Biometeorology, ESPM 129

Lecture 20 Wind and Turbulence, Part 1, Canopy Air Space: Observations and Principles

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A. Processes

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L20.1 Introduction

> *I'll huff and puff and blow your house down*
> Big-Bad Wolf

The structure and characteristics of wind and turbulence inside plant canopies is more complex than what is observed in the surface layer above vegetation. A canopy acts as a porous medium. How wind interacts with layers of leaves and stems that are situated above the solid lower boundary, the soil, is much different than how it varies in the surface boundary layer, as has been discussed in the past few lectures.

As biometeorologists, we are interested in how wind varies in the vicinity of plants for a number of reasons:

1. Wind affects rates of trace gas and particle exchange through its impact on the thickness of the leaf and soil boundary layers and on the mixing, diffusion and advection of scalars in the canopy air space.

2. It has a mechanical effect on plants by causing them to sway and bend. Honami, the waving of crops, is a wind-generated phenomenon. Stems bend over when a

wind gust passes and re-bound in the lee of the gust. The plant's bend oscillates in accordance to the natural frequency of their stalks. Gusts have streamwise periodicities of 5 to 8 canopy heights. The phase velocity equals 2 U(h).

3. In climates with persistent winds, such forcing will affect the shape of tree crowns. Krummholz trees near the alpine tree line or bent over Cypress trees at Point Reyes are classic examples of wind forcing growth shape. High winds can also cause abrasion, as limbs rub against on another or the movement of sand sandblasts and tears leaves. Under extreme wind loads, catastrophic damage can occur as when tree blow over and crops lodge. Wind affects plant pathology by causing spores to be released and dispersed.

4. Finally, a phenomenon, known as thigmomorphogenesis, has been reported to affect plant growth in the presence or absence of wind.

Several types of air flow are associated with biometeorology [*Lee*, 2000]. These include:

1. wind through homogeneous forest and crop canopies
2. flow into forests and hedges
3. flow exiting forests and hedges
4. flow in isolated clearings
5. flow through forests on complex terrain
6. drainage flow at night on complex terrain and tall vegetation.

Physical interactions between plants, soil and wind involve the transfer and conversion of momentum, kinetic energy and work:

1. *aerodynamic drag of plant parts extracts momentum from the mean wind flow.*

2. *plant parts break down large scale eddies into smaller eddies.*

3. *behind obstructing elements, kinetic energy of the mean flow is converted into turbulent kinetic energy of the wakes.*

4. *in aeroelastic canopies, mean kinetic energy is used to create waving foliage or wind loads, which can bend or break vegetation*

In this lecture we will discuss that statistical properties of wind and turbulence in vegetation and how they vary in space. This information is needed to parameterize models and to understand the turbulent transfer and diffusion of material in and outside of canopies.

L20.2 Mean Wind Profiles

Figure 1 shows a typical profile of wind above and below a crop, soybeans. Several characteristics merit note. Above the canopy one observes the now-familiar logarithmic wind profile. At the **canopy-atmosphere** interface there is a **large shear** (du/dz) induced inflexion in the wind profile. This region is followed by zone with an **exponential decrease** in wind speed. A **secondary wind maximum** often occurs deep in the canopy in the stem space. Below this level, there is another **logarithmic** wind profile between the stem space and the ground.

