Turbulence and transports in vegetation canopies

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CONTENT:

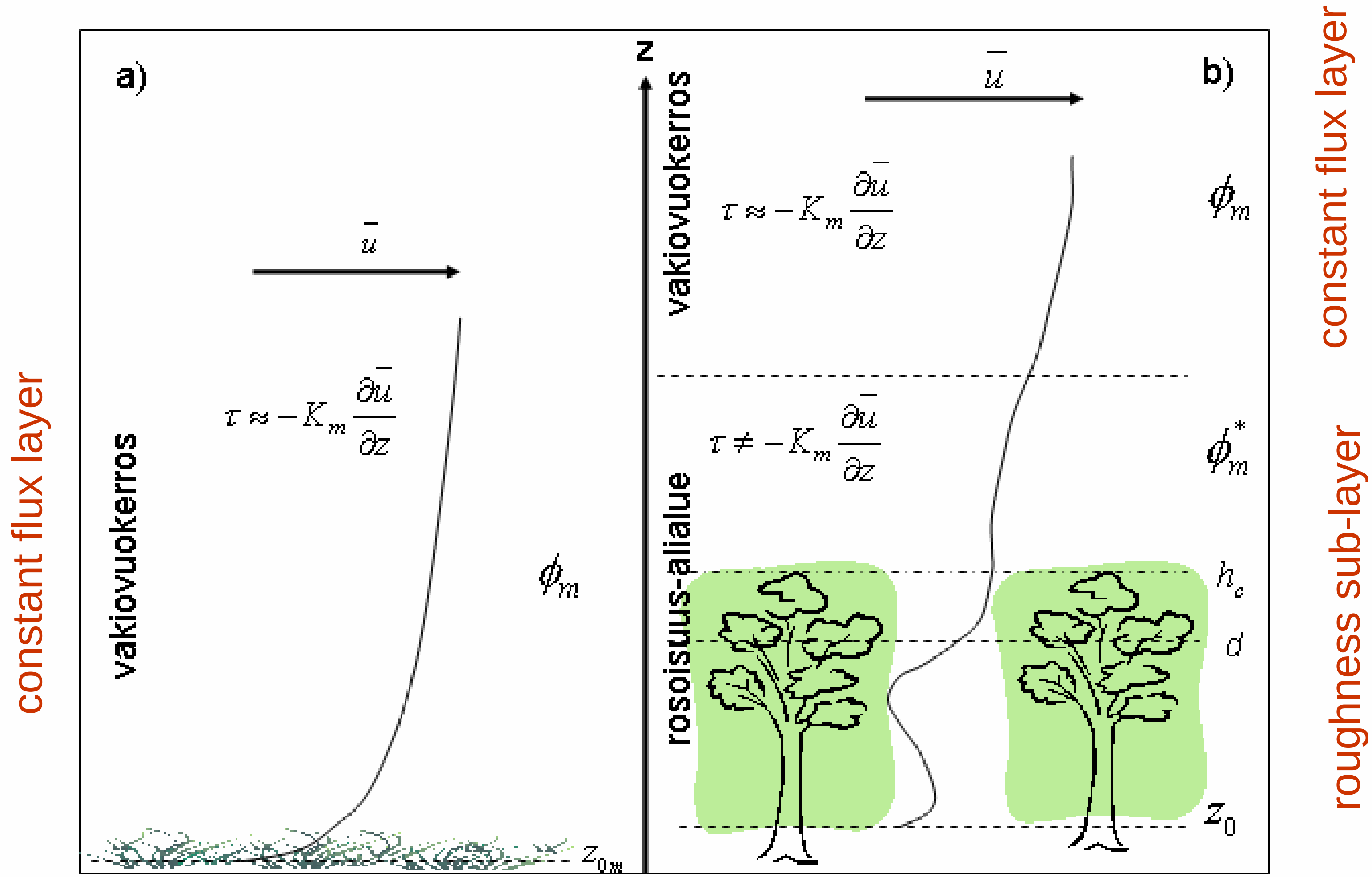
- **Wakes and spectra**
- **Volume averaging**
- **Turbulence characteristics**
- **Transport of scalars**

•**Finnigan J. 2000. Turbulence in Plant Canopies. *Annu. Rev. Fluid Mech.* 32, 519-571.**

Canopy turbulence

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.



