

ESPM 129 Biometeorology Wind and Turbulence, Part 2, Canopy Air Space: Observations and Principles

Lecture 21 Wind and Turbulence, Part 2, Canopy Air Space: Observations and Principles

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Topics to be Covered

1. Momentum Transfer
 - a. Conditional Sampling
2. Turbulence Spectra in Forests
3. Coherent Structures
4. K-Theory and Mixing Layer Theory
5. Summary

L21.1 Momentum transfer

Momentum is transferred from the atmosphere to the vegetation due to form drag by the ground and vegetation. But, momentum transfer also varies with depth in vegetation, in association with the leaf area profile, leave and shoot shapes and orientations. The drag force responsible for this transfer is assessed as:

$$\frac{\partial \tau}{\partial z} = -\rho C_d a |u| \bar{U}$$

C_d is the drag coefficient, a is leaf area density, u is wind velocity, U is wind speed and ρ is air density. At its simplest level, momentum transfer through foliage can be modeled using a simple model based on drag coefficient, wind speed and leaf area density (Raupach; Thom 1981):

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

In practice, this equation is not very useful for we must provide information on the wind profile. But we need to know how momentum is absorbed to compute wind. Obviously, there is a close coupling between wind velocity and momentum transfer. We will show

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later in the scaling and modeling lecture how to construct an equal set of equations and unknowns for wind and momentum transfer.

Simple and static representations of momentum transfer tend to fail, as we use modern and fast responding instruments to study the dynamics of fluid flow in the canopy. Figure 1 shows that the mean momentum transfer profile experiences a constant stress layer is observed over the canopy, decreases rapidly with depth in the canopy turbulence properties. Notice that the mean case is resolved by extreme contributions of both downward and upward directed momentum transfer. Here is counter-directed movement of momentum that is not captured by mean, inferential K theory.

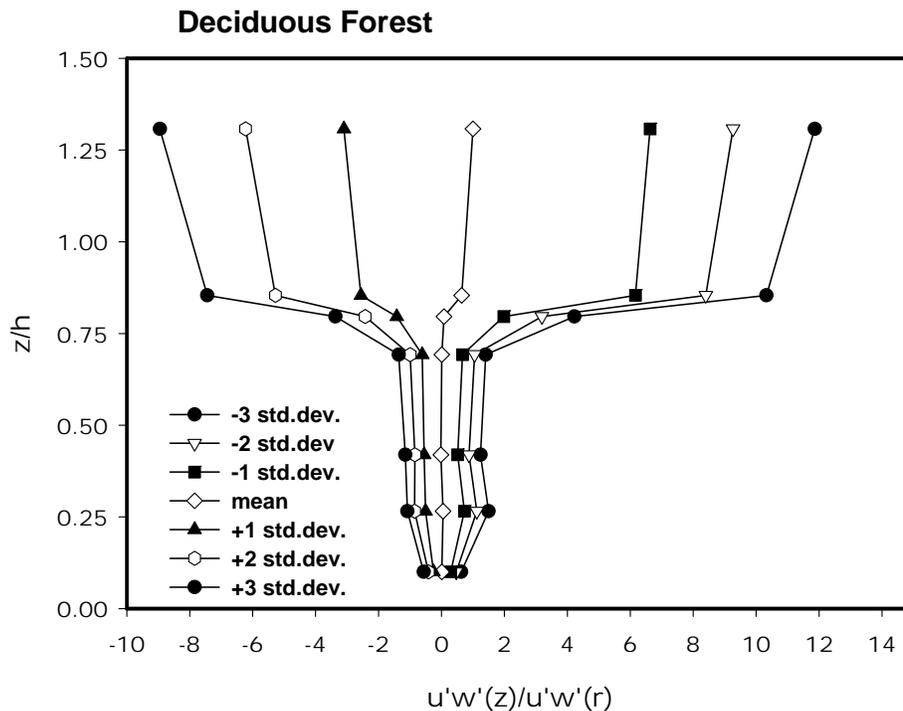


Figure 1 Profiles of shear stress in a deciduous forest. Note up and down directed transfer

L21.1 Conditional Sampling

Conditional sampling has been used as a means of understanding the behavior of turbulent transfer within and above canopies by numerous authors (Finnigan 2000; Shaw et al. 1983; Wallace et al. 1972). The idea was originally derived from fluid mechanics

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studies. Conditional sampling involves understanding the contribution of instantaneous products of w' and u' to the computation of the mean covariance, $w'u'$. It plots the data by placing w' on the y axis and u' on the x axis. Four quadrants are identified

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: $u' > 0, w' < 0$

Figure 2 shows the interactions among w and u at a site near the floor of a boreal forest. Typically horizontal wind gusts are associated with downward directed air and updrafts are associated with slowly moving air. This motion is associated with the downward transfer of momentum. Nevertheless, there is an appreciable amount of events associated with the inward and outward interactions, which represents a sloshing of the wind.

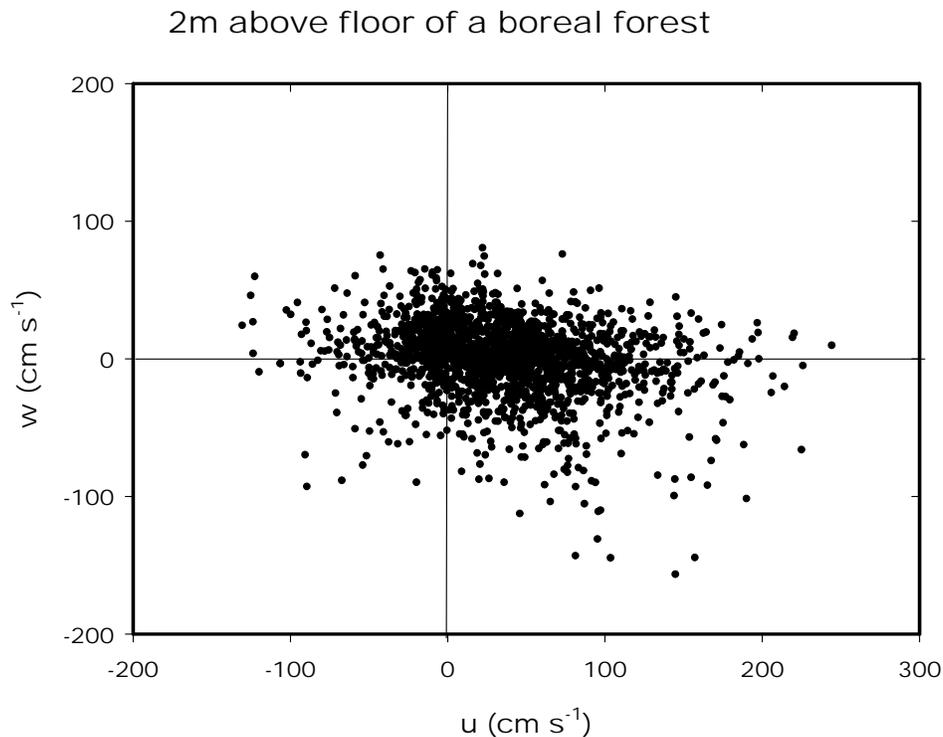


Figure 2 Correlation between horizontal and vertical velocity fluctuations in a boreal jack pine forest

