rho \int_z^h C_d a(z) u(z)^2 \, dz$$

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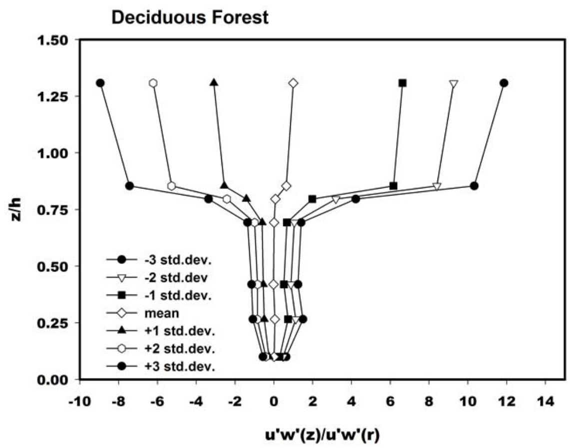
Inside the canopy there is a flux divergence of momentum transfer. It changes with height and it decreases in an exponential manner, like Beer's law for light. The flux divergence for momentum transfer is a function of the drag coefficient of the plant elements, leaf area density (see why we spend so much time on this topic early in this class) and wind velocity squared.

Profiles of shear stress in a deciduous forest.



Note up and down directed momentum transfer

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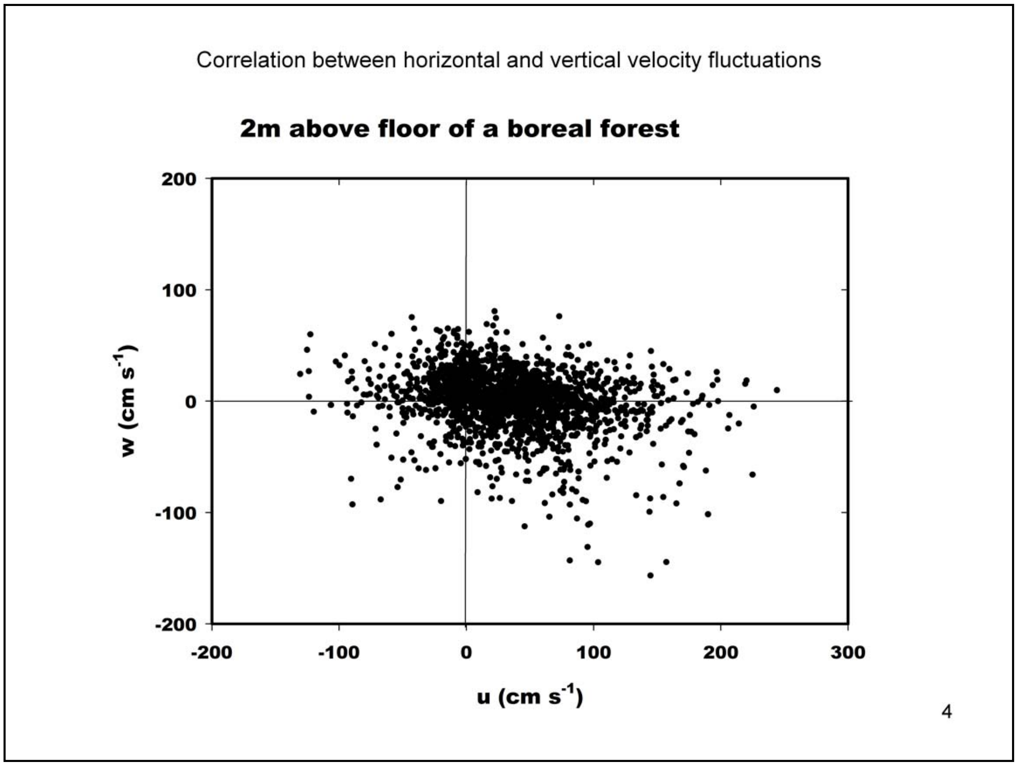
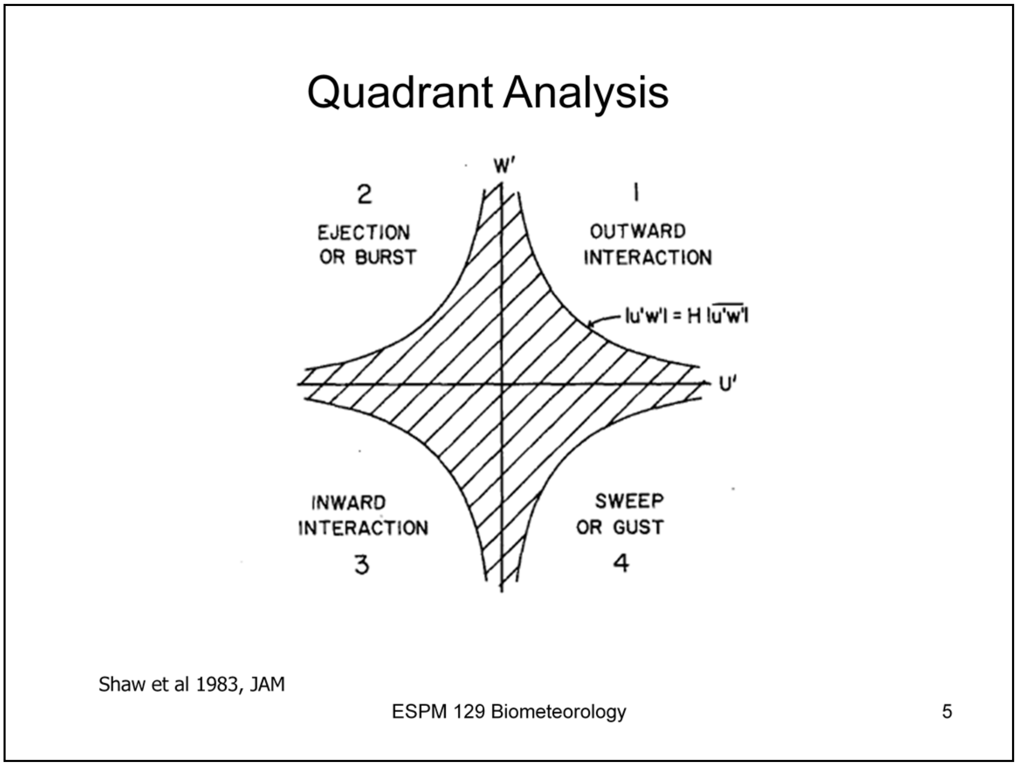
The mean exponential decrease in momentum transfer is determined by a complex and extreme statistics. This is not pretty normal or Gaussian statistics. And even in principle, the surface must be a sink for momentum, we see incidences when there is upward transfer, as the extremes, during ejections. What is happening and why?