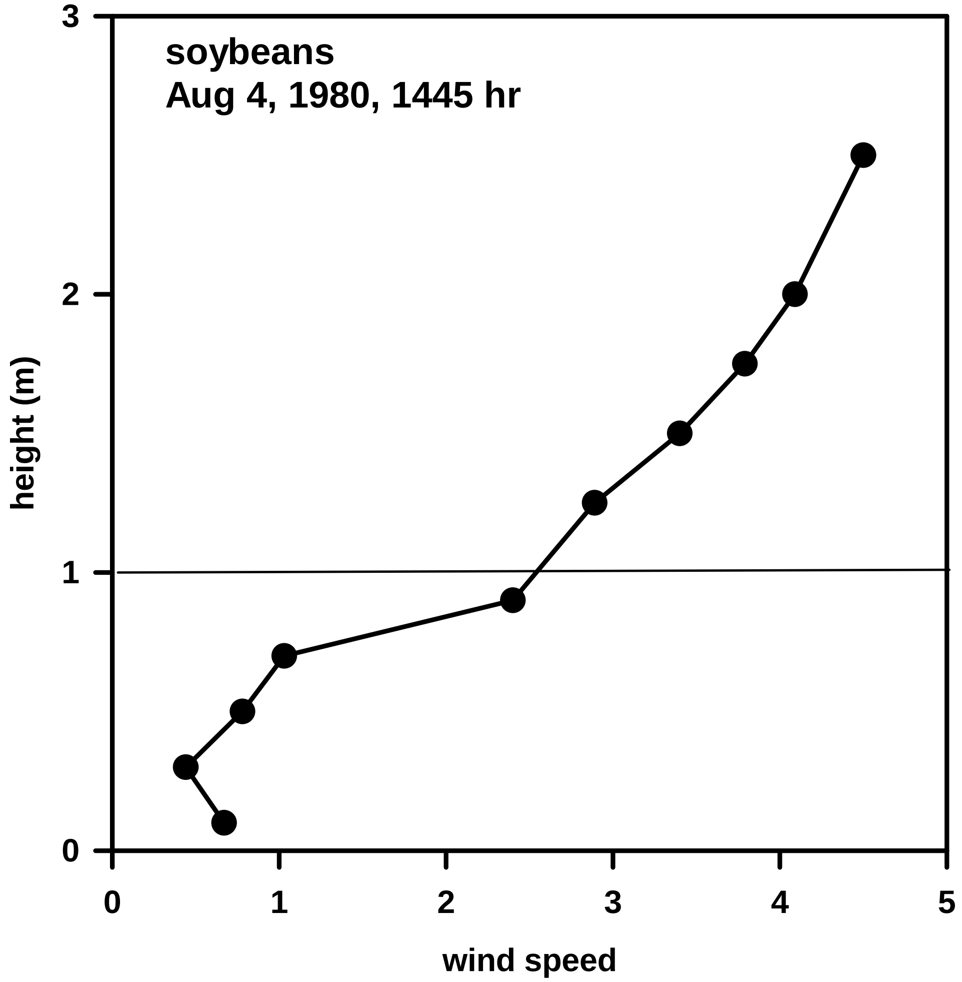


Figure 1 wind profile in a soybean canopy. Note the secondary wind maximum. [*Baldocchi et al.*, 1983].

Numerous investigators have attempted to quantify wind profiles within canopies using an exponential relation. The early and classic papers on this topic were conducted in the

1960s and early 1970s [*Cionco*, 1965; *Landsberg and Jarvis*, 1973; *Uchijima and Wright*, 1964].

Simple models for wind in canopies follow an exponential decay with depth into the canopy from the top, like light, because cumulative leaf area index exerts drag on the wind and attenuates it:

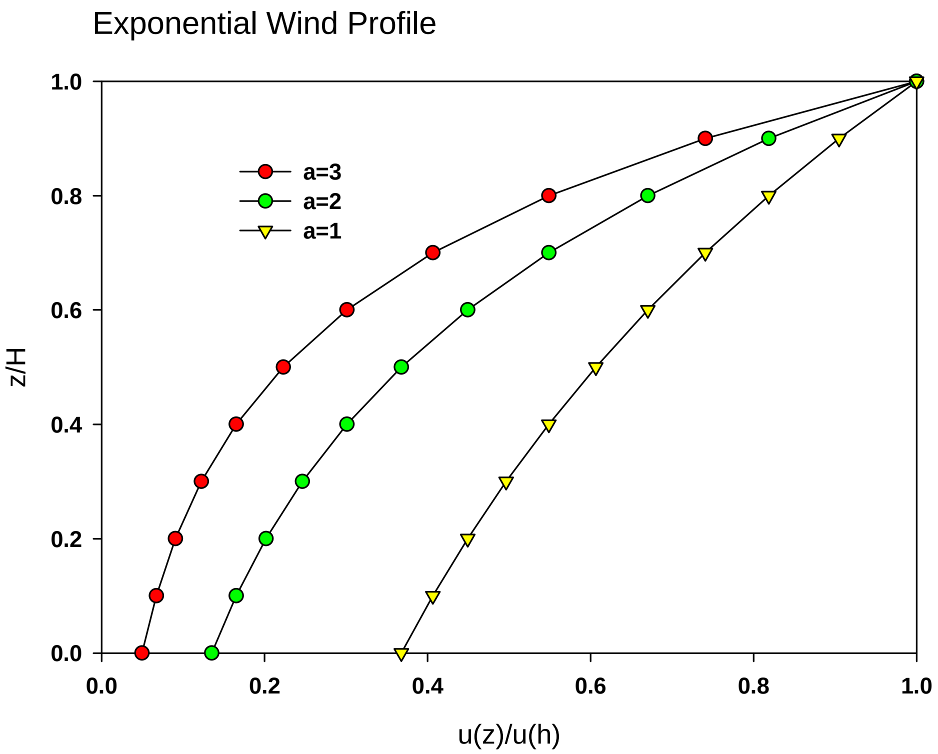
$$u(z) = u_h \exp(\alpha(\frac{z}{h} - 1))$$

Phenomenological studies have parameterized the wind extinction coefficient as a function of canopy height (h), leaf area, and drag coefficients associated with the canopy and leaf elements

$$\alpha = \frac{haC_d^{'}}{2C_d}$$

A survey of values is listed below.

Vegetation	α	**Reference**
immature corn	2.8	[*Cionco*, 1972b]
oats	2.8	[*Cionco*, 1972b]
wheat	2.5	[*Cionco*, 1972b]
corn	2.0	[*Cionco*, 1972b]
Sunflower	1.3	[*Cionco*, 1972b]
Larch		[*Cionco*, 1972b]
deciduous forest		[*Baldocchi and Meyers*, 1988b]
jack pine		[*Amiro*, 1990a]
Spruce	2.4	[*Amiro*, 1990a]
Soybean		[*Baldocchi et al.*, 1983]



The **secondary wind maximum** is a unique aspect of wind flow inside turbulence. It presence had a revolutionary much impact on how we view theoretical transfer of mass and momentum in plant canopies ([*Shaw*, 1977; *Wilson and Shaw*, 1977]. The earliest citation I have found, so far, on wind profiles in forests and their secondary maxima is attributed to Fons [*Fons*, 1940] in 1940s!

