Galileo Galilei: We will understand the movement of the stars long before we understand canopy turbulence

Raupach and Thom, 1981:A warning is necessary about oversimplifications. The micrometeorological custom of searching for scaling schemes using non-dimensional variables is not likely to correct results in canopy-flow studies, except in very simple cases. For this reason, the subject will probably remain partially empirical for some time to come.

June 6, 2005

Structure of atmospheric BL

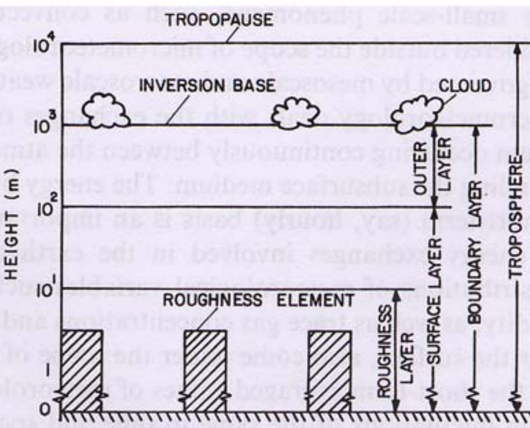


Figure 1.1 Schematic of the planetary boundary layer as the lower part of the troposphere. [From Arya (1982).]

Details on turbulence above and within plant canopies

Material is from:

Finnigan, J. (2000) Turbulence in Plant Canopies. Annu. Rev. Fluid Mech. 32, 519.

Kaimal, J.C. and J.J. Finnigan (1994). Atmospheric Boundary Layer Flows. Oxford University Press, New York.

Markkanen, T., Ü. Rannik, B. Marcolla, A. Cescatti and T. Vesala (2003) Footprints and fetches for fluxes over forest canopies with varying structure and density. Boundary-Layer Meteorol. 106, 437.

Rannik, Ü., T. Markkanen, J. Raittila, P. Hari and T. Vesala (2003) Turbulence statistics inside and over forest: influence on footprint prediction. Boundary-Layer Meteorol. 109, 163.

Raupach, M.R. and A.S. Thom (1981) Turbulence in and above Plant Canopies. Annu. Rev. Fluid Mech. 13, 519.

In some parts, we use notations $u_i = (u, v, w)$ and $x_i = (x, y, z)$.

Roughness sub-layer correction

The influence upon the flow of a canopy of height h is felt throughout a roughness sublayer that extends considerably above $z = h$.

At its upper limit, RSL merges with an inertial sublayer in which the wind profile expressions follow the classical similarity laws.

The presence of the surface has basically twofold influences on the mean wind field

- horizontal inhomogeneity; the effects extends up to about $z = h + D$, where D is the mean inter-element spacing

- perturbation on the horizontally averaged mean wind gradient; the gradient in RSL is less than in ISL, that is $\phi_M < 1$ in ISL, attributed to the wake turbulence by the elements and making the turbulent transport coefficient K_M greater than its ISL value

For a cylinders in the wind tunnel the region of wake influence is about $h + 1.5 l_t$ where l_t is the transverse-element length scale.

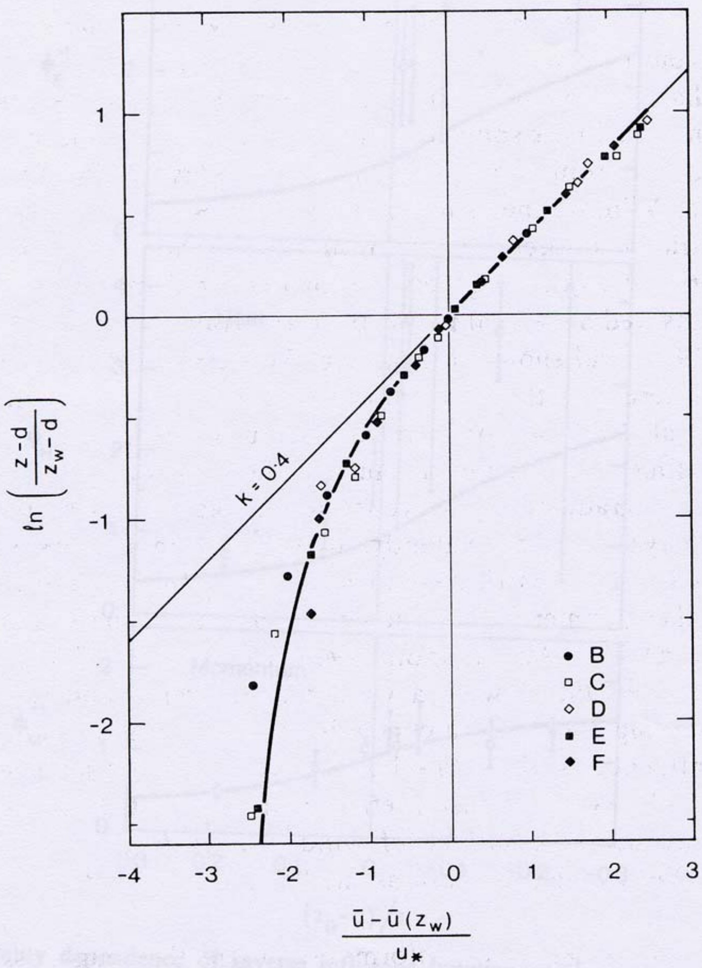


Figure 7 Wind profiles in the roughness sublayer over a series of regularly arrayed rough surfaces of cylindrical elements of height and diameter both 6 mm. The profiles have been normalized so that the point $[z_w - d, \bar{u}(z_w)]$, the top of the region of wake influence, is the origin. For all surfaces shown here, $z_w \approx 15$ mm. Surface descriptions, specifying array type and nearest neighbor separation: *B* (diamond, 56.6 mm); *C* (square, 40 mm); *D* (diamond, 28.3 mm); *E* (square, 20 mm); *F* (diamond, 14.1 mm). Data from Raupach et al (1980).

Rannik *et al.* (2003) presents expressions for mean wind in RSL fitted for Hyytiälä pine forest and the assumption that RSL is located at $h + d$ enabled a good fit the observed profiles.

However, great care must be taken in applying the standard micrometeorological relationships in the layers immediately above vegetation canopies and RSL is often assumed to extend even two or three times the canopy height.

The analysis is even more difficult for the transport of heat and gases since the flow is influenced not only by wake-diffusion but the spatial distributions of sources and sinks for heat and gases.

Similarly, to momentum, the temperature and concentration profiles are modified and the transport coefficient are larger than ISL values.

General features of turbulence in plant canopies

The single-point statistics of turbulence in RSL and in the space within the canopy (and trunk-space) differ significantly from those in the rest of the surface layer. Especially:

- mean wind profile inflected
- second moments inhomogeneous with height
- skewness large
- 2^{nd} moment budgets far from local equilibrium, that is shear production is not simply equal to viscous dissipation
- large coherent structures; sweeps generated by counter-rotating vortices
- aerodynamic drag due to form and skin-friction leads to short-cut in spectra bypassing the inertial eddy-cascade;

- the elements generate turbulent wakes which convert the mean kinetic energy (MKE) into turbulent kinetic energy (TKE) at length scales of elements

- total dissipation rates large

- most plants wave thereby storing MKE as strain potential energy, to release it as TKE

Analysis framework

Classically, the turbulent flow is analyzed by means of time averaging giving rise to the concept of temporal fluctuations due to temporal inhomogeneities in the flow. In the canopy, the flow is inhomogeneous also due to spatial variability.

The effects of the canopy do not appear explicitly in the equations until a horizontal averaging is considered.