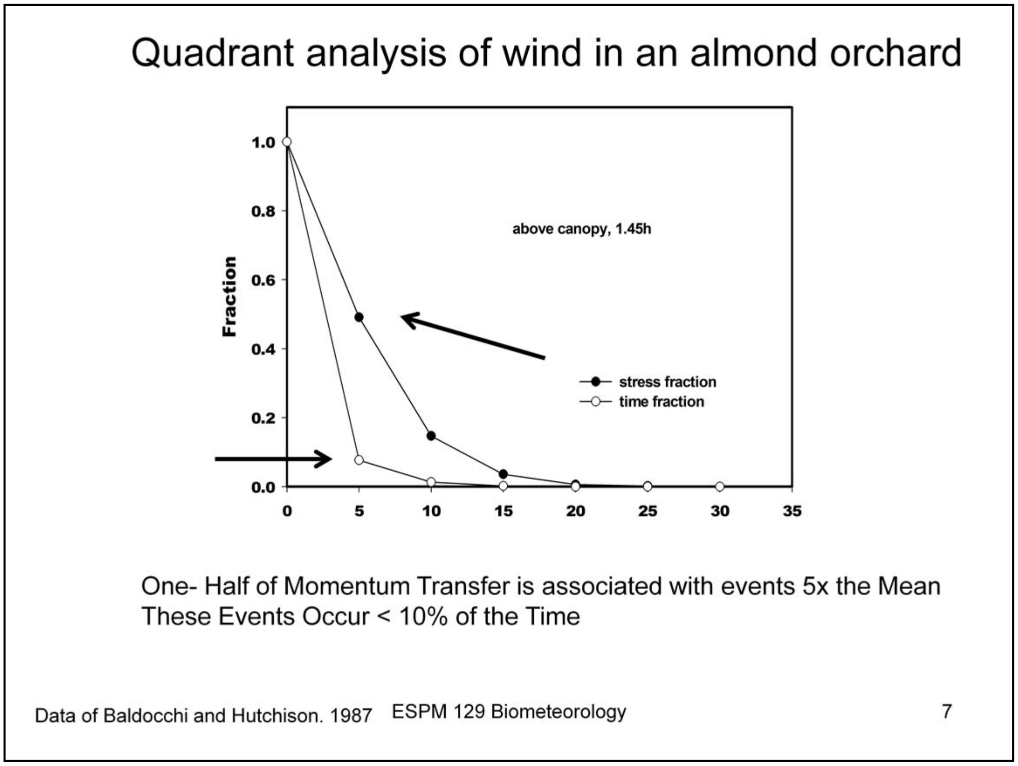
Momentum transfer on average is the covariance between <w'u'>. From looking at this graph momentum is extracted from the atmosphere when u'>0, a fluctuation greater than the mean, and when w' < 0, downward motion. Yet we can also see extraction for the covariance when w' >0 and u' < 0. But also notice lots of events happen in the adjacent quadrants.