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In this case the **correlation coefficient** between w and u is -0.21. Raupach reports that the correlation coefficient between w and u is about -0.3 above the canopy, near -0.45 at canopy interface, attenuates with depth in the canopy.

Information on the importance of turbulent events of different magnitude are quantified by the hole size, H :

$$H = \frac{|w' u'|}{\overline{w' u'}}$$

Conditional sampling is performed by using a criterion that $I_{i,H}$ equals one if u' and w' lie in the i th quadrant and $|w'u'| \geq H \overline{w'u'}$, otherwise I is zero.

The conditionally averaged momentum stress fraction can be computed as:

$$w' u'_{i,H} = \frac{1}{T} \int_0^T w' u' (t) I_{i,H} dt$$

The stress fraction with each hole size and quadrant is:

$$S(i, H) = \frac{w' u'_{i,H}}{\overline{w' u'}}$$

The time fraction associated with each hole size and quadrant is:

$$T(i, H) = \frac{1}{T} \int_0^T I_{i,H} dt$$

The covariance between two non-Gaussian wind velocities yields an even more non-Gaussian and intermittent transfer of momentum. Figure 12 shows, for instance, that 50% of momentum transfer above the canopy is associated with events less than 5 times the mean and these events occur less than 20% of the time. The distribution is even more extreme deep in the canopy. Sixty percent of momentum transfer is associated with events more than 30 times the mean, yet these events only occur 20% of the time. Similar extreme events have been observed by us in an almond orchard (Balducchi; Hutchison 1988) and by Shaw et al. (Shaw et al. 1983) in corn and Finnigan (Finnigan 1979) in wheat.

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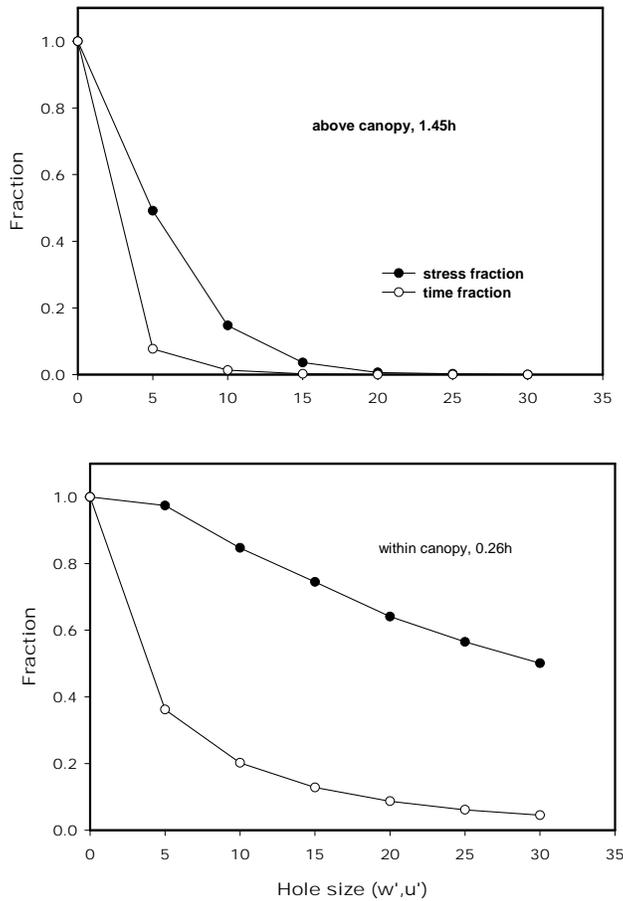


Figure 3 Hole analysis of wind in an almond orchard. Data of (Baldocchi; Hutchison 1988)

L21.2 Turbulence Spectra within a forest canopy

Turbulence in the atmospheric surface layer is comprised of a spectrum of eddies ranging in size from hundreds of meters to millimeters. This spectrum exists because turbulent energy must flow from large to small scales in order to dissipate turbulent kinetic energy into heat.

Within plant canopies, the turbulent kinetic budget and its spectrum are modified by interactions between wind and plant parts. Until the advent of modern turbulence instruments, the conventional wisdom was that turbulence inside canopies was fine-scaled because of the shedding of eddies by leaves, stems and twigs.

Figure 4 shows turbulence spectra above and within a forest. The spectrum contains several distinct ranges. The largest eddies are generated by shear and buoyancy. The next range is the inertial subrange. In this range the length scales of turbulent kinetic

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energy cascade from larger to smaller eddy sizes. The inertial cascade has a $-2/3$ slope above the canopy. Within the canopy the slopes are steeper (see Table 23.1). There the spectra is affected by wake and waving production. The chopping of eddies from large to small scales produces a spectral short circuit. Work against form drag produces wakes with scales on the length scale of the obstructions. This smaller sized turbulence can dissipate much more quickly than the normal eddy cascade that is observed in the surface layer. This process short-circuits the inertial cascade. An analogous effect would be the result of throwing a large plate of glass against the ground. The one large coherent plate will immediately become a pile of small broken pieces. The plant-turbulence interactions cause the slope of the spectra to deviate markedly from the classical $-2/3$ slope, that is noted for the atmospheric surface layer.

At the smallest scales the effect of viscosity becomes important, which eventually converts the turbulent fluctuations to heat. The characteristic scale is the Kolmogoroff scale, which is on the order of 1 mm.