Analogously, we introduce the volume averaging of the a scalar or vector function ϕ

$$\langle \phi_j \rangle(\vec{x}, t) = \frac{1}{V} \int\int\int_V \phi_j(\vec{x} + \vec{r}, t) d^3 r \qquad (1)$$

where the averaging volume V

- excludes solid plant parts
- consists of a horizontal slab extensive enough to eliminate plant-to-plant variations
- is thin enough to preserve vertical variations

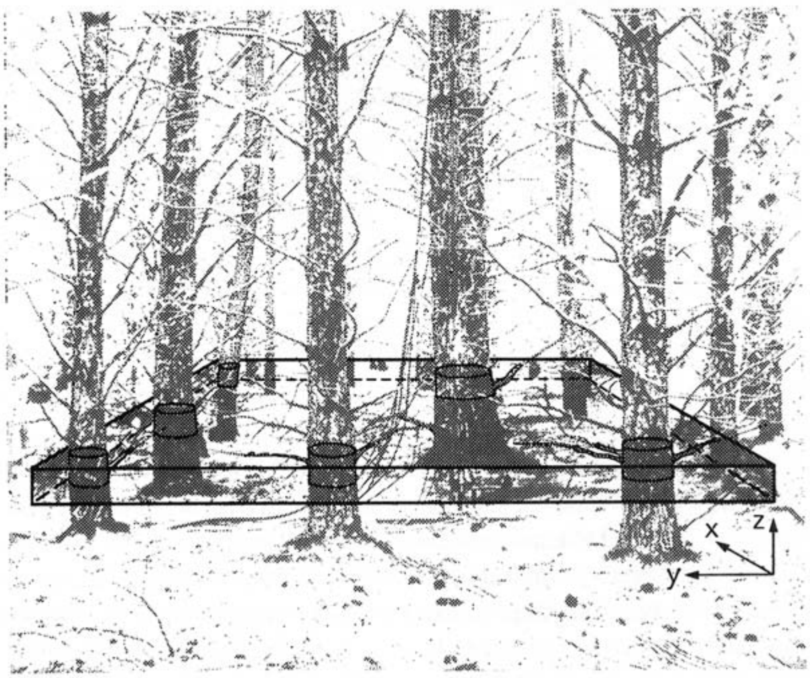


Fig. 3.7. Schematic view of an averaging volume V in a forest. The solid plant parts are excluded from the average, causing V to be a "multiply connected" space.

Thus

$$\phi_j = \langle \phi_j \rangle + \phi_j'' \qquad (2)$$

It is important to note that differentiation and volume averaging are not commuting (that is the average of derivative is not the same as the derivative of the average), if the variable is not constant at air-canopy interface, mathematically

$$\langle \frac{\partial \phi_j}{\partial x_i} \rangle = \frac{\partial \langle \phi_j \rangle}{\partial x_i} - \frac{1}{V} \int \int_{S_t} \phi_j n_i dS \quad (3)$$

where S_t is the sum of all the solid plant surfaces that intersect the averaging volume and n_i is the unit normal vector pointing away from S_t.

Let us consider a simple example of the pressure field for the flow (x_1-axis is along the flow) across a series of adjacent fences

- $\frac{\partial \overline{p}}{\partial x_1} = \frac{\partial \overline{p}''}{\partial x_1}$ since $\frac{\partial \langle \overline{p} \rangle}{\partial x_1} = 0$ ($\langle \overline{p} \rangle$ is constant)

- there is naturally pressure differential in the space between the fences and thus $\frac{\partial \overline{p}}{\partial x_1} = \frac{\partial \overline{p}''}{\partial x_1} \neq 0$, and over the several fences thus $\langle \frac{\partial \overline{p}''}{\partial x_1} \rangle \neq 0$

- however, $\frac{\partial\langle\overline{p}''\rangle}{\partial x_1} = 0$ by definition

- thus the averaging and differentiation do not commute

The resulting first-moment or momentum equation for adiabatic flow is

$$\frac{\partial\langle\overline{u_i}\rangle}{\partial t} + \langle\overline{u_j}\rangle\frac{\partial\langle\overline{u_i}\rangle}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial\tau_{ij}}{\partial x_j} + f_{Fi} + f_{Vi} \quad (4)$$

where

$$\tau_{ij} = -\langle\overline{u_i'u_j'}\rangle - \langle\overline{u_i''u_j''}\rangle + \nu\frac{\partial\langle\overline{u_i}\rangle}{\partial x_j} \quad (5)$$

$$f_{Fi} = \frac{1}{V}\int\int_{S_t} \overline{p} n_i dS \quad (6)$$

$$f_{Vi} = -\frac{\nu}{V}\int\int_{S_t} \frac{\partial\overline{u_i}}{\partial n} dS \quad (7)$$

The second term of τ_{ij} describes the dispersive flux which stems from spatial correlations in the time-averaged velocity field, that is from spatial correlations of regions of mean updraft or down-draft with regions where $\overline{u}$ differs form its spatial mean:

- The dispersive flux is not a truly turbulent flux, since it could also arise if the flow were laminar.

- The dispersive flux is potentially significant not only within the canopy, but also in RSL where constancy of flux with height applies to the sum $\langle \overline{u_1'' u_3''} + \overline{u_1' u_3'} \rangle$ and not to the turbulent component alone.

- it is not yet known (Raupach and Thom, 1981) how significant dispersive fluxes may be in real canopies.

f_{Fi} represents the form or pressure drag and f_{Vi} the viscous drag. Together they form the aerodynamic drag.

The drag converts MKE to TKE in the element wakes, contributing to the very high turbulence levels inside canopies.

Eq. 4 can be compared with the classical time averaged equations and one can notice that simple time-averaged free-air Eqs. are now time and volume averaged.

The similar procedure can be applied to the second moment equations giving the volume-averaged stress budget.

The formula is rather complicated, and considerable simplification is gained by considering only a horizontally homogeneous canopy subject to stationary flow and with the mean wind vector in the surface layer aligned with the x axis. The result is

$$\frac{\partial\langle\overline{u}''\overline{w}''\rangle}{\partial z}+\frac{\partial\langle\overline{u'w'}\rangle}{\partial z}=-\frac{1}{\rho}\langle\frac{\partial\overline{p}''}{\partial x}\rangle+\nu\langle\nabla^2\overline{u}''\rangle \quad (8)$$

Again, the first term represents the dispersive flux. The right-hand side represents the drag due to the canopy. In the absence of them, Eq. simply state that the vertical flux is constant with height.

Similarly for any scalar s

$$\frac{\partial\langle\overline{w}''\overline{s}''\rangle}{\partial z}+\frac{\partial\langle\overline{w's'}\rangle}{\partial z}=D_s\langle\nabla^2\overline{s}''\rangle \quad (9)$$

where D_s is the molecular diffusivity.

The term on the right can be identified as the specific creation density, or emission rate per mass of air of the property s by canopy elements, for example horizontally averaged emission rate of sensible heat, water vapor or carbon dioxide.

There is some evidence that $\overline{u's'}$ alone successfully measures property fluxes in RSL above forest canopies, suggesting that the dispersive mechanisms are not significant for scalars.

We can summarize:

- wakes and boundary-layers of individual plant elements appear as spatial correlations

- coherently waving canopies appear as surface integrals

- volume averaging removes the dependence on stochastic distribution of foliage but note that rarely, if ever we measure volume-averaged variables, since sensors are placed in the open spaces (this is true also for example with radiation measurements in canopies)

Characteristics of canopy turbulence

Let us look at canopy wind profiles and the height dependence of turbulence first.

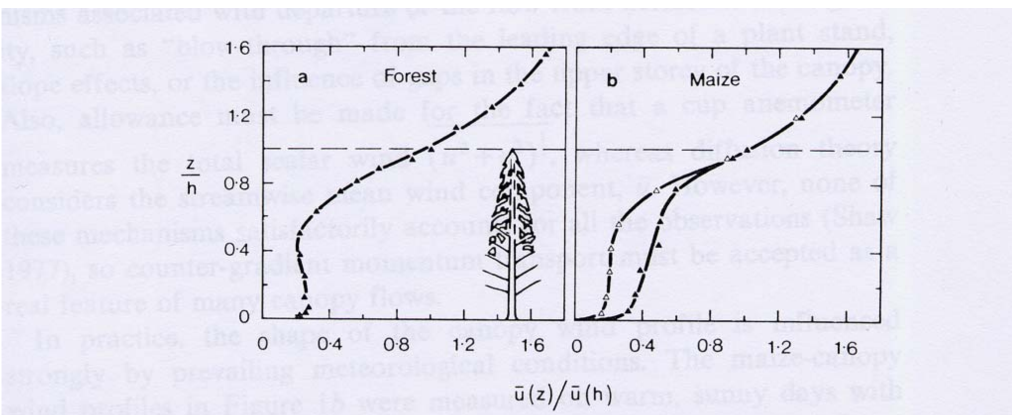


Figure 1 (*a*) Profile of mean wind speed in a pine forest canopy ($h = 16$ m); data averaged from 18 very-near-neutral one-hour runs. (*b*) Profiles of mean wind speed in a maize canopy ($h = 2.1$ m) during periods of light wind [$\bar{u}(h) = 0.88$ m s^{-1}, ▲] and strong wind [$\bar{u}(h) = 2.66$ m s^{-1}, △].