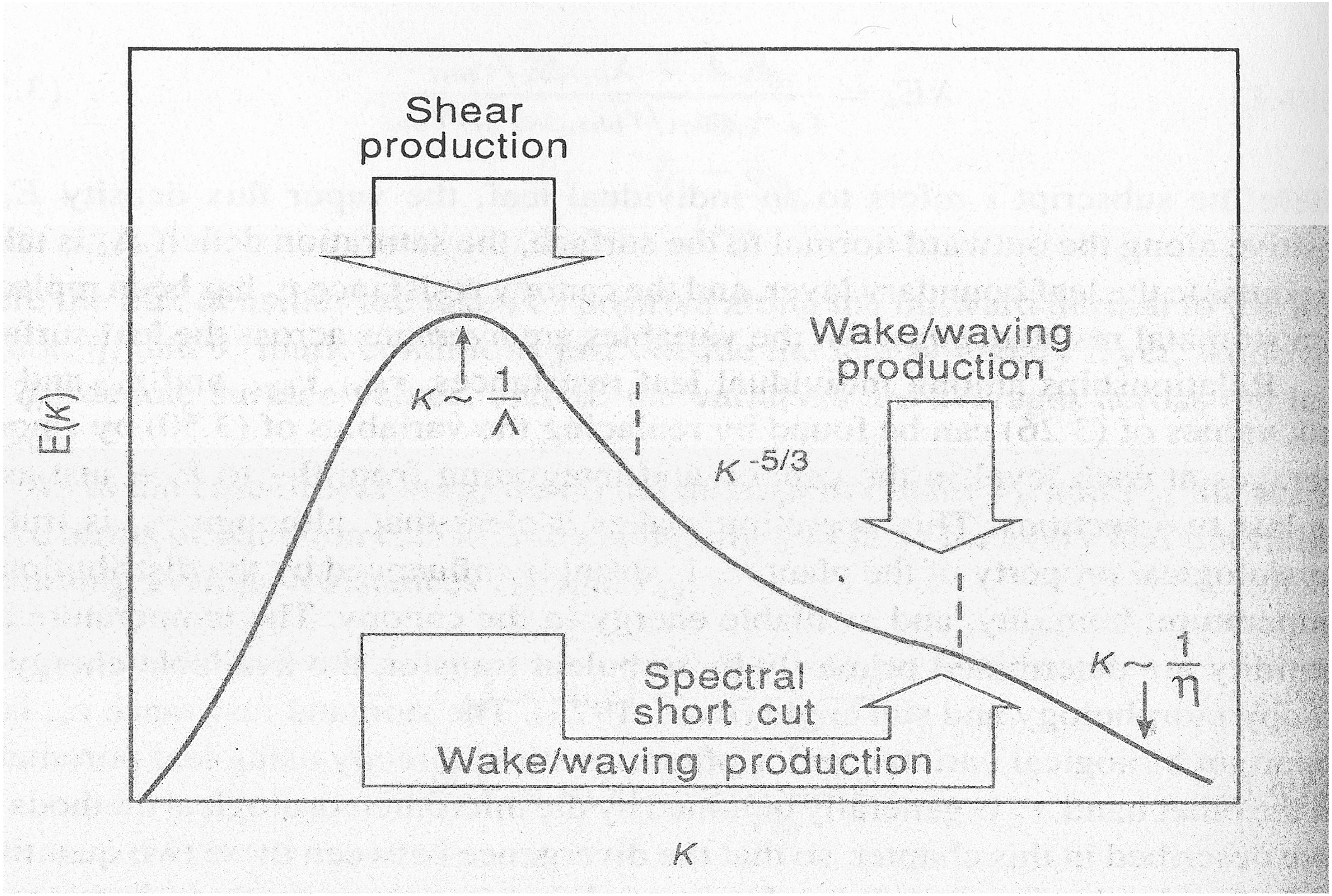
Scematic view of the lower boundary layer: The wind profiles and layers where M-O-theory applies above low vegetation (smooth surface) (a) and above a forest (rough surface) (b).