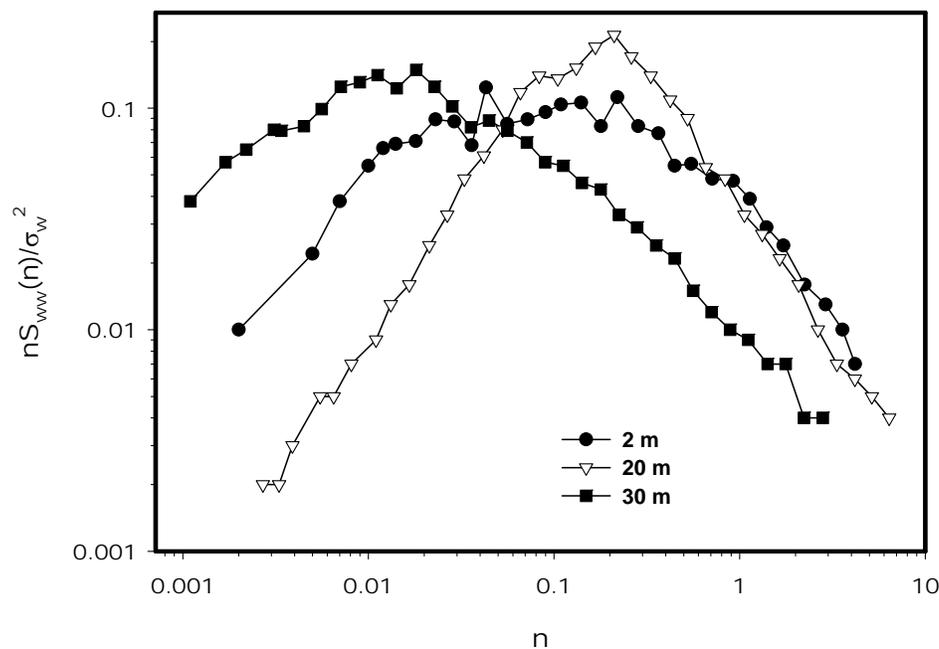


Figure 4 Turbulence spectrum for vertical velocity above and within a deciduous broadleaved forest (Baldochi; Meyers 1988a)

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Another feature of the turbulence spectra in canopies is their lack of isotropy (equal dimensions in all directions). If the spectra are isotropic then: $S_w(k):S_v(k):1.33S_u(k)$. In the canopy, the ratios are nearer to 1:1:1.

Table 1 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

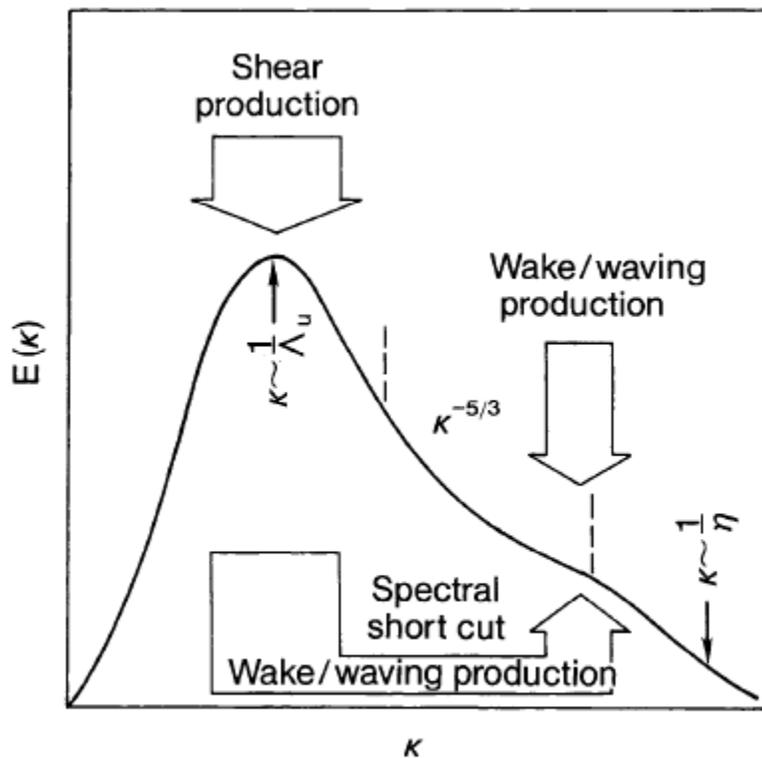


Figure 14 Schematic diagram illustrating the extra processes that must be accounted for in theories of spectra in canopies.

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Figure 5 Conceptual diagram of spectral cascade of turbulence in a plant canopy, after Finnigan 2000.

Typically, we normalize spectra so the data can be compared with one another and for different conditions. As recalled from the earlier lecture we can scale spectra as:

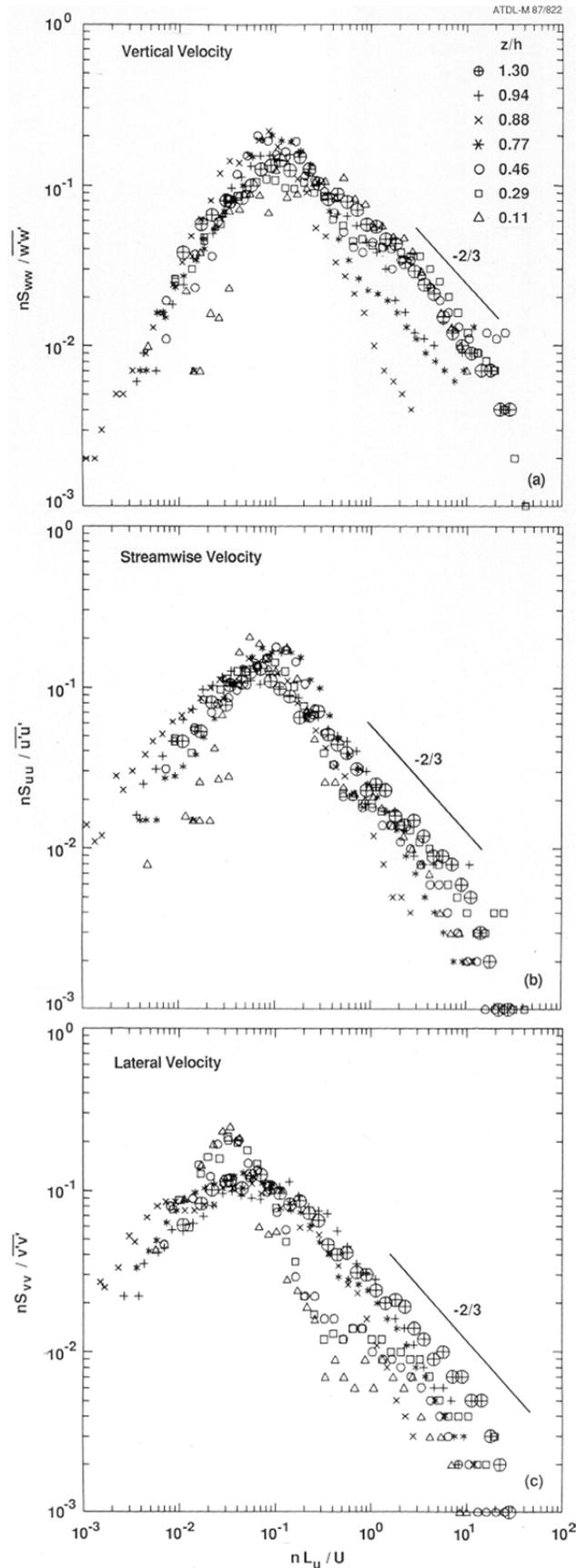
$$f = \frac{nz}{u(z)} \text{ or } \frac{n(z-d)}{u(z)}$$