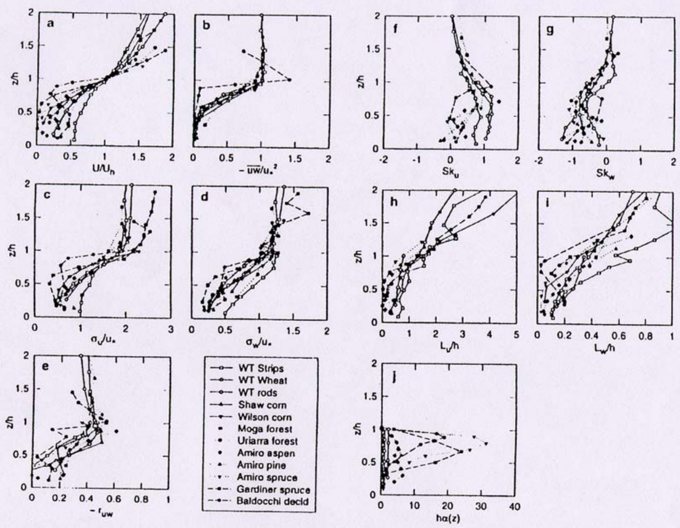


Figure 1 (a–e) A "family portrait" of canopy turbulence for canopies A to L in Table (1), showing profiles with normalized height z/h of (a) $U/U_h = \langle\overline{u_1}\rangle(z)/\langle\overline{u_1}\rangle(h)$; (b) $-\overline{u'w'}/u*$; (c) $\sigma_u/u*$; (d) $\sigma_w/u*$; (e) $-r_{uw} = -\overline{u'w'}/\sigma_u\sigma_w$; (f) Sk_u; (g) Sk_w; (h) L_u; (i) L_w; (j) $h\alpha(z)$ where $\alpha(z)$ is leaf area per unit volume. L_u and L_w are defined in equation (3.1). Figure from Raupach et al (1996)

The main features are

- $\dfrac{\overline{u_1(z)}}{\overline{u_1(h)}}$ has an inflection point at $z = h$; within the canopy the ratio is roughly exponential

- max shear occurs at $z = h$ and high shear in the upper part; very low to negligible shear in the lower part; highly sheared layer may exist close to the ground

- reversal of the wind gradient may occur in the lower part, resulting in the secondary maximum

- wind profiles are also influenced by prevailing meteorological conditions; in the previous Fig. there is relatively more wind in the light wind conditions, since free convective activity (data was collected during sunny days)

- σ_u and σ_w are strongly inhomogeneous

- correlation coefficient r_{uw} gives the efficiency of momentum transport; it is more efficient at canopy top

- the skewness of u is order of 1 and the skewness of w is order of -1.

Widely used (although it is just a single-parameter empirical fit) formula predicting the wind profile well is

$$\frac{U(z)}{U(h)} = \exp(\alpha(z/h - 1)) \qquad (10)$$

where α usually lies between 2 and 3.

The following Figs. presents the model calculations by Markkanen et al. (2003) for wind velocities and standard deviation of w for different LAI and different leaf area distributions, shown in the first Fig.

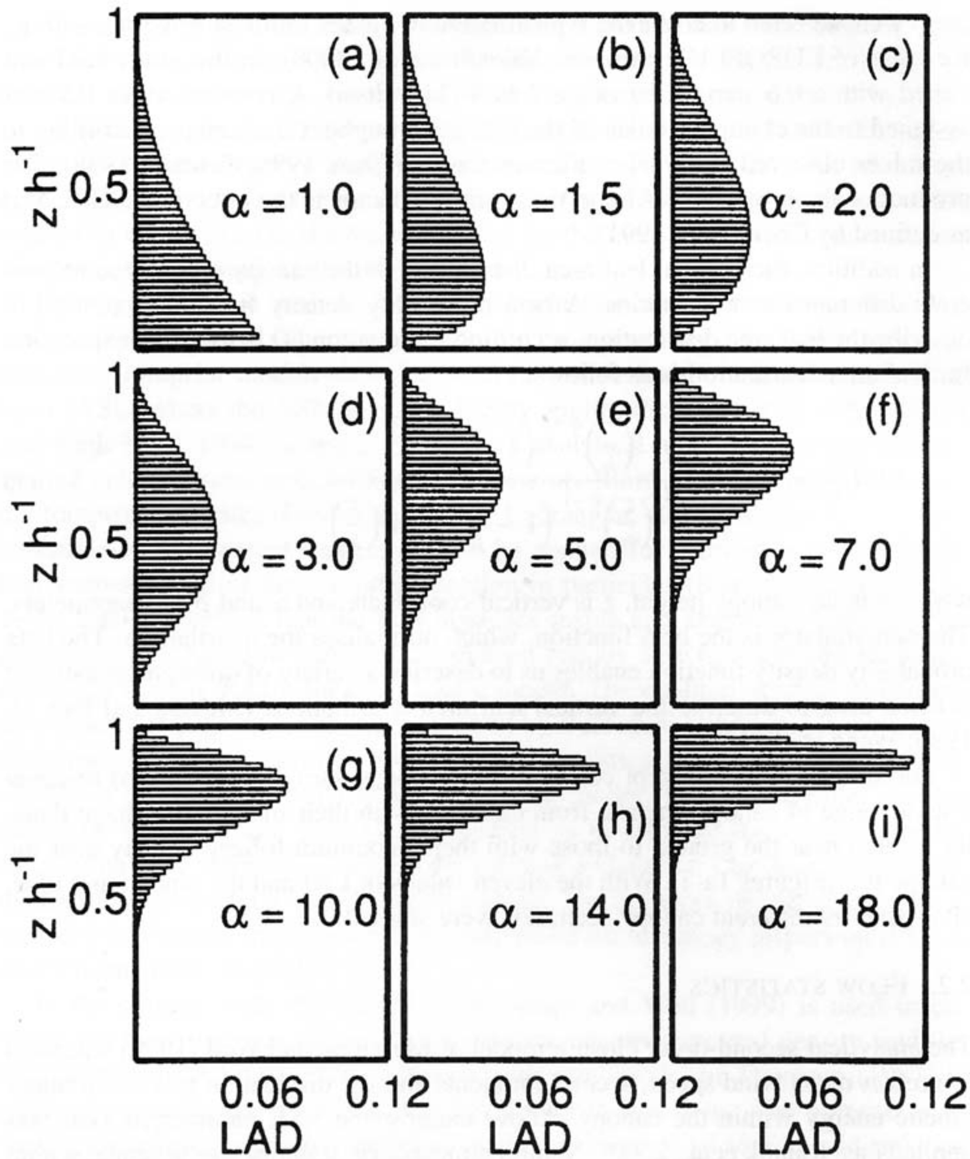


Figure 1. Leaf area distributions (LAD) used in the analysis. The parameter β has a constant value of 3 in nine cases studied. The parameter α governs the vertical distribution of the leaf area.