Quadrant analysis lets us explain the statistics better and conditionally. Most momentum transfer is associated with sweeps and ejections. Yet there are interaction terms, too.

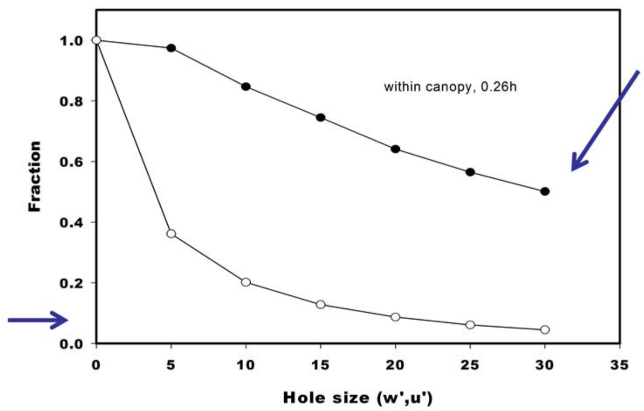
Quadrant Analysis

- *Quadrant 1: outward interactions, u'>0, w'>0*
- *Quadrant 2, burst or ejections: u'<0, w'>0*
- *Quadrant 3, inward interaction: u'< 0, w'<0*
- *Quadrant 4, sweep or gust: u'>0, w'<0*



With quadrant analysis we discover that mean momentum transfer is associated with events more than 5 times the mean

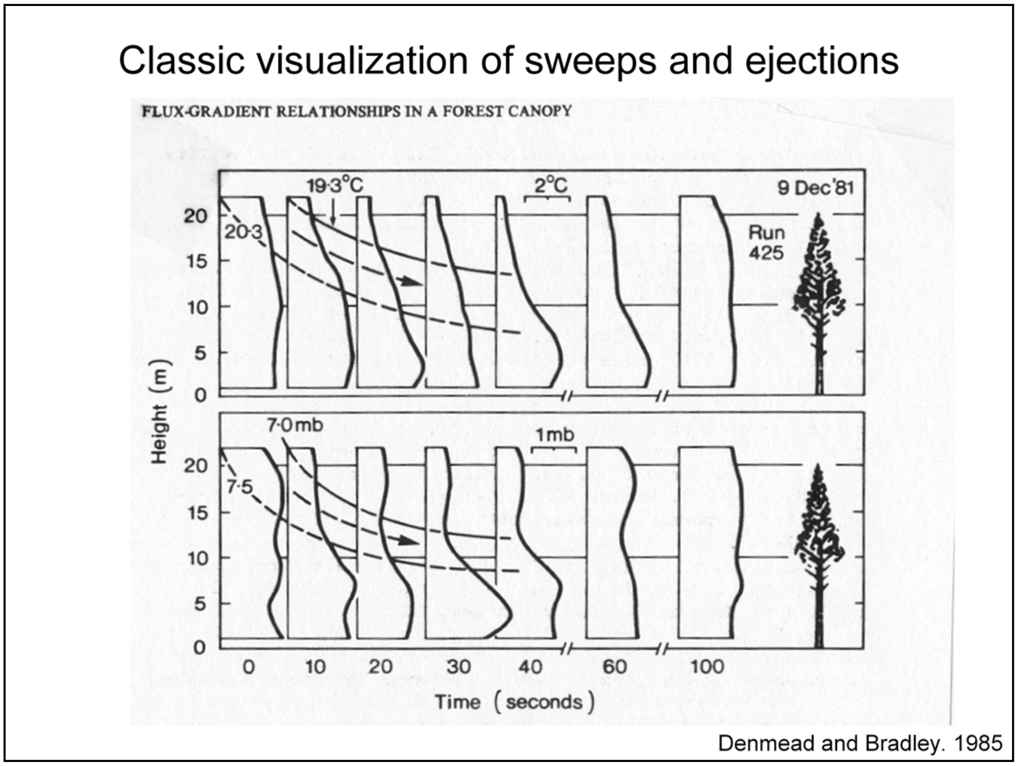
Quadrant analysis of wind in an almond orchard, (cont.)