Launiainen 2005

WAKES AND SPECTRA

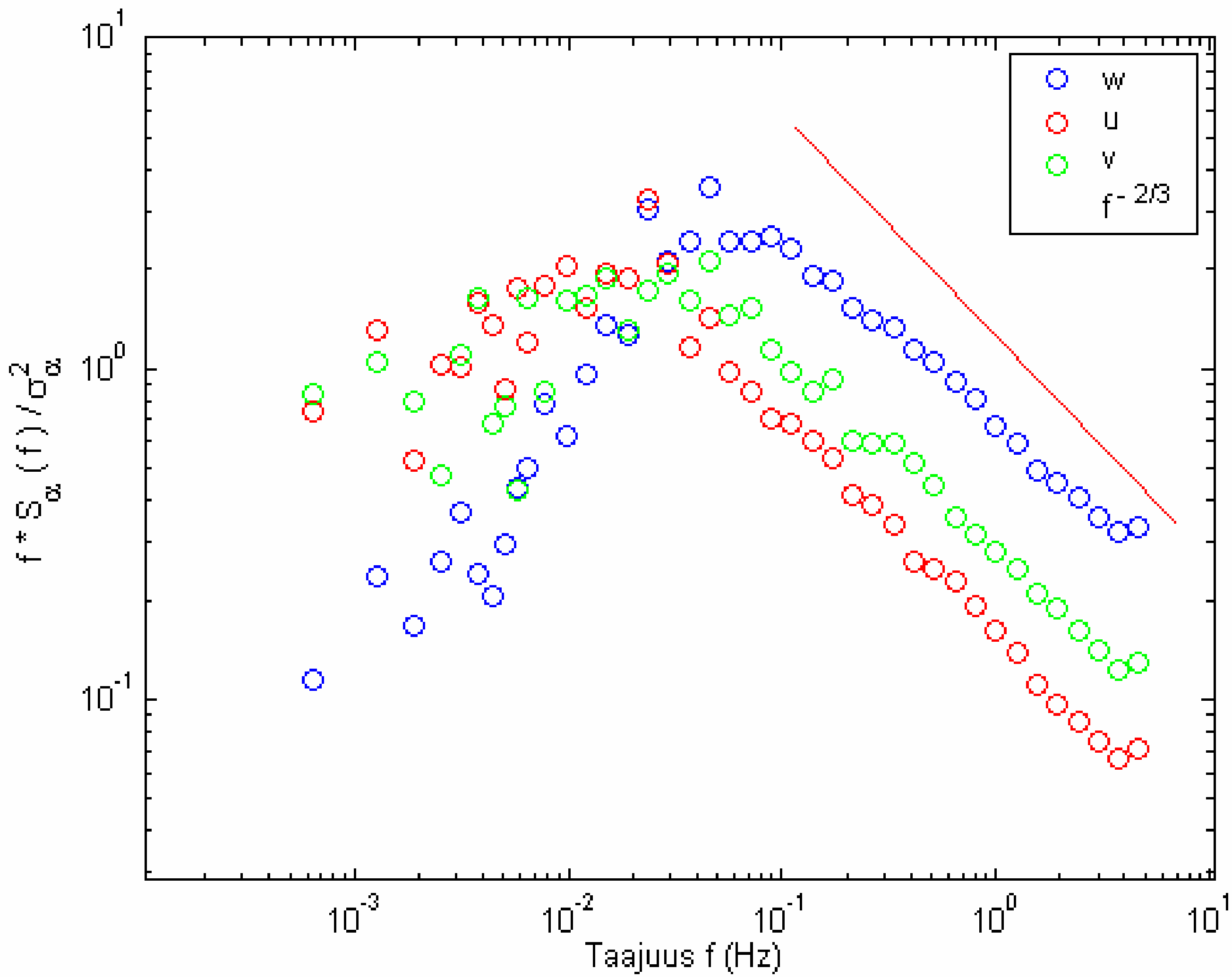
NOTE:

when the mean flow interacts with rough canopy, turbulence is created not only by shear but also in the wakes behind the roughness elements (tree stems, branches) into scales depending on the scale of roughness elements



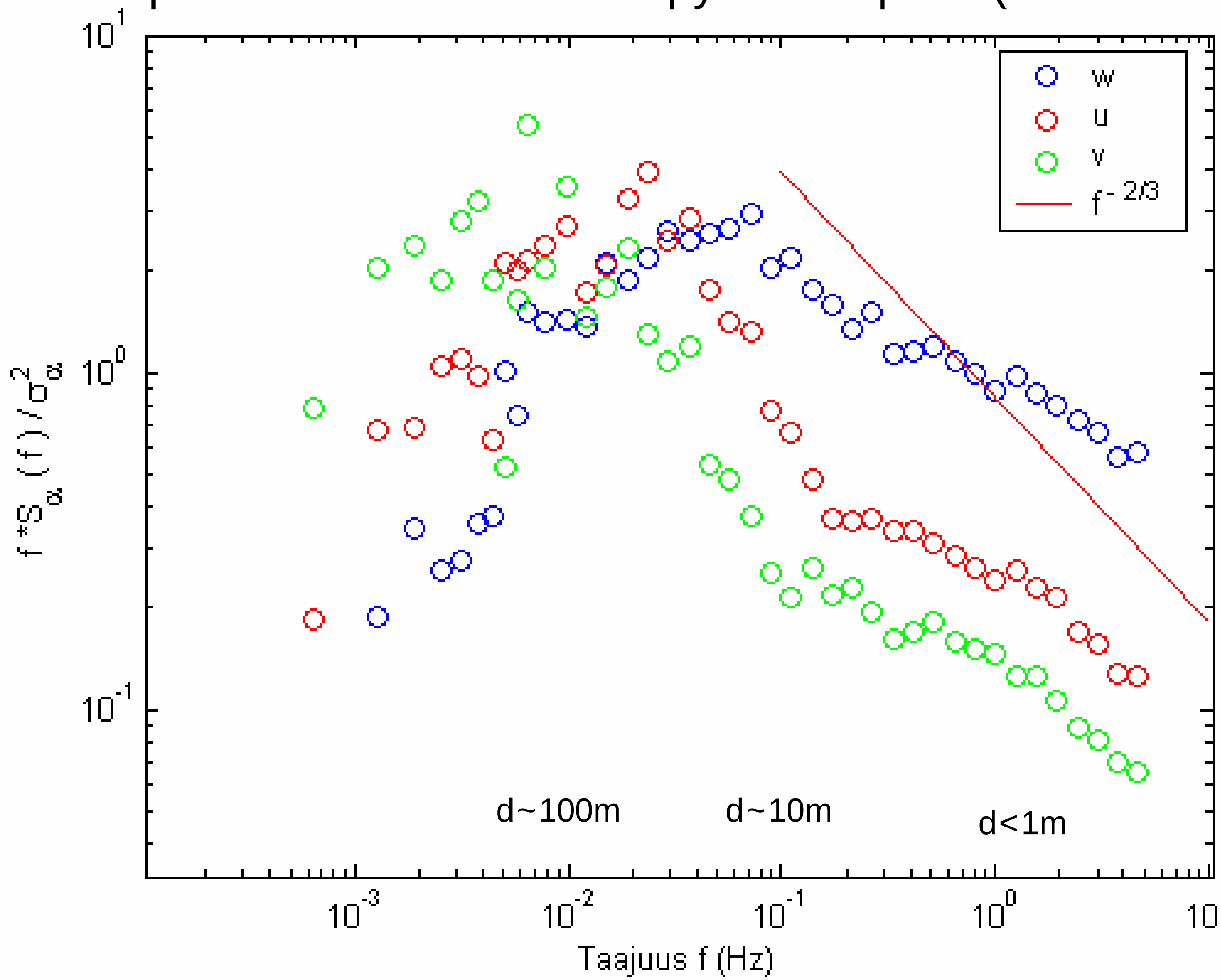
(Kaimal ja Finnigan (1994): Turbulent boundary-layer flows: Their structure and measurement, Oxford Univ. Press)