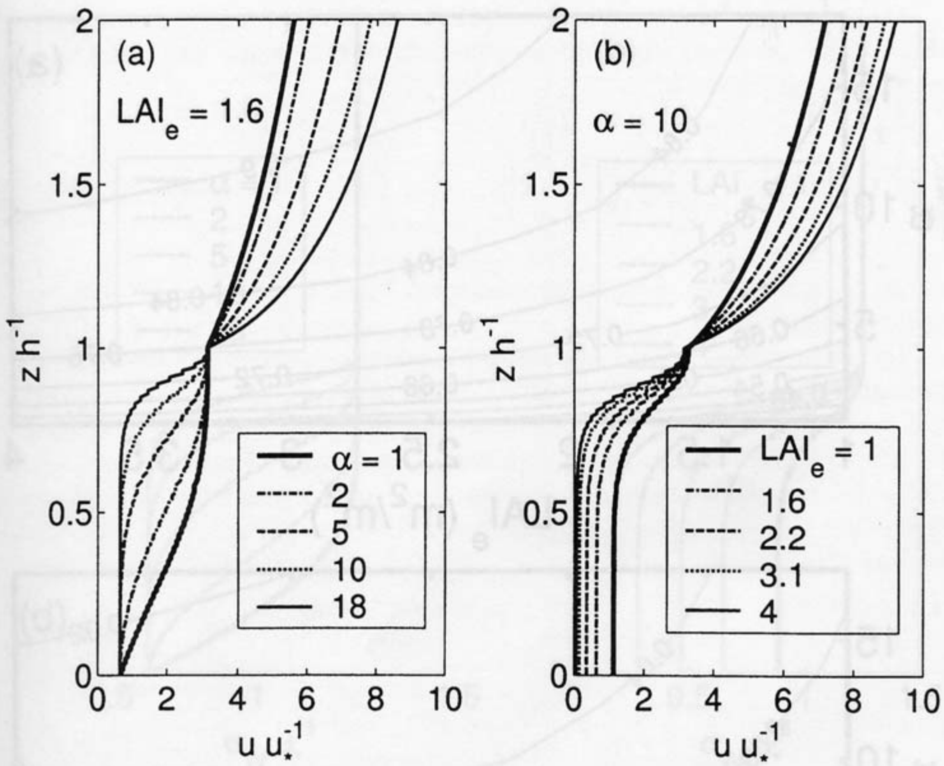


Figure 2. Normalised mean wind velocity uu_*^{-1} as a function of normalised height zh^{-1}; (a) LAI_e = 1.6 and α varies, (b) α = 10 and LAI_e varies as indicated.

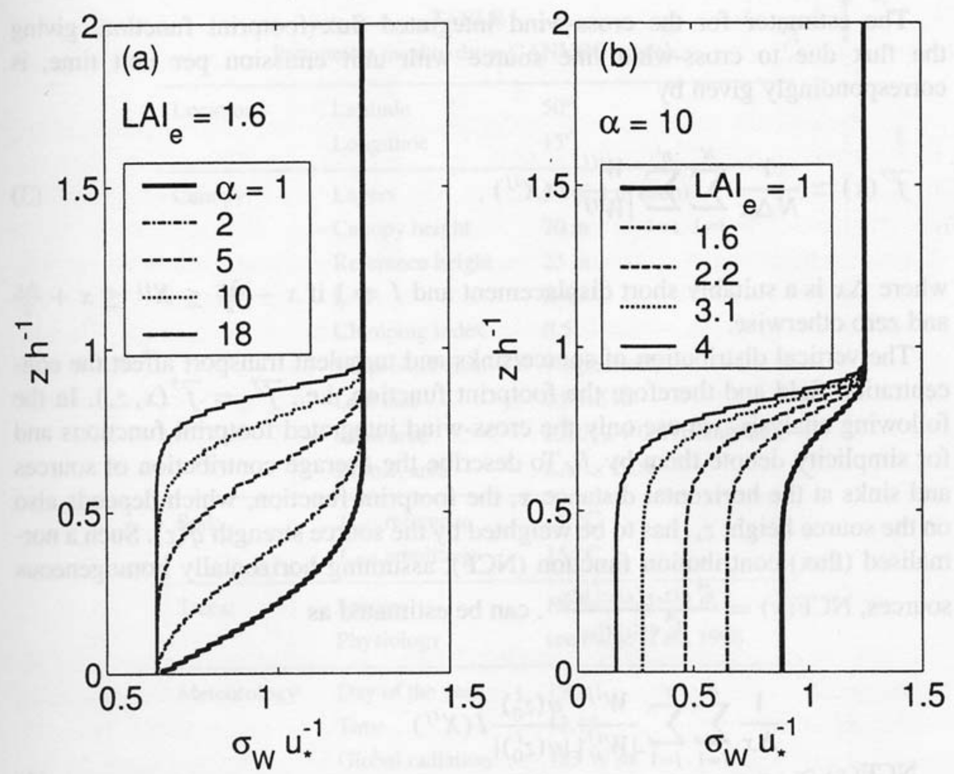


Figure 4. Normalised standard deviation of vertical wind velocity $\sigma_w u_*^{-1}$ as a function of normalised height zh^{-1}; (a) $\mathrm{LAI}_e = 1.6$ and α varies (b) $\alpha = 10$ and LAI_e varies as indicated.

CHANGE IN LECTURE NOTES.

The correlation c_{uw} is typically of the order of -0.35 at levels above RSL but reaches values as high as -0.6 at the top of tall vegetation, indicating highly organized nature of the flow.

The next Figs. show typical profiles of skewness and the skewness and kurtosis determined for a Scots pine forest in Hyytiälä.

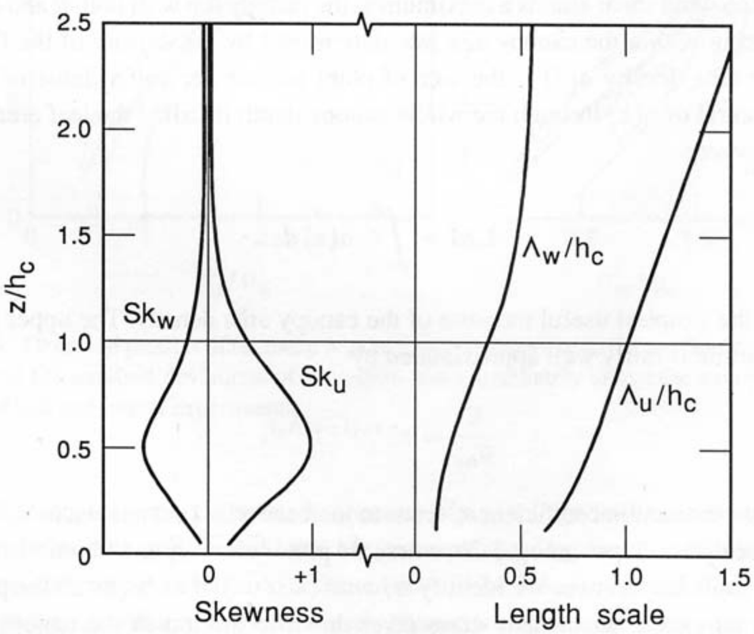
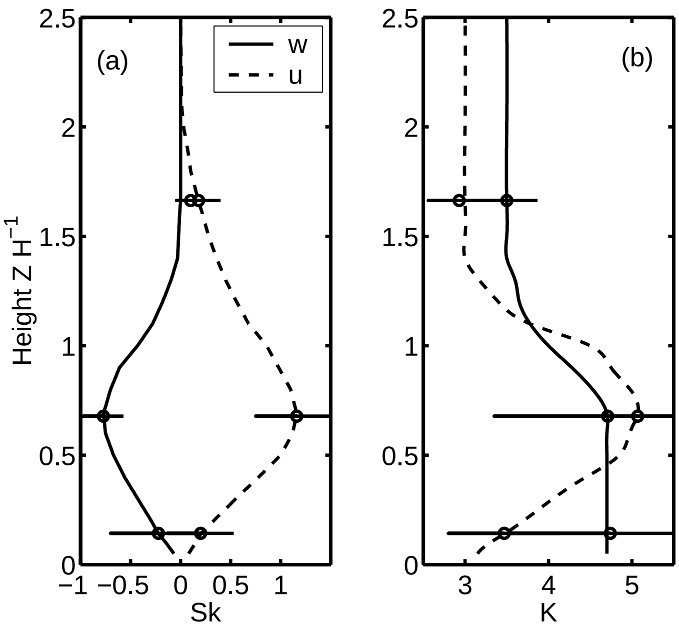
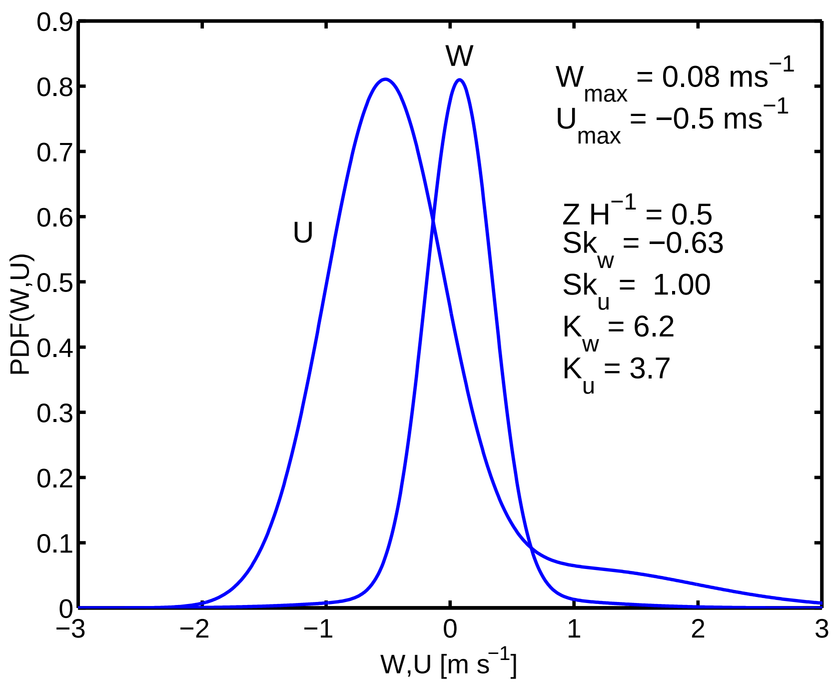