One- Half of Momentum Transfer is associated with events > 30x the Mean
These Events Occur < 10% of the Time

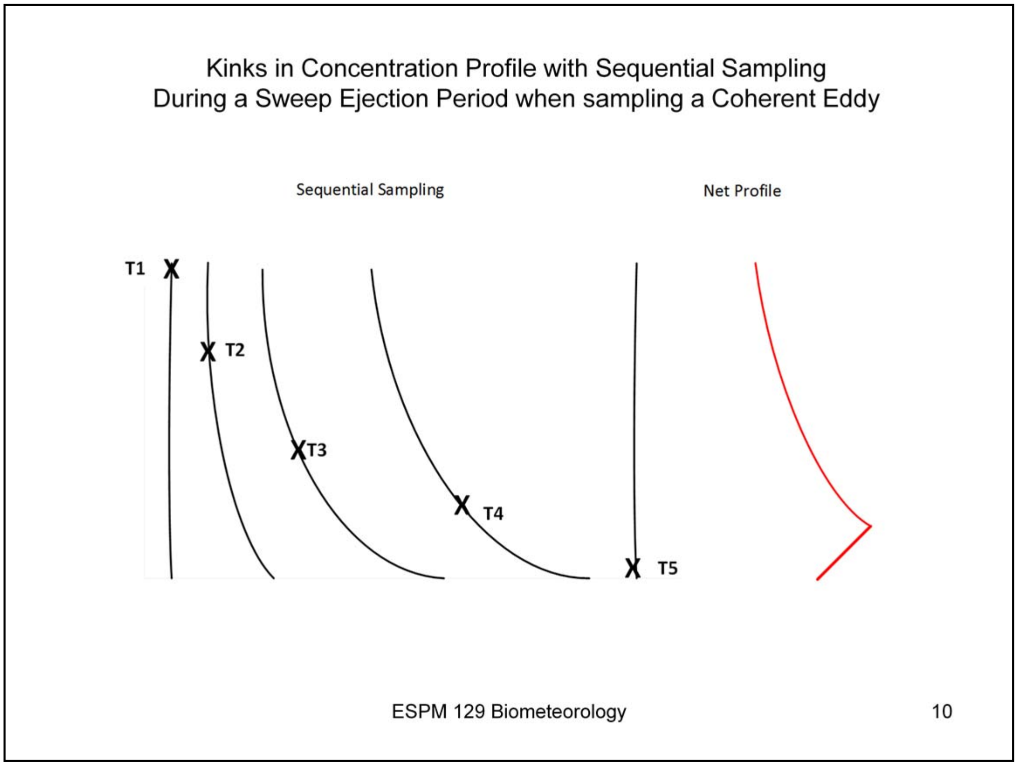
Baldocchi and Hutchison. 1987 ESPM 129 Biometeorology 8

Inside the canopy the momentum transfer events are even more intermittent. Mean conditions are associated with events about 30 times the mean. These happen less than 10% of the time



It was the emergences of this new vision that heat and mass transfer was associated with sweeps and ejections that led to a paradigm shift and put a nail in the coffin on applying K theory in the canopy.