The observation of a secondary wind maxima suggests **counter-gradient transfer** since momentum transfer is directed downward and is diminishing with depth, despite the local increase in wind velocity. It also led to a major finding that **K theory is wrong**, when applied in vegetation. Wilson and Shaw [*Wilson and Shaw*, 1977] applied a second order closure model to assess this phenomenon.

The budget equation for Reynold's stress (<w'u'>), assuming horizontal homogeneity, steady-state conditions and neutral buoyancy, can be assessed this observation:

$$\frac{\partial \overline{w'u'}}{\partial t} = 0 = -\overline{w'^2}\frac{\partial \overline{u}}{\partial z} + \frac{\partial \overline{w'w'u'}}{\partial z} + \overline{p'(\frac{\partial u'}{\partial z} + \frac{\partial w'}{\partial x})}$$

Solving for the wind gradient, one can conclude that a reversal in the wind gradient will occur when the transport of Reynold's stress (2^{nd} term on RHS) exceeds the pressure-velocity interaction term, a typical sink for momentum (3^{rd} term on RHS). As will be shown later in this lecture, canopy turbulence is dominated by large-scale coherent structures that are able to transfer much momentum.

This equation can also be manipulated to show how and why K theory fails deep in the canopy. We can parameterize the pressure velocity interaction term as a function of the Reynolds' stress divided by a turbulence time scale, τ: $\overline{w'u'} / \tau$

This reduces to the fact that in the canopy Reynolds stress is not only a function of K theory, but is augmented by the non local transport, defined as the flux divergence of the flux of the momentum flux:

$$\overline{w'u'} = \frac{-\overline{w'^2}}{\tau}\frac{\partial \overline{u}}{\partial z} - \frac{\partial \overline{w'w'u'}}{\tau \partial z} \approx K_m \frac{\partial \overline{u}}{\partial z} - \frac{\partial \overline{w'w'u'}}{\tau \partial z}$$

Thermal stability has an impact on the amount of momentum that is available to the canopy and how it is distributed through the canopy. Stable thermal stratification causes the ratio of u/u* to be greater at night than by day (Figure 2). The stable stratification of the surface and canopy boundary layer reduces momentum transfer, as measured by u* for a given wind speed.

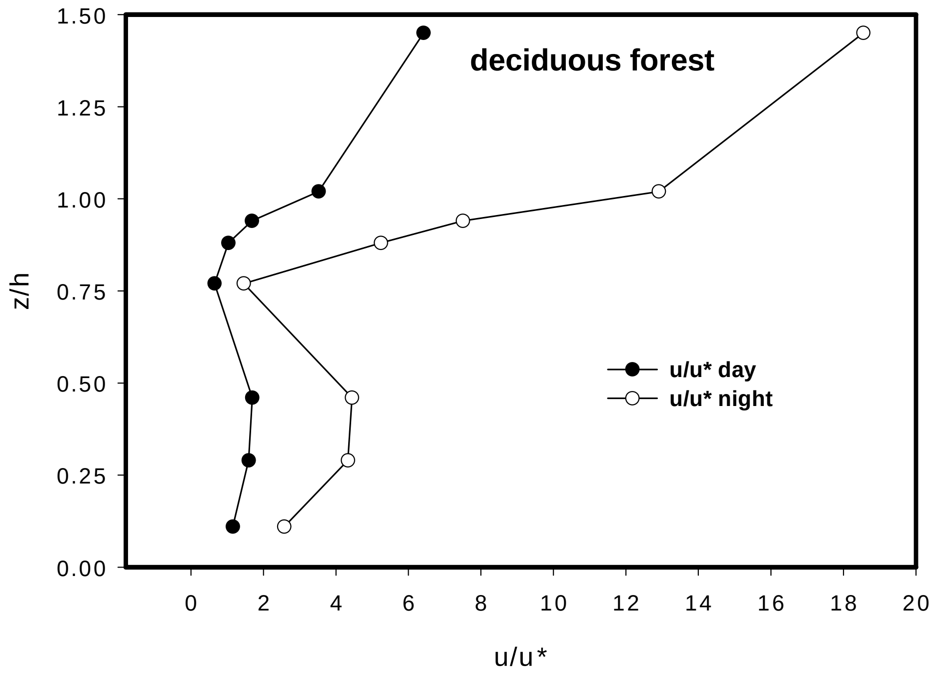


Figure 2 Wind profiles in a deciduous forest during day and night [*Baldocchi and Meyers,* 1988b]

L20.3 Turbulence Statistics: Variance, Skewness and Kurtosis

The mean picture shown above gives one a distorted picture of wind and turbulence since the mean rarely occurs in a plant canopy. It is only the condition of central tendency and is representative of daytime conditions.

If you stand in a field and feel the wind you will notice the passage of large-scale, coherent eddies that have energetic periods. These will be followed by quiescent periods.