Inside vegetation, numerous investigators have adopted, a canopy height-dependent scaling factor

$$f = \frac{nh}{u(z)}$$

When the spectra are normalized we observe that the scale of the spectral peak does not vary much as one descends into the canopy. Turbulence throughout the canopy is generated and dominated by large scale, coherent and intermittent eddies. This can be visualized by these large energetic events that sweep through the whole forest.

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Figure 6 Turbulence spectra in a deciduous forest, normalized by the integral length scale (Baldocchi; Meyers 1988a)

A survey of recent data by Finnigan (Finnigan 2000) quantify the normalized spectral peak and show how the values for u, v and w compare with one another.

Normalized Spectral Peaks ($f_{\max} u/u(h)$),

u	v	w
0.15 +/- 0.05	0.1	0.45 +/- 0.05

L21.3 Coherent Structures

Turbulent transfer occurs by way of quick sweeps and ejections, followed by a longer quiescent period and a ramping of the concentration of scalar material (Bergstrom; Hogstrom 1989; Denmead; Bradley 1987; Gao et al. 1989a). The within-canopy profile of a measured scalar is, thereby, heavily weighted by the duration of the quiescent period. For example, during the quiescent period relatively great drawdowns or build-up of scalar can occur in comparison to the well-mixed scalar profile that occurs during sweep-ejection event (Denmead; Bradley 1987).

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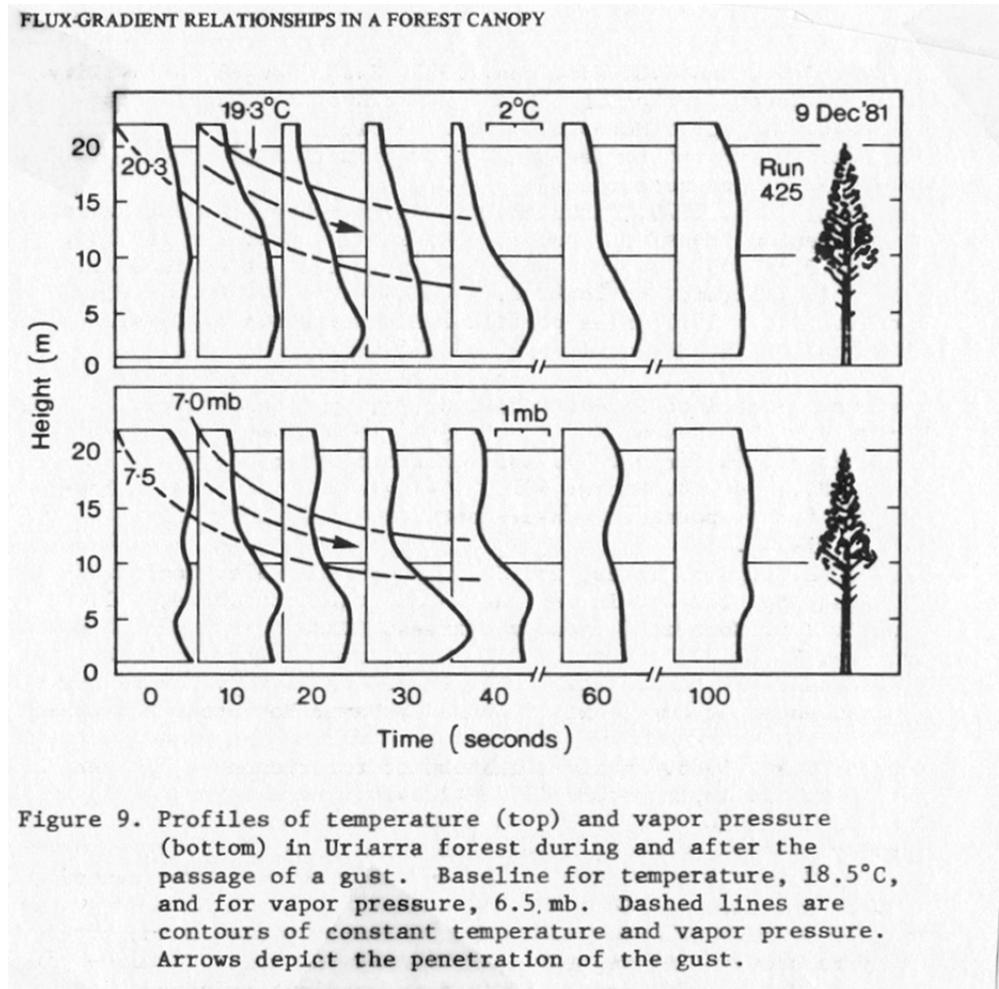


Figure 7 Classic visualization of sweeps and ejections by Denmead and Bradley. 1987

Recent measurements have improved upon the conceptual picture, first posited by Denmead and colleagues. Gao et al (Gao et al. 1989b) show the time course of sweeps and ejections, that are associated with microfronts. Sudden gusts penetrate quickly moving air into the canopy, forming a microfront. This front can be a cool front if cooler air is entrained into the canopy or a warm front if vice versa. The air is then heated (or cooled). This is associated with a slow rising period, the ejection.