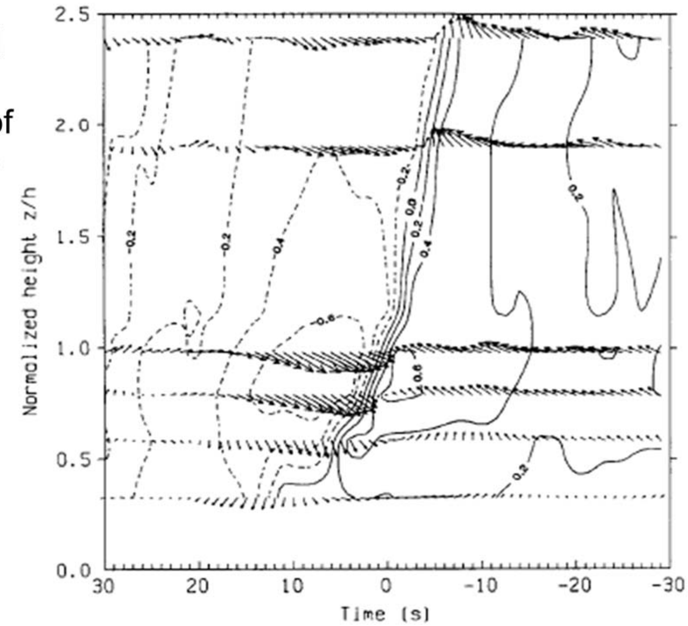
My thesis was performed before this new paradigm was discovered. With slow sampling rates and primitive instruments, we were blind to this effect. Yet we had measurements suggesting something was wrong. I sampled CO2 profiles and often found kinks in my profiles. The sampling system pulled air from different levels every 30 seconds or so and ran the air through a gas analyzer. The data logger would take a single reading of a noisy signal. With sweeps and ejections occurring over 2 to 3 minutes I would sample part of the profile that was well mixed and another where there was a buildup in concentration, giving me kinks.



You can see if the time scale of the sequence of sweeps and ejections is shorter than the time duration to sample the profile, kinks can occur.

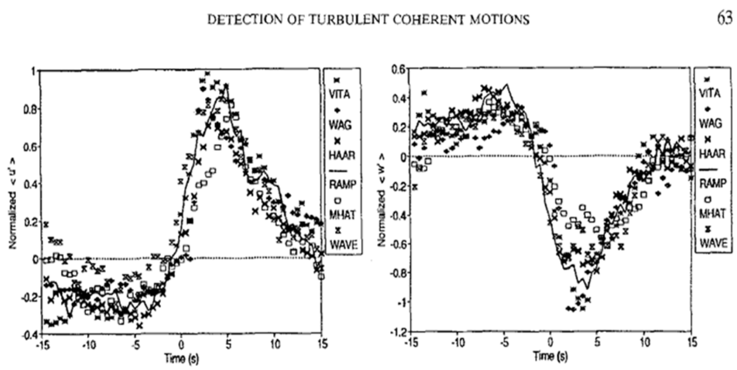
Now I did not see kinks in my temperature and humidity profiles because I measured these simultaneously at multiple levels. Hence, the reason for the mystery, at the time

Fronts and coherent structures of turbulence



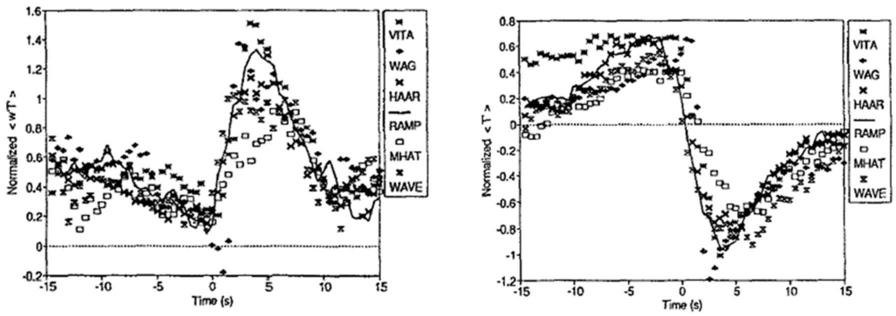
Gao et al. 1989

Sweeps and ejections calculated with wavelet analysis



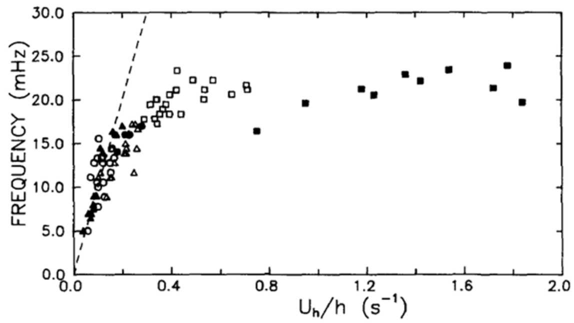
Collineau and Brunet 1993, BLM

Sweeps and ejections calculated with T' and w'T'