Fig. 3.4. Typical profiles of skewness and normalized integral length scales for u and w within and above the same range of canopies as in Fig 3.3.



The next Fig. illustrates the typical (not measured) pdfs for u and w components.



It is very important to note that within the canopy no local relationship between the flux and the gradient necessarily exists since counter-gradient transport may occur due to intermittent coherent structures. Conventional diffusion theory may be seriously in error in the canopy environment.

With sufficient homogeneous upwind fetch, the momentum flux must be downward since there are no source of mean momentum anywhere in the canopy; therefore counter-gradient momentum transport is occurring in regions where $\frac{\partial \overline{u}}{\partial z} < 0$

The next Fig. illustrates the counter-gradient transport for scalars.

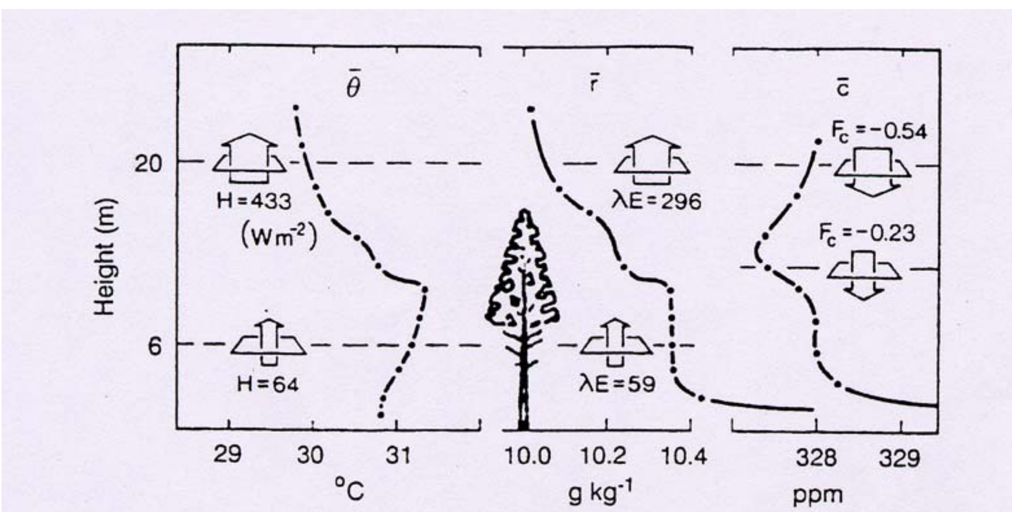


Figure 2 Simultaneous fluxes and gradients of heat and temperature, latent heat and water vapor mixing ratio and carbon dioxide (gm m^{-2}s^{-1}) and ppm. Obtained in a pine forest (Canopy G of Table 1). Figure from Denmead & Bradley (1987).

The underlying reason for this kind of behaviour is twofold

- turbulence is inherently nonlocal; diffusion equation can only describe transport if the length scales of flux-carrying motions are much smaller than the scales over which average gradients change appreciably

- multiplicity of length and velocity scales; the diffusivities cannot be determined on dimensional grounds since the scales are not unique

Coherent eddies

In the canopy, the consistent patterns may occur in streamwise and vertical two-point space-time correlations.

Within the apparent chaos, there exist large structures distributed randomly, with finite lifetimes and with length scales ranging from surface-element scale to the BL thickness.

The single-point statistics can provide spatial information if Taylor's frozen turbulence hypothesis is valid, but it is questionable in high-intensity canopy turbulence.

So called conditional analysis or conditional sampling is based on consideration of four sign combinations and can provide some structural information

Quadrant 1: $u' > 0$; $w' > 0$; outward interaction

Quadrant 2: $u' > 0$; $w' < 0$; sweep

Quadrant 3: $u' < 0$; $w' < 0$; inward interaction

Quadrant 4: $u' < 0$; $w' > 0$; ejection

Stress is thus transported downwards by ejections and sweeps and upwards by two interaction events, so that the overall stress is naturally downwards.

The major contributor to the momentum transport is sweep which correspond to the penetration of fast, downward moving gusts. Sweeps can be individually very large: 50% of stress is being delivered in less than 10% of the time, that is they are very intermittent.

The next most important is ejection.

The others are significant only in coherently waving canopies.

The next Figs. shows the joint probability density functions (pdf) of four quadrants and stress fractions over a rough surface.

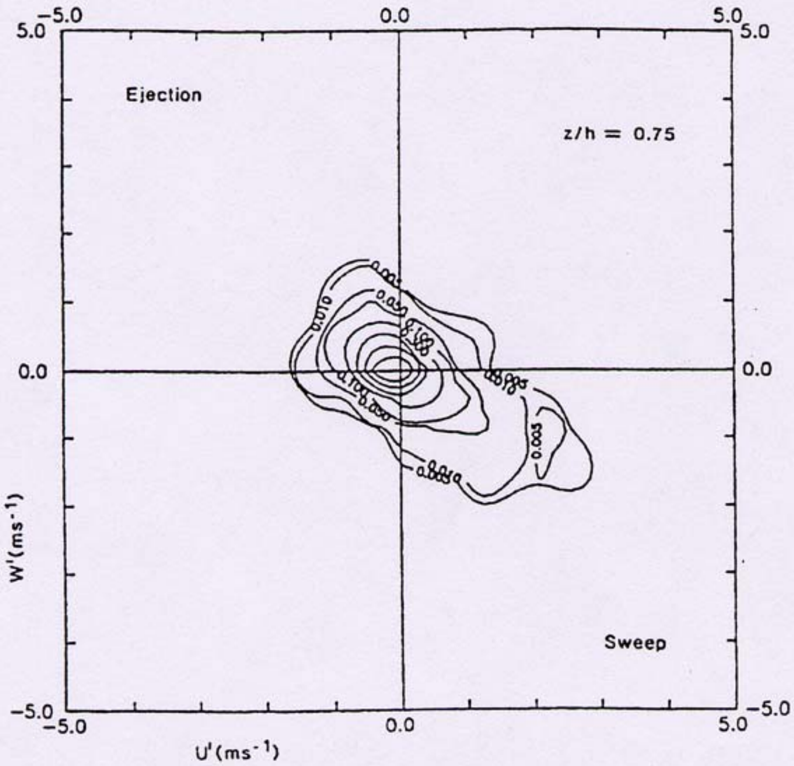


Figure 5 Contours of the joint pdf of $U' = u'/\sigma_u$ and $W' = w'/\sigma_w$ measured in a spruce forest. Figure from Gardiner (1994).