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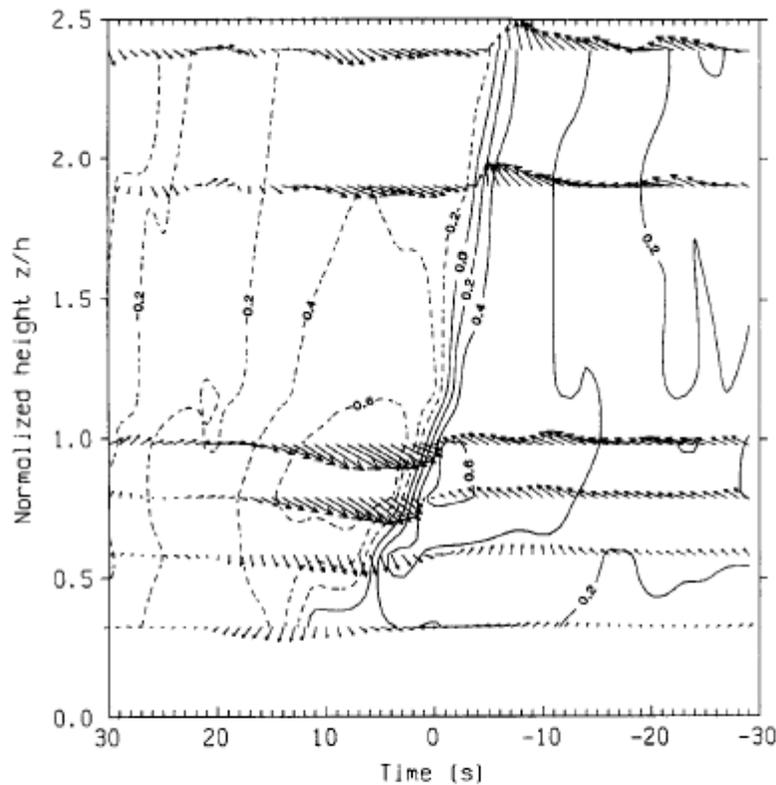


Figure 6 Time-height plot of ensemble averaged temperature and fluctuating velocity fields measured in moderately unstable conditions ($L = -138\text{m}$, where L is Monin-Obukhov length) in a 18-m-tall mixed forest. Dashed lines are isotherms below the mean and solid lines are isotherms above the mean. Contour interval is 0.2°C and the maximum arrow length represents a wind magnitude of 1.9 ms^{-1} . Figure from Gao et al (1989).

Figure 8 Fronts and coherent structures of turbulence, (Gao et al. 1989b)

In reality, the length of the 'calm', ramping and well-mixed periods are not equal. For instance, Collineau and Brunet (Collineau; Brunet 1993) show a **ramping** phase of temperature inside a conifer forest occurs over a 25 s period, while a sharp drop in temperature, in association with the well-mixed sweep-ejection phase occurs over a shorter 5 s interval. If we assume, for simplicity, that the calm phase occurs 80% of the time and the mixed phase happens during 20% of the time, then the time averaged profile equal 0.8. Consequently, the hypothetical time averaged profile from the non-Gaussian scenario is 38% greater than the profile of the Gaussian scenario. Furthermore, the concept just illustrated is consistent with the biased difference between measured and modeled scalar profiles the CO_2 drawdown and heat and moisture build-ups measured within the canopy exceeded those simulated.

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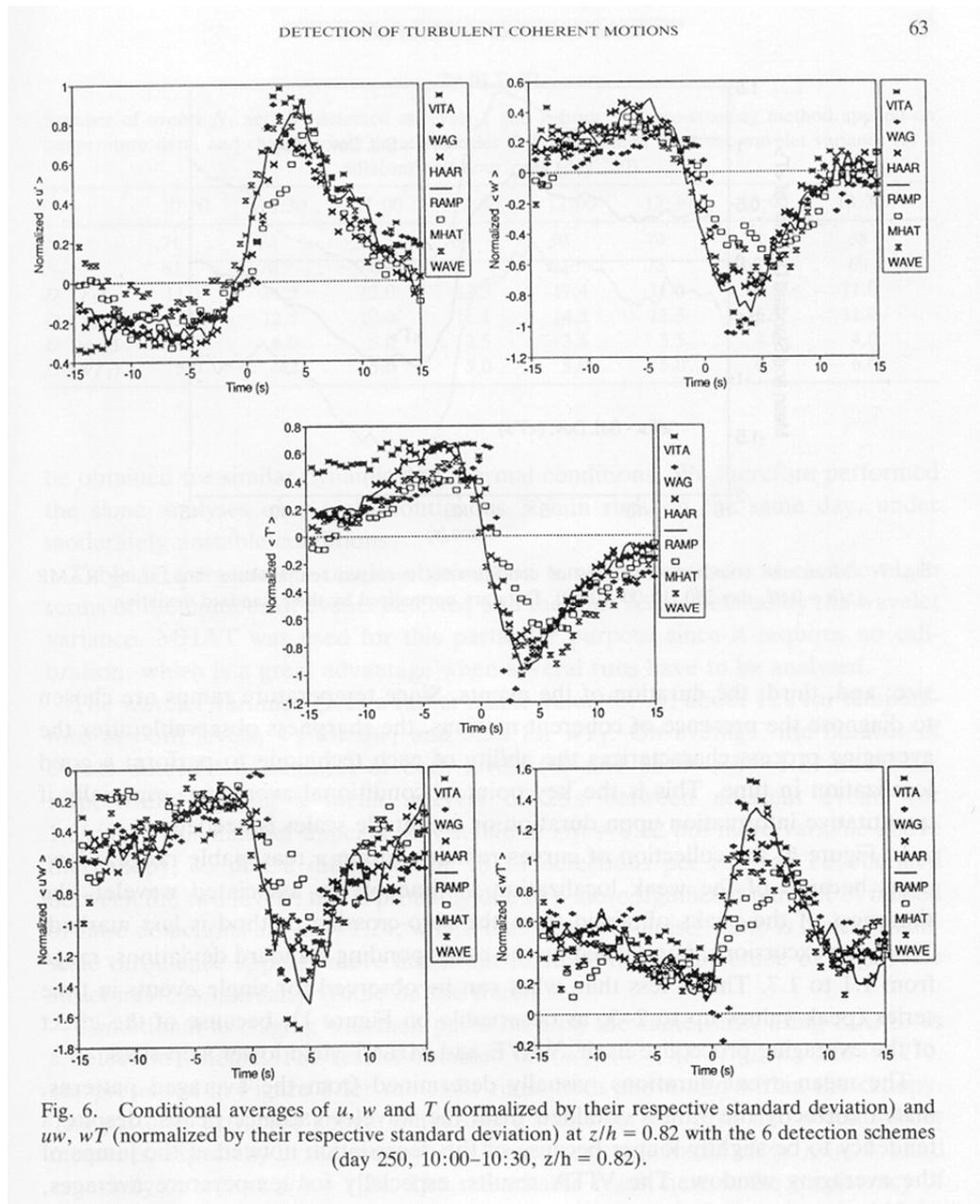


Figure 9 Sweeps and ejections calculated with wavelet analysis, (Collineau; Brunet 1993)

The time course of the sweeps and ejections has the potential to influence the isotope signal that occurs in the final equilibrium between plants and the atmosphere, depending on the residence time of downward eddies with one depletion signature and the upward eddies that may have another signature.