The gusts cause the highest wind speeds. They also have exaggerated secondary wind maxima. Under calm conditions one can even observe a reversal in wind speed.   Hence, if you release a smoke plume in a forest, you will notice that the air meanders forward and backward in a canopy, then accelerate for short periods of time.

Below we show wind velocity profiles, normalized by friction velocity, that are subdivided into difference classes, associated with standard deviations. Note how all eddies are not directed longitudinally in a forward direction. Slow moving ejections of air are associated with sloshing and backward moving air. The fastest gusts have greatest shear at the canopy interface and the most exaggerated secondary wind maxima.

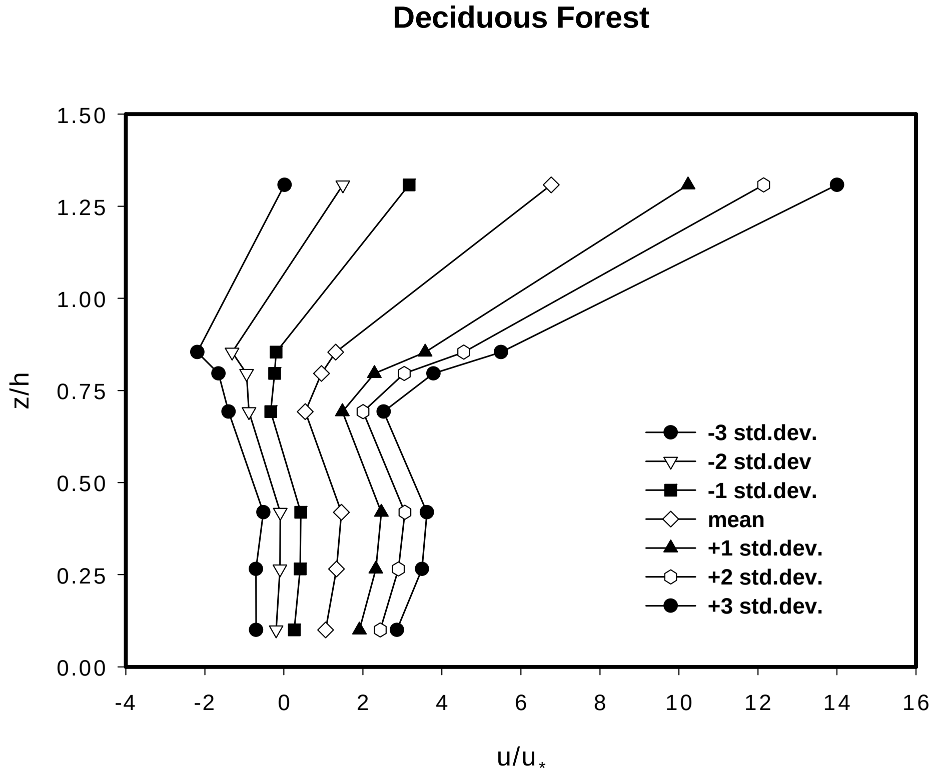


Figure 3 Detailed statistical distribution of wind velocity profiles in a forest. Note the deformation of the wind profile with high and low wind velocities. Unpublished data of Baldocchi and Meyers.

Second, third and fourth order statistics moments are often used to characterize wind and turbulence in plant canopies. The Variance, standard deviation and **turbulence intensity** ($i_u = \sigma_u / U; i_w = \sigma_w / U$) are measures of how steady or unsteady the wind is. The variance has physical importance, as well as statistical, as it is related to turbulent kinetic energy ($\overline{u'^2}$). In the surface boundary layer turbulence intensity is rather small, less than 10%. In contrast turbulence intensity tends to range between 0.5 and one in canopies. Information on turbulence intensities has important consequences on mass, momentum and energy transfer, as high values experienced in crops will perturb the normal and classical develop of boundary layers over leaves (eg Chen, BLM 1988,45, 137-156).

A consequence of high turbulence intensities is that Taylor's Frozen Eddy Hypothesis is violated: $u \cdot t \neq x$. In other words it relates the wavelength of an eddy to the wind speed and the time it takes to pass by a sensor $\lambda \sim u \cdot t$. Taylor's hypothesis assumes that properties of the eddy remain unchanged by the time it passes a sensor. With high turbulence intensity, this assumption is not true.

Data on turbulence intensities in vegetation is shown in Table 1.

Table 1 Turbulence intensities in vegetation [*Amiro*, 1990a; *Amiro and Davis*, 1988; *Baldocchi and Meyers*, 1988b; *Cionco*, 1972a; *Wilson*, 1989]

Canopy	turbulence intensity
Rice	0.33
Vineyard	0.45
wheat	0.50
black spruce	0.51
corn	0.52
soybean	0.52
immature corn	0.52
leafless forest	0.53
broadleaved forest	0.80
larch	0.54
sunflower	0.59
tropical forest	0.76
jungle	1.10
pine plantation	0.53
almond	0.8-1.0
corn	1-4

Though, not shown, it has been observed that turbulence intensities for u are generally greater than those for v and w, indicating that turbulence is not isotropic, but that vortices can have a pan-cake shape at times.