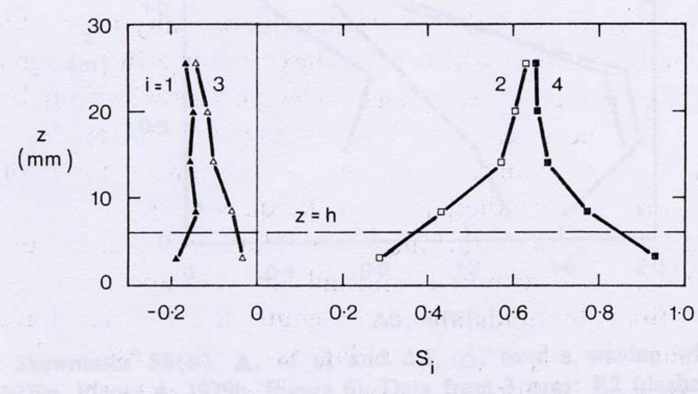


Figure 10 Stress fractions S_i over a rough surface of cylindrical elements of height 6 mm (surface *F*, Figure 7): ▲, outward interaction ($i = 1$); □, ejection ($i = 2$); △, inward interaction ($i = 3$); ■, sweep ($i = 4$). Data from Raupach (1981).

The same features are valid for scalars, for which kind of ramps and microfronts may occur. Temperature field exhibits a sloping microfront between warm air being ejected from the canopy, and cool air being swept into the canopy.

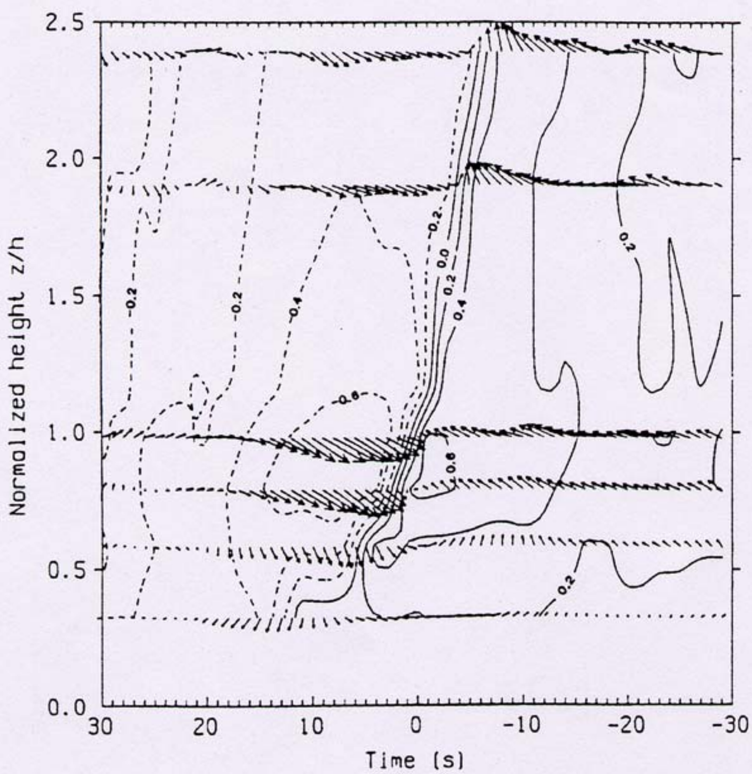


Figure 6 Time-height plot of ensemble averaged temperature and fluctuating velocity fields measured in moderately unstable conditions ($L = -138$m, where L is Monin-Obukhov length) in a 18-m-tall mixed forest. Dashed lines are isotherms below the mean and solid lines are isotherms above the mean. Contour 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).

Pressure perturbations are also closely connected to coherent structures. The pressure pulse is a consequence of the convergence in the flow field and is a dominant influence on the air flow lower in the canopy.

CHANGE IN LECTURE NOTES.

Turbulent fine structure

In the canopy, momentum is absorbed from air stream over an extended vertical region rather than just at the surface plane. It affects

- aerodynamic drag
- eddy cascade
- spectral shapes

- viscous dissipation

- TKE budget

Aerodynamic drag

The force per unit volume $F_i \equiv f_{Fi} + f_{Vi}$ can be parameterised

$$F_i(\vec{x}) = -C_D(\vec{x})a(\vec{x})\langle\overline{u_i}\rangle|\overline{u}| \tag{11}$$

where $|\overline{u}| = \sqrt{\langle\overline{u_i}\rangle\langle\overline{u_i}\rangle}$ and a is the local foliage per unit volume.

C_D is a drag coefficient and it depends on the Reynolds number, which ranges from 100 to 10^5 from near ground to upper, well-ventilated part.

Kinematic pressure drag C_{DF} is order of 0.5 when $10^3 < Re < 10^5$ and order of 1 when $Re < 100$.

For the viscous drag $C_{DV} \sim \sqrt{Re}$.

C_{DF} is the major component. Note that C_D of individual elements has been found to be larger by the factors up to 3 and 4 than that *in situ*, due to shelter effect (not completely understood).

Turbulence intensities and spectra

The longitudinal turbulence intensity $i_u = \frac{\sigma_u}{\overline{u}}$ is higher within canopies than above them. i_u increases with canopy density, typically from 0.4 (crops) to 0.6 (temperate forests) to 0.7-1.2 in tropical forests.

The lateral and vertical components are usually proportional to i_u such that $i_w < i_v < i_u$. Close to the ground, i_w usually decreases rapidly because vertical fluctuations are constrained there.

Frequency spectra can be again used as a window on the fine structure of turbulence.

The spectral peaks do not seem to change as we descend into the canopy.