Raupach et al. in a related analysis report that the periodicity of active eddies near the canopy scale as $8.1 L_s$. Paw U et al (Paw et al. 1992) surveyed the literature and report that the frequency of the intermittent eddies is a function of canopy shear.

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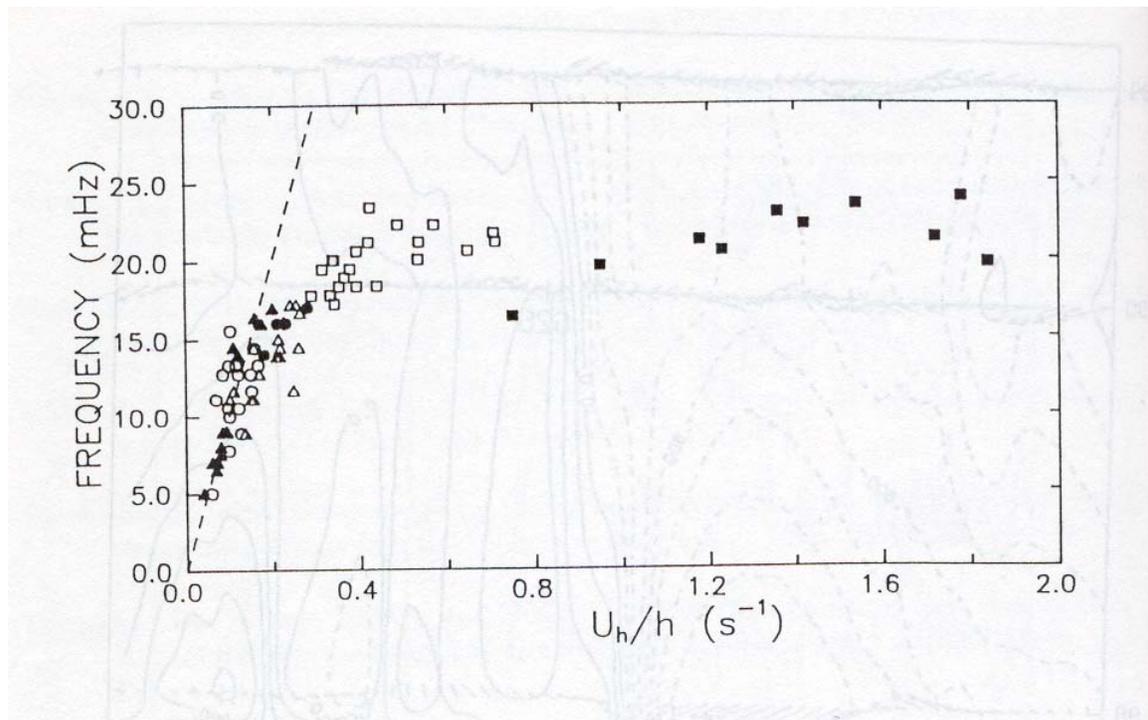


Figure 10 Frequency of coherent structures and shear (Paw et al. 1992)

They concluded that the time frequency of events was not a function of buoyancy, an important and controversial finding at the time

L21.4 K- Theory and Mixing Layer Theory

Early models on turbulent exchange in plant canopies adopted a first order closure approach (called 'K-theory'). These models assumed that turbulent transfer and molecular diffusion were analogs. In other words, the flux density of a momentum or scalar transfer is assumed to be proportional to the local velocity or concentration gradient:

$$\tau = -K_m \frac{\partial u}{\partial z}$$

K is the eddy exchange coefficient, having units of $m^2 s^{-1}$. It is often derived from measurements of wind speed profiles (the aerodynamic approach) or by measurement of the net radiation balance and temperature and humidity profiles (the energy balance approach). Up to a decade ago, many practitioners often assessed the eddy exchange coefficient on the basis of some version of Prandtl's mixing length theory, $K_m = u \cdot l$. Prior to modern turbulence measurements with sonic anemometers, a common

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assumption was that the length scale was a function of von Karman's constant (0.4) and the height above the ground.

Corrsin (Corrsin 1974) states that several conditions must hold to apply K-theory.

1. the length scales of the turbulent transfer must be less than the length scales associated with the curvature of the concentration gradient of the scalar.
2. the turbulence length scale must be constant over the distance where the concentration gradient changes significantly.

K-theory models were originally thought to be valid because it was presumed that turbulence was produced in the wakes of the foliage. On this assumption, turbulent length scales were assumed to be sufficiently small to comply with Corrsin's (1974) restrictions.

An accumulating body of evidence now shows that these prior assumptions are often not valid inside plant canopies. Much turbulent transfer is associated with coherent and intermittent wind gusts, whose length scales are comparable to or greater than the vegetation height. Since concentration gradients of many scalars exhibit strong curvature due to the local contribution of its source the length scale that represents the curvature of the scalar profile will be less than that for turbulence, violating one of Corrsin's rules. Additional proof that first order K-theory can be invalid inside plant canopies comes from observations of counter-gradient transfer of heat and momentum (Baldocchi; Meyers 1988b; Denmead; Bradley 1987); the diffusion analogy cannot admit negative values for K, as would otherwise occur under such circumstances.