If we go one step further and examine probability distributions of turbulence few find that measures of wind velocity inside a canopy are very **non-Gaussian**. Instead, probability density distributions have positive or negative skewness (depending if one is examining horizontal or vertical velocity) and high kurtosis.

Figure shows the probability distribution for horizontal wind speed measured above and below a forest. Winds inside the canopy are skewed toward greater wind speeds, that are produced by intermittent wind gusts.

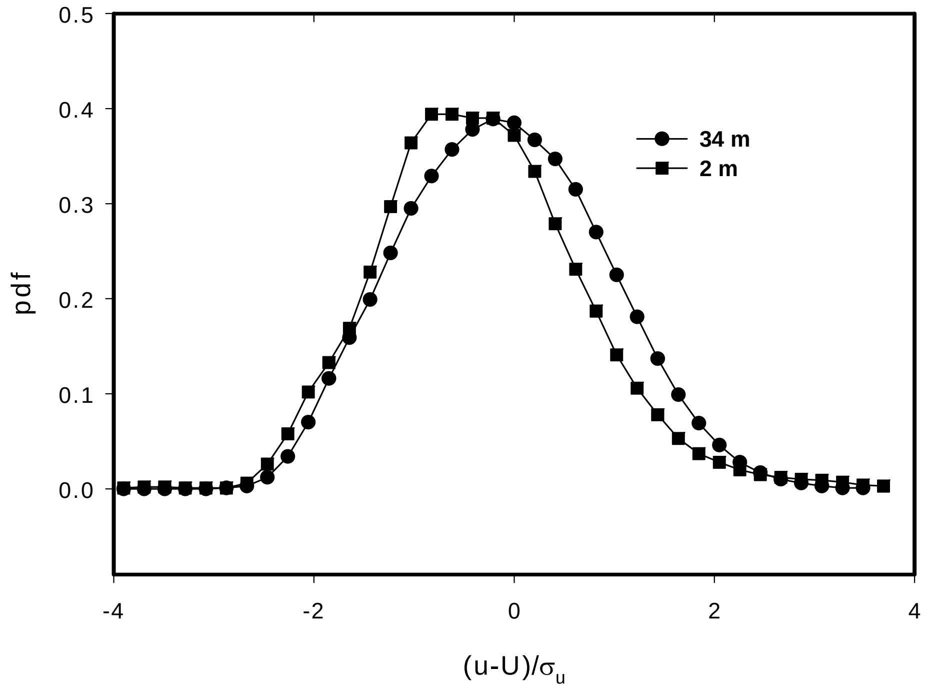


Figure 4 Probability distribution of wind speed above and within a forest [*Baldocchi and Meyers*, 1989]

In contrast the probability distribution for vertical velocity reveals that vertical velocity is skewed towards, negative or downward motions and velocities (Figure 4).

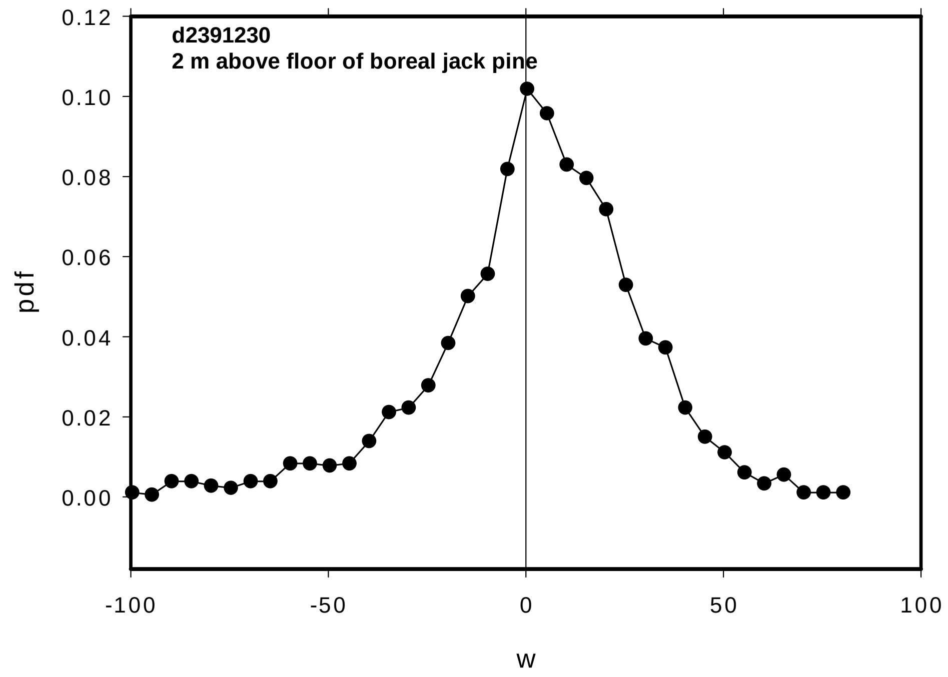


Figure 5 Probability distribution of vertical velocity near the floor of a jack pine forest

A ‘family’ portrait of turbulence statistics, compiled by Raupach et al. [*Raupach et al.*, 1996] and Finnigan [*Finnigan*, 2000] in numerous papers provides an excellent summary of how turbulence varies with depth across a spectrum of canopies, differing in height, leaf area and leaf area distribution, and how they differ from their characteristics in the surface layer.