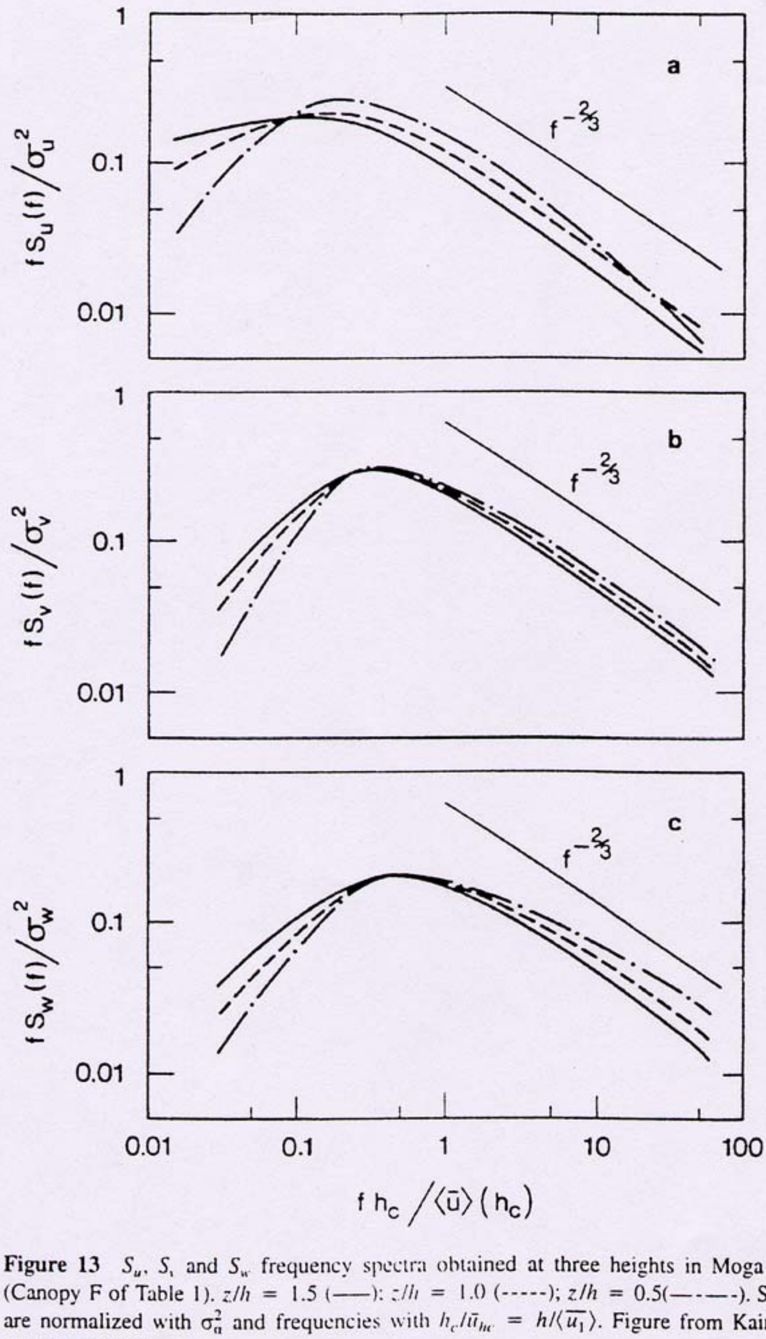


Figure 13 S_u, S_v and S_w frequency spectra obtained at three heights in Moga forest (Canopy F of Table 1). $z/h = 1.5$ (——); $z/h = 1.0$ (-----); $z/h = 0.5$(—-—-). Spectra are normalized with σ_α^2 and frequencies with $h_c/\bar{u}_{hc} = h/\langle\overline{u_1}\rangle$. Figure from Kaimal & Finnigan (1994).

Above a vegetation canopy the spectra scale with a dimensionless frequency $f = \frac{n(z-d)}{\overline{u}}$. within the canopy, spectra do not scale with any dimensionless frequency, rather their peak frequency n tends to be independent of height.

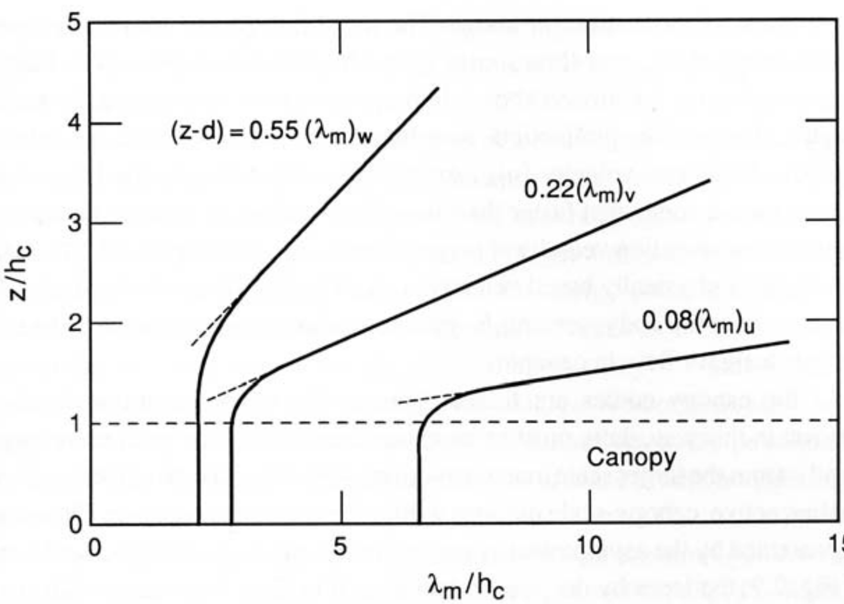


Fig. 3.13. Wavelength of the spectral peak, normalized by canopy height h_c, shown as a function of z/h_c. The peak wavelength stays invariant with height within the canopy (scaling with h_c) but quickly increases with height above the canopy top consistent with the neutral surface layer relationship in Fig. 2.9.

Kolmogorov's theory of equilibrium of high Reynolds number turbulence states that

- spectral gap of 10^2 - 10^3 between the energy containing scale Λ and microscale η is required for one-decade ISR to exist

- conversion from wave numbers (formulated by them) to frequencies (f) assumes Taylor's hypothesis

- ISR turbulence is isotropic that is eddies forget large scale anisotropy; this implies that $S_v(f) = S_w(f) = 4/3 S_u(f)$

- no process adding or subtracting TKE from ISR eddies

Neither of these are fulfilled in the canopy.

Compared to above-canopy conditions,

- S_u roll-offs more quickly in ISR

- S_w roll-offs more slowly

- S_v is about the same, that is slope is -2/3 for frequency-weighted frequency spectra

The next Fig. shows the schematic energy spectrum function ($\int_0^\infty K(\kappa)d\kappa = \frac{1}{2}\langle\overline{u_i'u_i'}\rangle$).

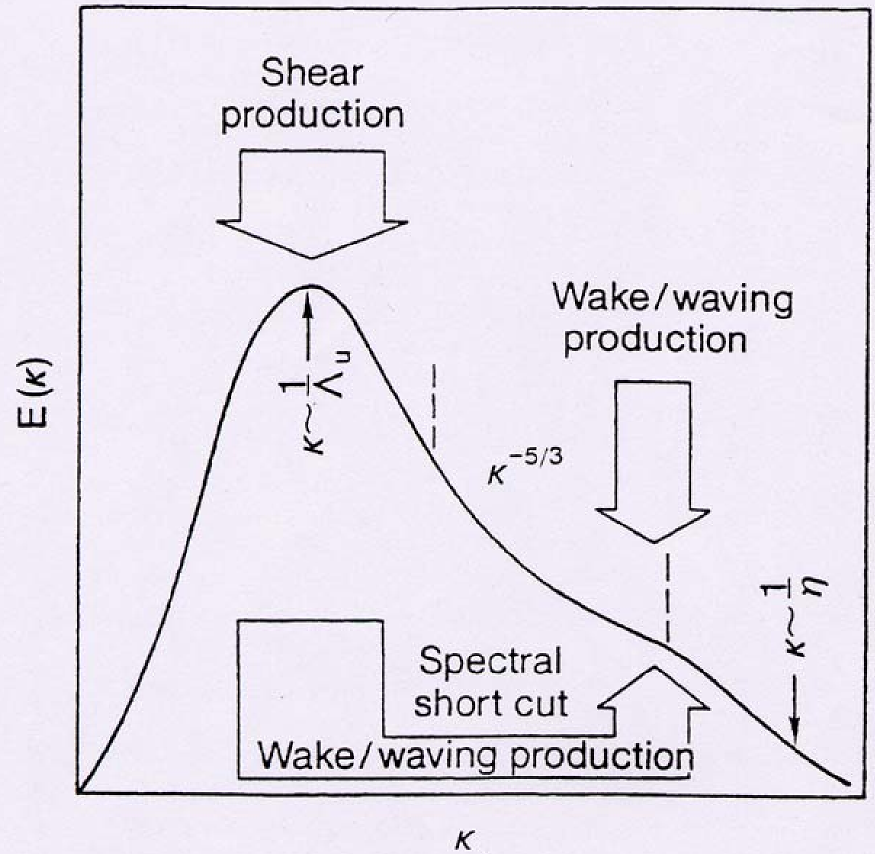


Figure 14 Schematic diagram illustrating the extra processes that must be accounted for in theories of spectra in canopies.

As the mean flow work against aerodynamic drag of the foliage, MKE $= \frac{1}{2}\langle\overline{u_i}\rangle\langle\overline{u_i}\rangle$ is directly converted into heat and fine-scale turbulence in the wakes (WKE).

Eddies of all scales (bigger than canopy elements) lose TKE to heat and WKE, which affects the different spectral components to different degrees and this further leads to anisotropy.

The spectral shape of ISR is modified.

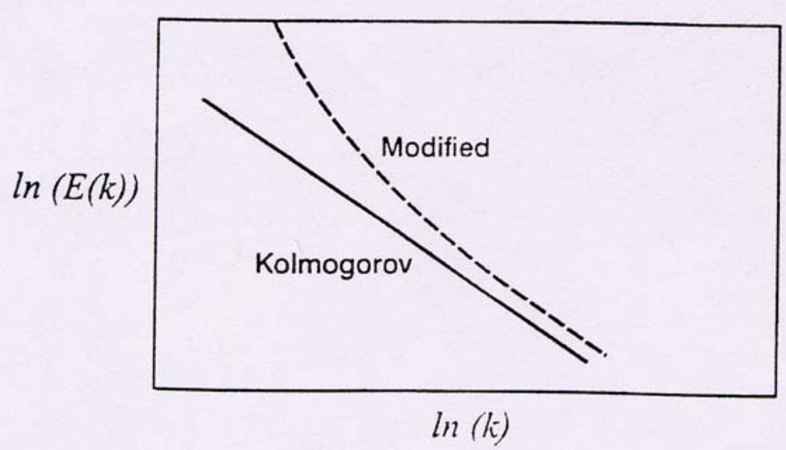


Figure 15 The modified spectral shape in the inertial subrange obtained from Equation 6.12 using parameters appropriate to Moga Forest (Canopy F, Table 1). The standard Kolmogorov form for the same dissipation ϵ is included for comparison.