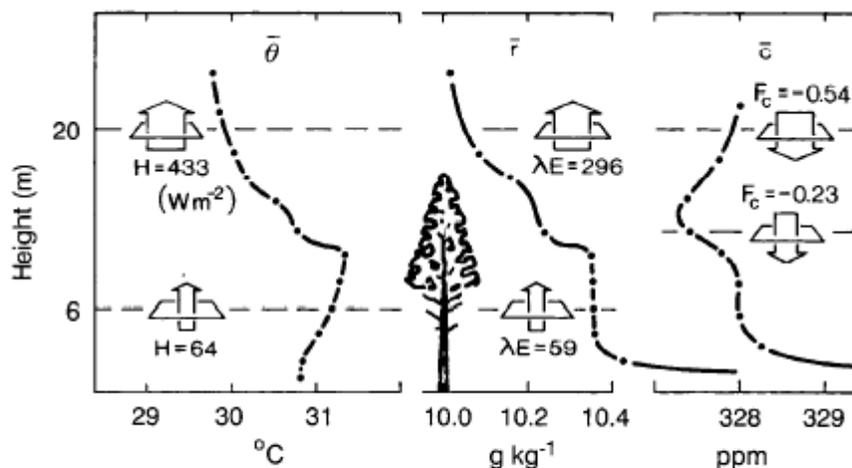


Figure 2 Simultaneous fluxes and gradients of heat and temperature, latent heat and water vapor mixing ratio and carbon dioxide ($\text{gm m}^{-2}\text{s}^{-1}$) and ppm. Obtained in a pine forest (Canopy G of Table 1). Figure from Denmead & Bradley (1987).

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The superpositioning of near-field and far-field diffusion upon one another is another factor contributing to counter gradient transfer. Near field diffusion occurs within the vicinity of a source. The width of the diffusing plume grows in linear proportion with time that the parcel has left the source. The far field diffusion occurs when the transit time starts exceeding the turbulence time scale. In this regime the width of the plume grows in proportion to the square root of travel time.

Raupach (Raupach 1987) explains counter-gradient transfer with the following:

'(because) scalar from nearby elementary sources is dispersing in a near-field regime...its contribution to the overall gradient (is) much greater than its contribution to the overall flux density. Just below a fairly localized and intense source in the canopy, the near-field gradient contribution is large and positive; when this is combined with the upward flux of scalar required by conservation of scalar mass, a counter-gradient flux is obtained'.

With hindsight, it is readily acceptable that K theory is wrong inside the canopy, but it took a succession of measurements over 20 years to draw this conclusion.

More recently, a team of Australian researcher has noted a close parallel between the turbulence characteristics in plant canopies and with a **plane mixing layer** (Raupach et al. 1996). This phenomenon occurs when a plate separates two fluids moving at different speeds and they are allowed to merge downstream.

1. An inflection occurs between the logarithm above canopy wind profile and the exponential within canopy wind flow, for this condition is analogous to mixing theory where two fluids with different velocities are allowed to mix.
2. The inflection causes instability and turbulent flow to be intermittent and driven by large scale eddies.
3. The skewnesses of w and u are of large magnitude and opposite sign

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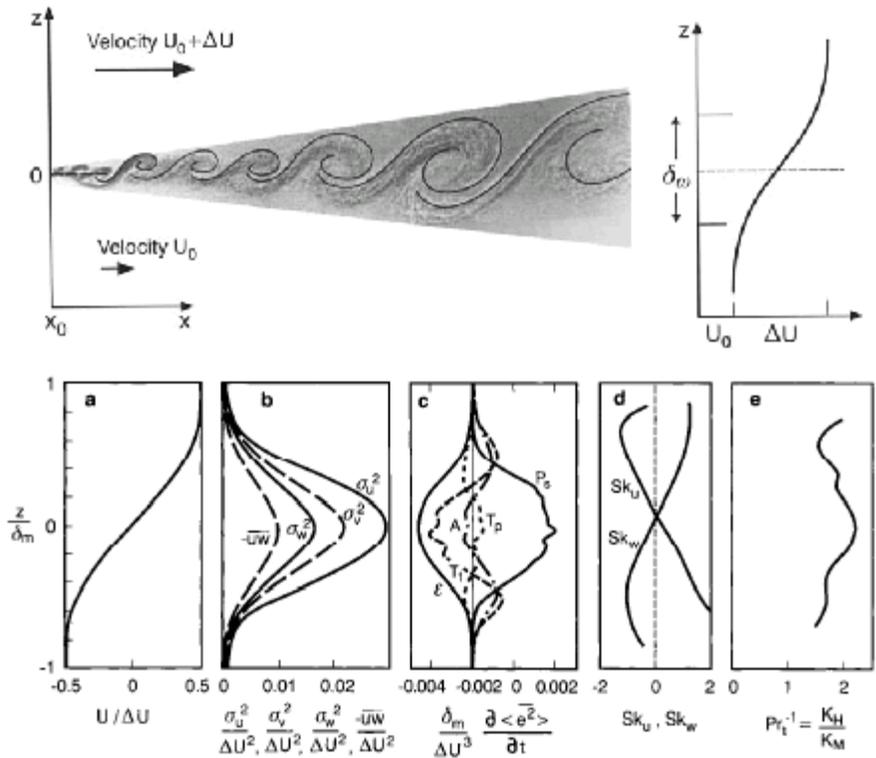


Figure 10 Composite plot defining the parameters and flow statistics in the self-preserving region of a plane mixing layer. Variables are normalised with vorticity thickness δ_w and velocity difference ΔU . (a) $U = \langle \bar{u}_1 \rangle$; (b) $\sigma_u, \sigma_v, \sigma_w$ and $-\overline{u'w'}$; (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).

Canopy wind flow and turbulence share many properties with mixing layer flows, flows of two velocities, that are allowed to mix.

General properties of canopy turbulence and wind flow.

1. **Vertical heterogeneity** of $u, w'u', \sigma_w$ and σ_u inside the canopy.

Strong inflexion point near the top of the canopy, that scales with a shear length scale:

$$L_s = \frac{u(h)}{\partial u(h) / \partial z}$$

The length scale of this shear is on the order of 0.5h, but its value will vary according to leaf area index and the distribution of leaf area. The Oak Ridge forest, for example, experiences 75% of its leaf area in the upper 25% of the canopy. So it produces one of the greatest shears and lowest length scales noted. Wind tunnel ‘plant’ by contrast are very open, so they produce larger length scales. . From the scale analysis of Raupach et

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al. (1996) they identify $u/(du/dz)$ as the principle length scale for canopy flow. Its value corresponds with 0.1h, 0.5h and h for dense, moderate and sparse canopies.