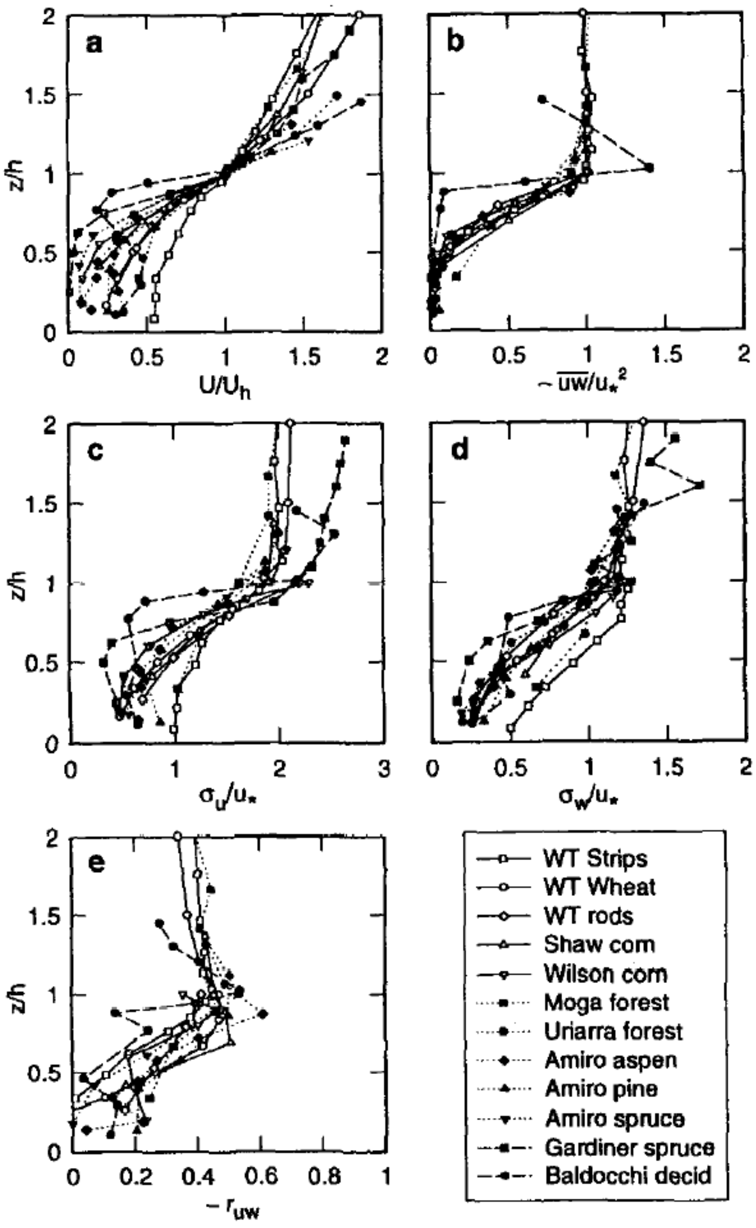


Figure 6 Family Portrait of turbulence in a vegetation [*Finnigan,* 2000; *Raupach et al.,* 1996]. Panel a is horizontal wind velocity normalized by wind velocity at the canopy height; Panel b is Reynolds stress normalized by friction velocity squared; Panel c is the standard deviation in horizontal velocity normalized by friction velocity; Panel d is the standard deviation in vertical velocity normalized by friction velocity; Panel e is the correlation coefficient between vertical and horizontal velocity.