TKE budget

The consideration of TKE budget brings together what we have discussed above.

The production of TKE occurs

- at $z = h$ there is a strong peak in shear production
- below $z = h$ there is wake production, which is the dominant term except very close to the canopy top

The dissipation occurs

- due to wake production by mean flow

- due to wake production by large scale eddies based on the same mechanism as by the mean flow

- modified, reduced eddy cascade

Considering stationary flow and a horizontally homogeneous canopy, the time-averaged TKE budget at a single point appears as (Raupach and Thom, 1981)

$$0 = -\langle\overline{u'w'}\rangle\frac{\partial\langle\overline{u}\rangle}{\partial z} - \langle\overline{u_i'u_j'}''\frac{\partial\overline{u}_i''}{\partial x_j}\rangle$$

$$-\frac{\partial}{\partial z}(\frac{\langle\overline{p'w'}}{\rho} + \frac{1}{2}\langle\overline{w'u_i'u_i'}\rangle + \frac{1}{2}\langle\overline{w}''\overline{u_i'u_i'}''\rangle) - \langle\epsilon\rangle \quad (12)$$

Note that the first, third, fourth and sixth terms correspond the classical TKE budget equation.

The remaining terms are unique to the canopy environment

- fifth term represents the transport of TKE by a dispersive flux; as with the corresponding momentum transport term in Eq. 5 its importance is unknown

- second term is wake production term and thus is of much more certain significance

The next Fig. illustrates the TKE budget in a model what canopy.

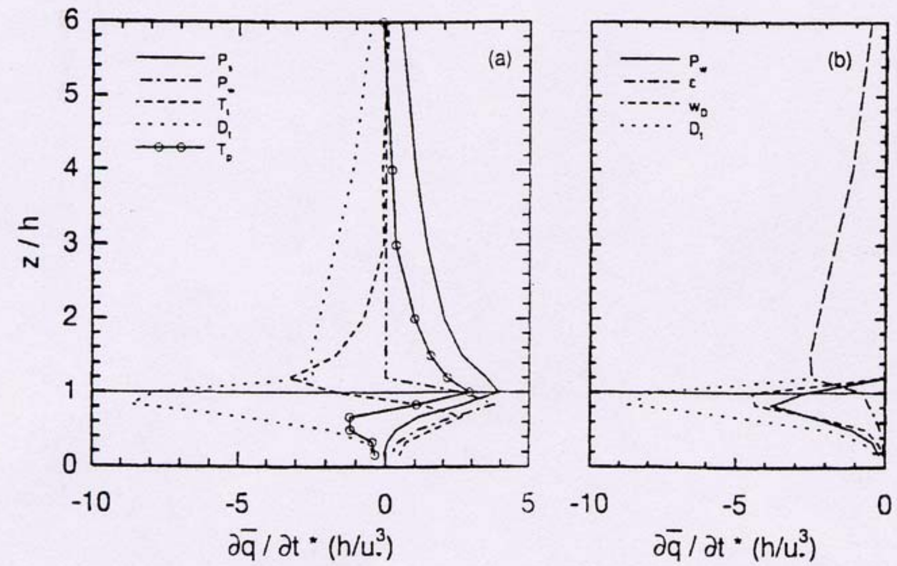


Figure 17 (a) TKE budget in a model wheat canopy calculated from the data of Brunet et al (1994). Symbols refers to Equation 7.1. (b) Breakdown of the total dissipation term *Dt* into the negative of wake production, $-P_W$, the eddy cascade component ϵ and the work done by turbulence against drag, W_D.

P_s correspond to the first term, P_w to the second term, T_t to the turbulent transport term (fourth one) and T_p the pressure transport (third term).

D_t is the total dissipation term, the breakdown of which is presented in Figure b.

Some comments on transport:

- there exists loss near the top and gain in the lower canopy

- T_t occurs via coherent large eddies

- pressure transport T_p is almost mirror image of T_t

Some of the transport terms are very difficult to assess (like pressure transport) but it is clear that large terms and a balance far from local equilibrium are features of the canopy.

Note finally that the eddy timescale drops abruptly as we descend into the canopy.

Future directions

Diabatic effects:

- large values of $|\frac{h}{L}|$ are required before significant influence of buoyancy is discernable

- most solar radiation is absorbed in the upper 30% of closed canopies, which may lead to at day to stably stratified lower canopy and weak gravity waves and under stable conditions K-H instabilities and gravity waves in the upper canopy

- importance for scalar (like carbon dioxide) transport

The next Figs. show typical mean potential temperature and humidity profiles.

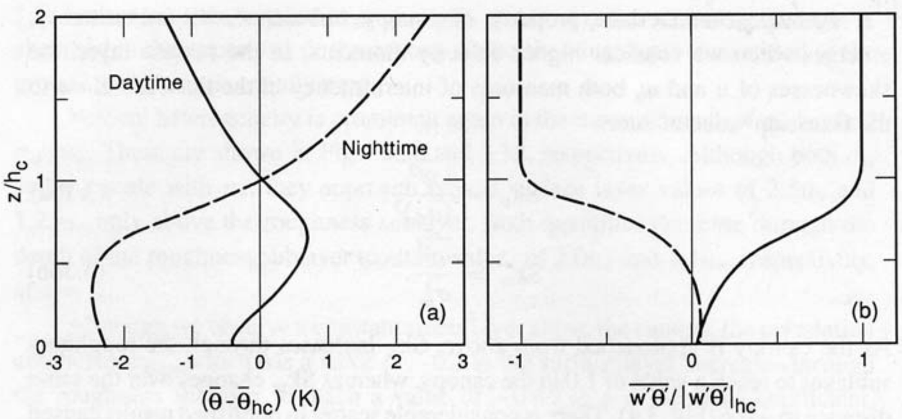


FIG. 3.5. Typical mean potential temperature and heat flux profiles in and above the canopy for daytime and nighttime conditions.

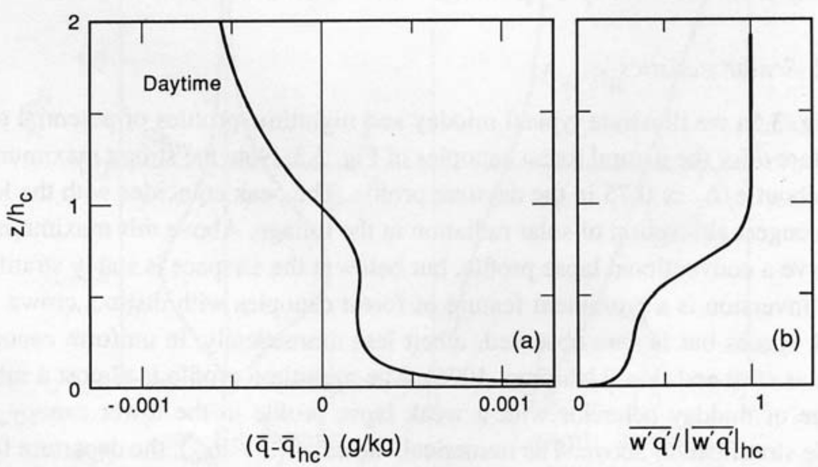


FIG. 3.6. Typical daytime mean humidity and humidity flux profiles in and above the canopy when the ground is moist.

Inhomogeneous flows:

- multiple measurements towers required

- canopies in hills
- non-uniform canopies
- these affect inflection-point profiles
- sparse canopies lead to superposition of wakes of isolated plants