Collineau and Brunet 1993, BLM

Frequency of coherent structures and shear

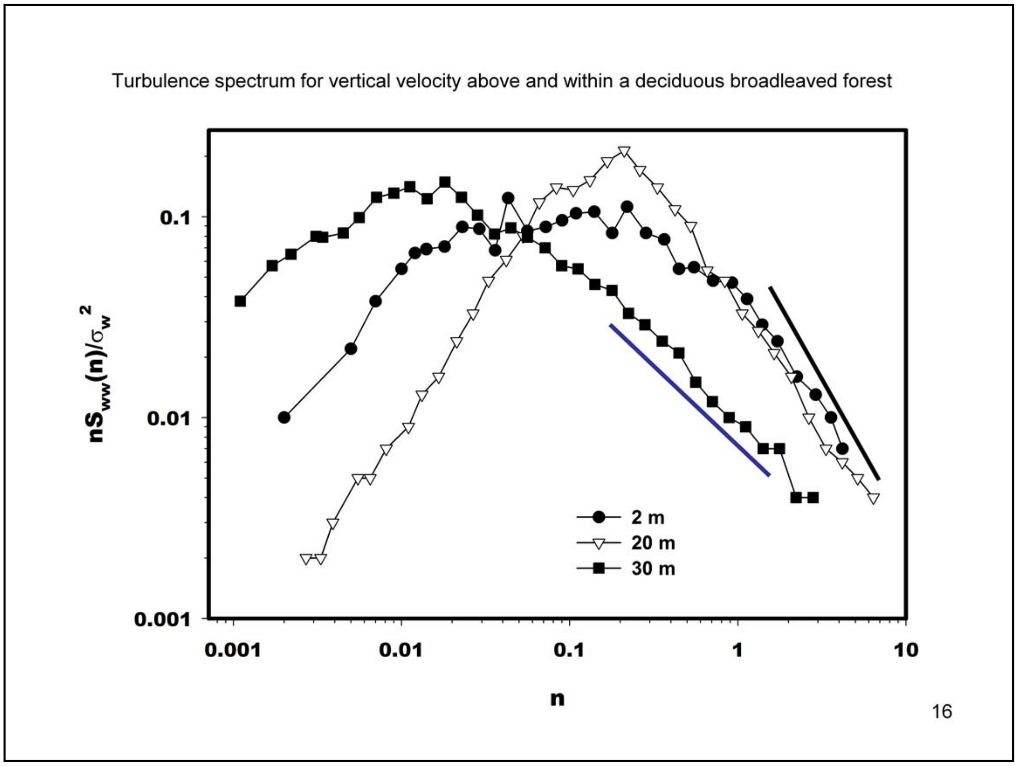


Paw U et al, 1992, AgForMet

The frequency of coherent eddies is a function of the shear

If K theory Fails what are our options?

- Higher Order Closure Eulerian models
- Lagrangian Random walk Models

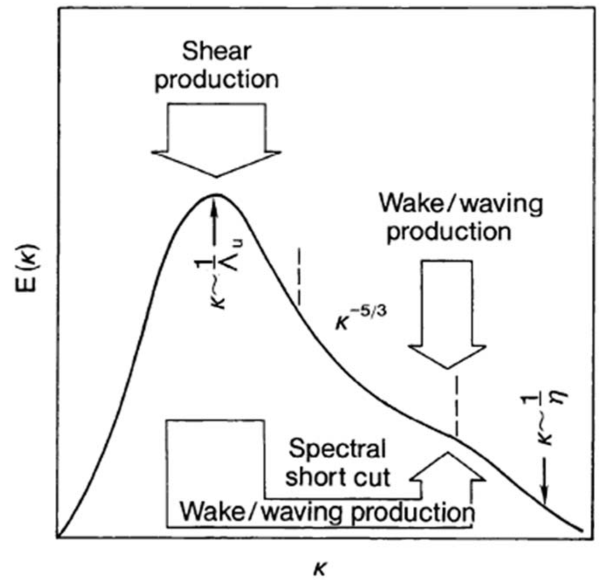


We use spectra, determined from Fourier Transforms (or wavelet transforms) of the high frequency turbulent time series. This shows us the frequency or wavenumber associated with the peak eddies. It also shows the inertial cascaded of energy from larger to smaller and smaller scales.

Understanding the spectrum tells us how long to sample, how fast to sample and identifies if our instruments and sampling system are filtering, or smearing, important information.

In the internal boundary layer the slope of the inertial cascade is -2/3 when plotted like this and the x axis is normalized by n, wave number. Inside the canopy we see the presence of foliage causes a much steeper slope, a short curcuiting of the inertial cascade. This is a scale emergent property of the fluid flow.