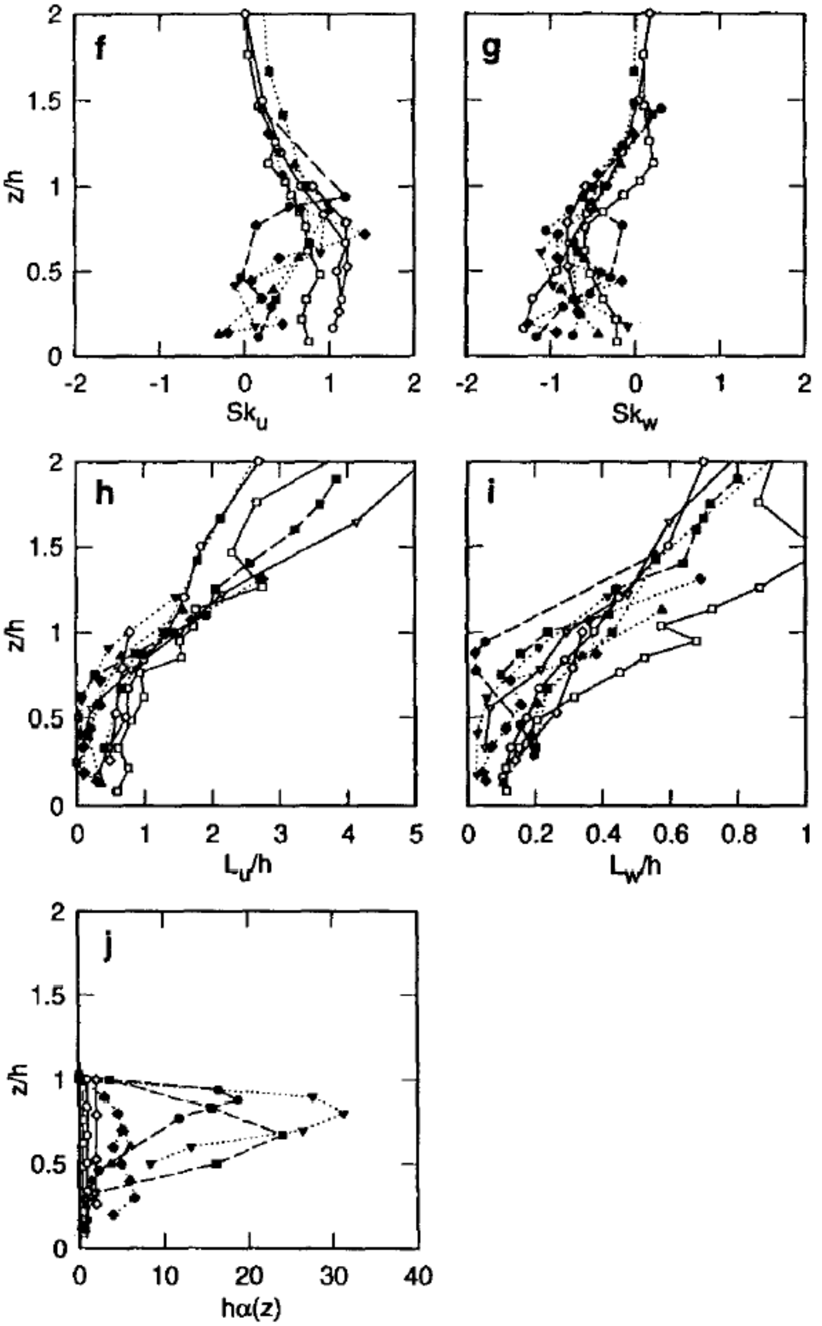


Figure 7 Family Portrait of turbulence above and within vegetation canopies, continued; Panel f is the vertical variation in horizontal velocity skewness; Panel g is vertical variation in vertical velocity skewness; panel h is the vertical profile in turbulent length scale for u; panel I is the vertical profile in turbulent length scale for w; panel j is the vertical profile in leaf area density

Several important characteristics are extracted from these Figures.

1. Turbulence intensities and momentum stress, normalized by friction velocity are invariant above the canopy during neutral conditions (σ_w/u* ~1.25; σ_u/u*~2.2; $\overline{w'u'}/u_*^2$ ~1)
2. Turbulence intensities and momentum stress, normalized by friction velocity, are heterogeneous inside the canopy; they diminish markedly with depth.
3. Skewnesses and kurtoses are greatest near the canopy-atmosphere interface, where shear is greatest.
4. Skewness of u is positive and skewness of w is negative, which is reminiscent of high energy eddies penetrating into the canopy and sweeping the air layer.
5. The correlation coefficient between u and w (r_{uw}) is greatest in magnitude (~-0.6) near the top of the canopy; this is a consequence shear-generated eddies that are large-scale and coherent.
6. Turbulence length scales are on the order of canopy height rather than the size of leaves and plant elements.

The large, coherent and shear-induced turbulent eddies cause turbulent transfer with a vegetated canopy to occur by way of quick sweeps and ejections, followed by a longer quiescent period and a ramping of the concentration of scalar material [*Collineau and Brunet*, 1993; *Paw et al.*, 1993; *Raupach et al.*, 1996]. The sweep and ejection are responsible for most of the momentum, mass and energy transfer and may last less than 10% of the time [*Baldocchi and Meyers*, 1988b; *Finnigan*, 2000; *Shaw et al.*, 1983]. Time-averaged profiles of scalars, on the other hand are heavily weighted by the duration of the quiescent period. For example, during the quiescent period relatively great drawdowns of scalar can occur (when there is a local sink) in comparison to the well-mixed scalar profile that occurs during sweep-ejection event [*Gao et al.*, 1989].

It is noteworthy that many of the features of turbulence at the canopy-atmosphere interface resembles mixing layer flows in engineering [*Raupach et al.*, 1996]. Mixing layers occurs when a plate separates two fluids moving at different speeds and they are allowed to merge downstream. In mixing layers an inflection occurs between the velocity fields of the two fluids. And this inflection induces shear instability. Large scale, coherent eddies are formed that scale with the shear length scale, $L_s = \frac{u(h)}{\partial u(h)/\partial z}$, and they are characterized by large relatively large correlation coefficients between w and u. Furthermore, the turbulent flow is intermittent, as characterized by skewnesses of w and u that are large in magnitude and opposite in sign.