Table 17.1 From (Raupach et al. 1996)

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

2. Well above the canopy (2h) the wind profile is logarithmic and $\sigma_w/u^*=1.25$, $\sigma_u/u^*=2.5$, so the correlation coefficient is -0.32 $r_{wu} = \frac{\overline{w'u'}}{\sigma_w \sigma_u} = \frac{u_*^2}{\sigma_w \sigma_u}$.
3. At the canopy-atmosphere interface, the **correlation coefficient** increases, to about 0.6. This is suggestive of **organized and coherent** eddies. The transfer of momentum is more efficient in this zone and the roughness sublayer. Hence, it helps explain why Km is enhanced in this region. The scaled variances also differ from their boundary layer values
4. u is positively skewed and w is negatively skewed in this regions, suggestive of **strong sweep events**.
5. Spectral peaks scale with h and u(h). The peak frequency for u ($f_p h/u(h)$) is 0.15 +/- 0.05. The peak frequency for w is $f_p h/u(h)$ 0.45 +/- 0.05. The spectral peak is relatively invariant with depth into the canopy.
6. The tke budget is used to describe how and where turbulence is produced.
 - a. Above the roughness sublayer (2h) shear production and viscous dissipation are in near balance (near neutral conditions).
 - b. In the roughness sublayer and within the canopy, turbulent transport is an important source of tke. Hence, turbulence is imported or exported in and out of the region, rather than created.

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- c. Wake production can exceed shear production inside the canopy. This energy is fine scaled, so it dissipates rapidly. It is not a major factor in creating tke, overall.
7. K_h/K_m is near 1.1 in the surface layer, but increases to 2 in the roughness sublayer. Negative values are computed in the canopy, suggesting counter-gradient transfer, as negative values of K are non admissible.
8. Conditional analysis. Quadrant analysis, visual detection, wavelets, VITA, WAG.

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
K_h/K_m	1.1	2	2
Sk_u, Sk_w	small	$O(1)$	$O(1)$
w & u	z-d	$\Delta u/du/dz$	h-d
tke	Shear Production (P) = Dissipation (ϵ)	P+Transport (T)= ϵ	P+T= ϵ

9. Streamwise periodicity, or the length between successive coherent structures. It equals about 8 times the shear length scale. It is also a function of the eddy convection velocity ($u_c/u_h=1.8$) and the peak frequency of the w power spectrum.

$$\Lambda = 8L_s = \frac{u_c}{f_{p,w}}$$

11. Three ranges of eddy size are important, the scale of inactive turbulence, as generated by pbl convection, the scale of active turbulence, as generated by shear and the fine scale turbulence, as generated in the wake of elements. Fine scale turbulence is generated by the inertial cascade and by wakes. Litter transfer is associated with this scale size, but it plays a role in viscous dissipation.

L21.5 Summary:

Wind and turbulence inside vegetation has many unique and distinct attributes, as compared to wind and turbulence observed in the surface layer.

1. The mean wind velocity profile experiences great shear and an inflexion point in the upper canopy. This behavior is reminiscent of mixing layer flows

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2. A secondary wind maximum is observed in the stem space of vegetation. This and the observation of counter-gradient transfer provide evidence that led to the conclusion that K is invalid in canopies.
3. Turbulence inside a canopy is highly non-Gaussian. It is skewed and kurtotic.
4. The statistical moments (variances of w , u and v) are vertically inhomogeneous in a vegetated canopy. u is positively skewed, w is negatively skewed and the integral length scales are on the order of the canopy height, rather than the scale of the canopy leaf and stem elements.
5. The turbulence spectra experiences a short circuiting of the inertial subrange, as a result of interaction between turbulence and leaf elements.
6. Hole analysis shows that turbulent transfer is associated with events many times the mean that occur a small fraction of the time.
7. Wind and turbulence in plant canopies shares many similarities with mixing layer theory.

End Note References

- Baldocchi, D. D., and B. A. Hutchison, 1988: Turbulence in an almond orchard: spatial variations in spectra and coherence. *Boundary Layer Meteorology*, **42**, 293-311.
- Baldocchi, D. D., and T. P. Meyers, 1988a: A spectral and lag-correlation analysis of turbulence in a deciduous forest canopy. *Boundary Layer Meteorology*, **45**, 31-58.
- , 1988b: Turbulence structure in a deciduous forest. *Boundary Layer Meteorology*, **43**, 345-365.
- Bergstrom, H., and U. Hogstrom, 1989: Turbulent Exchange above a Pine Forest .2. Organized Structures. *Boundary-Layer Meteorology*, **49**, 231-263.
- Collineau, S., and Y. Brunet, 1993: Detection of Turbulent Coherent Motions in a Forest Canopy .2. Time-Scales and Conditional Averages. *Boundary-Layer Meteorology*, **66**, 49-73.
- Corrsin, S., 1974: Limitations of gradient transport models in random walks and turbulence. *Advances in Geophysics*, **18**, 25-71.
- Denmead, O. T., and E. F. Bradley, 1987: On Scalar Transport in Plant Canopies. *Irrig. Sci.*, **8**, 131-149.
- Finnigan, J., 2000: Turbulence in Plant Canopies. *Annu. Rev. Fluid Mech.*, **32**, 519-571.
- Finnigan, J. J., 1979: Turbulence in Waving Wheat .2. Structure of Momentum-Transfer. *Boundary-Layer Meteorology*, **16**, 213-236.
- Gao, W., R. H. Shaw, and K. T. Paw U, 1989a: Observations of organized structure in turbulent flow within and above a forest canopy. *Boundary Layer Meteorology*, **47**, 349-377.
- Gao, W., R. H. Shaw, and K. T. Paw, 1989b: Observation of Organized Structure in Turbulent-Flow within and above a Forest Canopy. *Boundary-Layer Meteorology*, **47**, 349-377.
- Paw, K. T., Y. Brunet, S. Collineau, R. H. Shaw, T. Maitani, J. Qiu, and L. Hipps, 1992: On Coherent Structures in Turbulence above and within Agricultural Plant Canopies. *Agricultural and Forest Meteorology*, **61**, 55-68.

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Raupach, M. R., 1987: A Lagrangian Analysis of Scalar Transfer in Vegetation Canopies. *Q. J. R. Meteorol. Soc.*, **113**, 107-120.

Raupach, M. R., and A. S. Thom, 1981: Turbulence in and above Plant Canopies. *Annual Review of Fluid Mechanics*, **13**, 97-129.

Raupach, M. R., J. J. Finnigan, and Y. Brunet, 1996: Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy. *Boundary-Layer Meteorology*, **78**, 351-382.

Shaw, R. H., J. Tavangar, and D. P. Ward, 1983: Structure of the Reynolds Stress in a Canopy Layer. *Journal of Climate and Applied Meteorology*, **22**, 1922-1931.

Wallace, J. M., R. S. Brodkey, and Eckelman.H, 1972: WALL REGION IN TURBULENT SHEAR-FLOW. *Journal of Fluid Mechanics*, **54**, 39-&.