Conceptual diagram of spectral cascade of turbulence in a plant canopy



Finnigan, 2000 Ann Rev Fluid Mech

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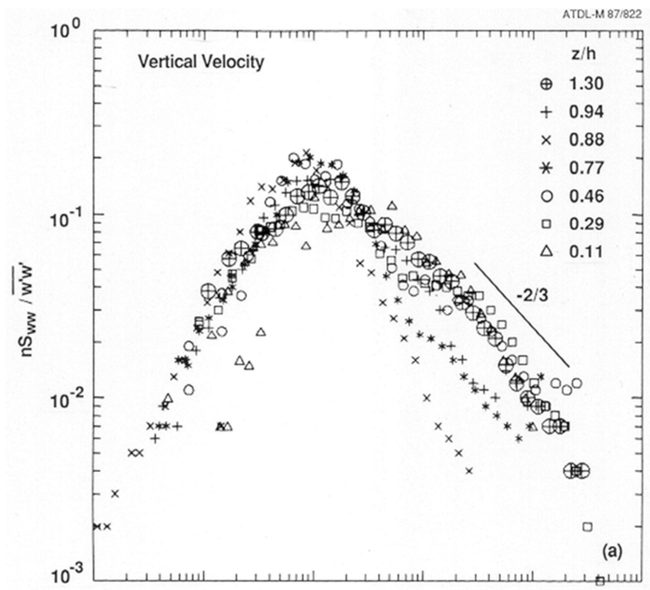
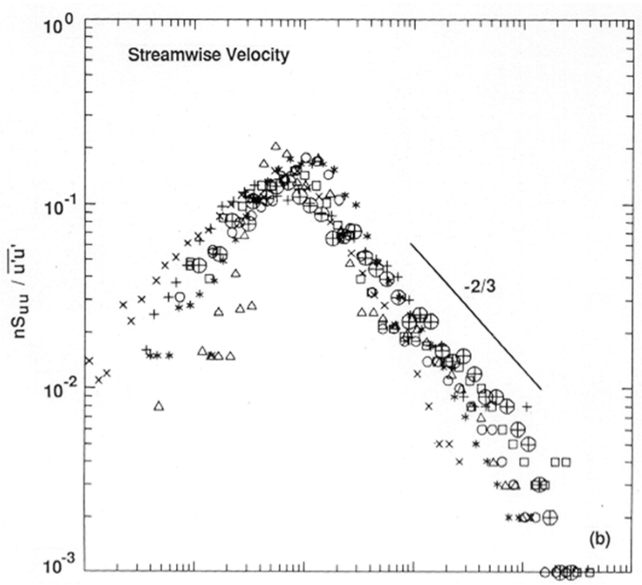
This cartoon emphasizes the key processes revealed in the spectrum.



Here are data we (Baldocchi and Meyers, 1988) took over and under a 25 m tall deciduous forest. Above the canopy we see a beautiful and classic inertial subrange, with -2/3 slope.



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Slope of inertial cascade in a deciduous forest

z/h	w	u	v
0.11	-0.83	-0.82	-1.13
0.29	-0.96	-0.89	-0.86
0.46	-0.81	-1.07	-1.14
0.77	-0.89	-1.09	-0.98
0.88	-1.21	-1.09	-1.29
0.94	-0.88	-0.79	-0.91
1.30	-0.68	-0.66	-0.66

You can see from this chart as we dive deeper into the canopy the slopes of the inertial cascade increase, more negatively, from the classic -2/3 slope associated with flows in the internal boundary layer