The family portraits of turbulence shown in Figures 11 and 12 do not address the role of atmospheric stability. Drawing on a set of newer and older studies, a few general statements can be made on how atmospheric stability affects turbulence statistics in forests [*Baldocchi and Meyers*, 1988b; *Kruijt et al.*, 2000; *Leclerc et al.*, 1990; *Shaw et al.*, 1988; *Villani et al.*, 2003]:

1) Normalized profiles of momentum transfer are attenuated much more effectively with depth in the canopy during near neutral stability than during stable conditions [*Kruijt et al.*, 2000; *Shaw et al.*, 1988].

2) stable thermal stratification causes normalized values of wind velocity to be greater at night, within the canopy, than by day and accentuates the secondary wind speed maximum deep in the canopy [*Baldocchi and Meyers*, 1988b; *Kruijt et al.*, 2000].
3) Turbulence intensities for w and u are greater throughout the canopy during stable conditions than during near neutral and unstable in some studies [*Kruijt et al.*, 2000; *Villani et al.*, 2003], and vice versa in others [*Baldocchi and Meyers*, 1988b; *Shaw et al.*, 1988].
4) Vertical velocity kurtosis is least during stable conditions [*Baldocchi and Meyers*, 1988b; *Kruijt et al.*, 2000].

Turbulent Kinetic Energy

Velocity variances are important because they relate to turbulent kinetic energy:

$$\frac{1}{2}\overline{q'^2} = \frac{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}{2}$$

Equation 1

Consequently, the turbulent kinetic budget can be derived and can be used to describe how turbulent fluctuations are created and destroyed [*Finnigan*, 2000; *Raupach and Thom*, 1981; *Wilson*, 1988]:

$$\frac{\partial \tfrac{1}{2}\overline{q'^2}}{\partial t} = \underbrace{-\overline{w'u'}\frac{\partial \bar{u}}{\partial z}}_{\textit{shear}} + \underbrace{\frac{g}{\theta_v}\overline{w'\theta_v}}_{\textit{buoyant}} \underbrace{- \frac{\partial}{\partial z}}_{\textit{transport}}\left(\tfrac{1}{2}\overline{q'^2 w'} + \tfrac{1}{2}\frac{1}{\rho}\overline{w'p'}\right) + \underbrace{P_{wake}}_{\textit{wake}} + \underbrace{P_{waving}}_{\textit{waving}} \underbrace{- \varepsilon}_{\textit{dissipation}}$$

Equation 2

Conceptually, the turbulent kinetic energy inside vegetation is produced by shear and wakes (Figure 13). Shear production ($\overline{w'u'}\frac{\partial \bar{u}}{\partial z}$) converts mean kinetic energy to turbulence. Wake production is unique to plant canopies and is associated with work against form drag ($C_d a U^3$). Wake production and work against form drag causes a short-circuiting of the inertial cascade of turbulence in the so-called 'inertial' subrange. Consequently, the power spectrum in the inertial sub-range decays at a rate faster inside forest canopies than the -5/3 slope that is associated with turbulence in the surface layer [*Amiro*, 1990b; *Baldocchi and Meyers*, 1988a; *Kruijt et al.*, 2000; *Villani et al.*, 2003]. On the other hand, atmospheric stability has little impact on turbulence spectra measured in forest canopies [*Villani et al.*, 2003].

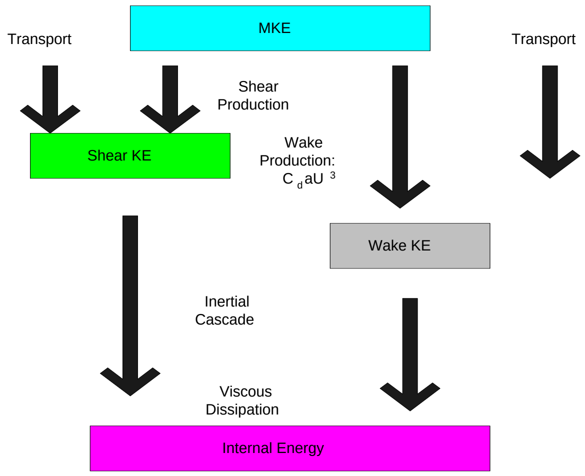


Figure 8 Conceptual Diagram of Turbulent Kinetic Energy Budget in a canopy. [*Wilson*, 1988].

Buoyancy can produce turbulence, while stable thermal stratification can suppress the creation of turbulence. So the buoyancy term can be positive or negative. Generally, buoyant production is a significant source of turbulent kinetic energy in a forest, as the trees intercept sunlight and warm the air [*Leclerc et al.*, 1990; *Meyers and Baldocchi*, 1991]. It is also noteworthy that turbulence can be transported in and out of a region by large scale eddies ($\frac{\partial(\overline{e' w'})}{\partial z}$) or by pressure ($\frac{\partial \overline{p' w'}}{\rho \partial z}$); this is true for both model canopies in wind tunnels [*Brunet et al.*, 1994] and tall forests [*Leclerc et al.*, 1990; *Meyers and Baldocchi*, 1991]. We stress that transport of turbulent kinetic energy does not create or destroy turbulence, it only moves it. Finally, turbulent kinetic energy is destroyed by viscous dissipation and is converted into heat (energy is conserved!).

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