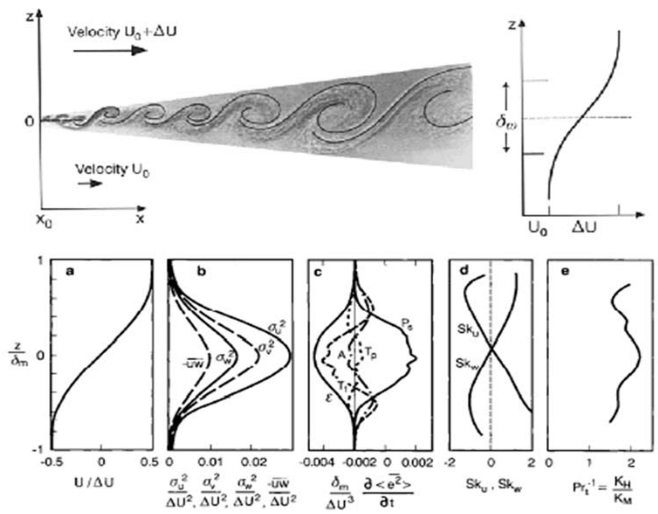

Figure 10 Composite plot defining the parameters and flow statistics in the self-preserving region of a plane mixing layer. Variables are normalised with vorticity thickness δ_ω and velocity difference ΔU. (a) $U = \langle \overline{u_1} \rangle$; (b) $\sigma_u, \sigma_v, \sigma_w$ and $-\overline{u'w'}$; (c) TKE budget terms as in equation (7.1); (d) Sk_u, Sk_w; (e) inverse turbulent Prandtl Number, Pr_t^{-1}. Figure from Raupach et al (1996).

Raupach et al., 1996

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This diagram shows the characteristics of mixing layer flows. This is a great analog for canopy flows. We see inflexions of the wind profile, heterogeneous turbulence profiles, non local transport, highly skewed turbulence and deviations between turbulent diffusivities for heat and momentum

Mixing Layer Theory

- An inflection occurs between the logarithm above canopy wind profile and the exponential within canopy wind flow
- Turbulence profiles are not uniform, they are heterogeneous
- The inflection causes instability and turbulent flow to be intermittent and driven by large scale eddies.
- The skewnesses of w and u are of large magnitude and opposite sign

Where does this bring us? We can now distinguish how and why. We also show how canopy flow has many similarities with mixing layer theory.

Attributes of Turbulence in the Environment

property	Surface layer	Mixing layer	Canopy
U inflexion	no	yes	Yes
σ_u/u^*	2.5	1.7	1.8
σ_w/u^*	1.25	1.3	1.1
r_{wu}	-0.32	-0.44	-0.5
Kh/Km	1.1	2	2
Sk_u, sk_w	small	O(1)	O(1)
Length Scale, w,u	z-d	Du/du/dz	h-d
tke	Shear=dissipation	Shear + Transport = Dissipation	Shear + Transport = Dissipation

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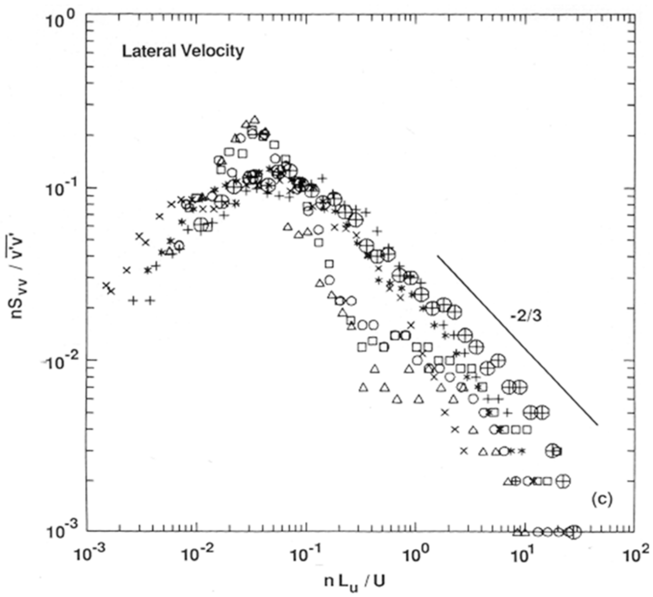
Key summary of the attributes

Summary

- The turbulence spectra experiences a short circuiting of the inertial subrange, as a result of interaction between turbulence and leaf elements.
- Hole analysis shows that turbulent transfer is associated with events many times the mean that occur a small fraction of the time.
- Wind and turbulence in plant canopies shares many similarities with mixing layer theory.


Lateral Velocity
$nS_{vv} / \overline{v'v'}$
$n L_u / U$
-2/3
(c)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

canopy	h	LAI	u(h)/u*	L_s/h
strips	0.060	0.5	3.3	0.85
wheat	0.047	1.0	4.1	0.57
rods	.19	2.0	5.0	0.49
corn	2.60	3.0	3.6	0.39
corn	2.25	2.9	3.2	0.46
Eucalypt forest	12	1.0	2.9	0.58
pine forest	20	4.1	2.5	0.29
Aspen forest	10	3.9	2.6	0.58
Pine forest	15	2	2.2	0.50
Spruce	12	10	2.4	0.44
Spruce	12	10.2	4.0	0.30
Deciduous broadleaf	24	5.0	2.8	0.12

From Raupach et al. 1996