Power specra of u, v and w above canopy (23m)



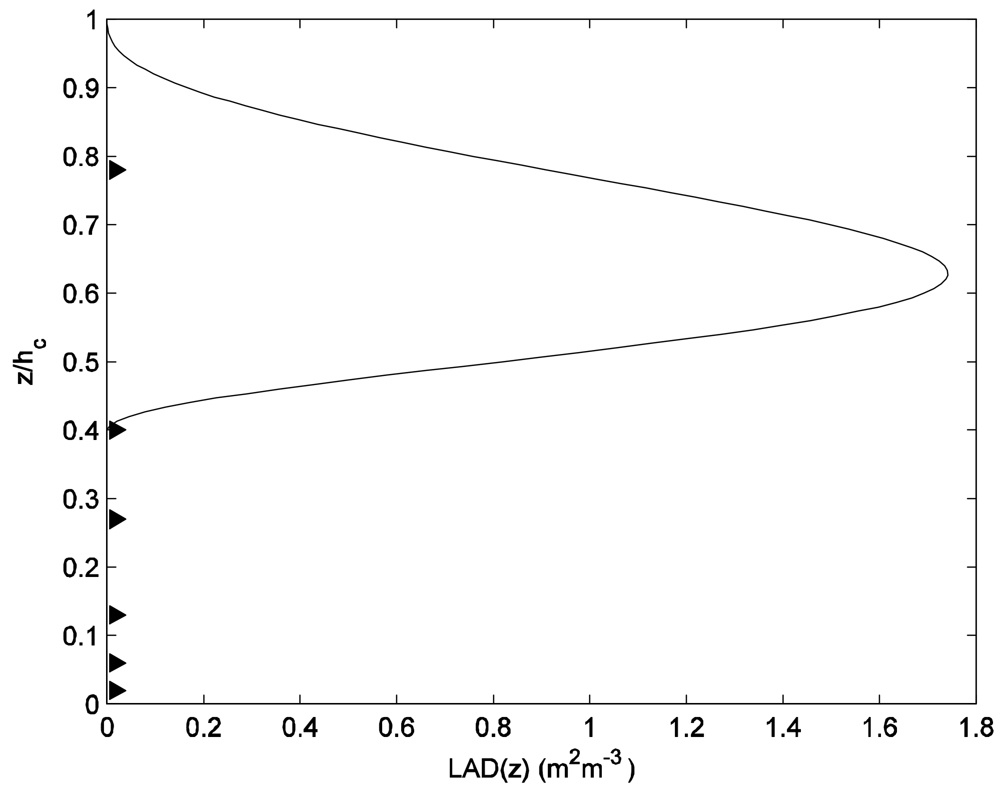
Frequency weighted power spectra normalized by total variance and plotted as a function of frequency(Hz). Red line represents inertial subrange behaviour suggested by Kolmogorov.

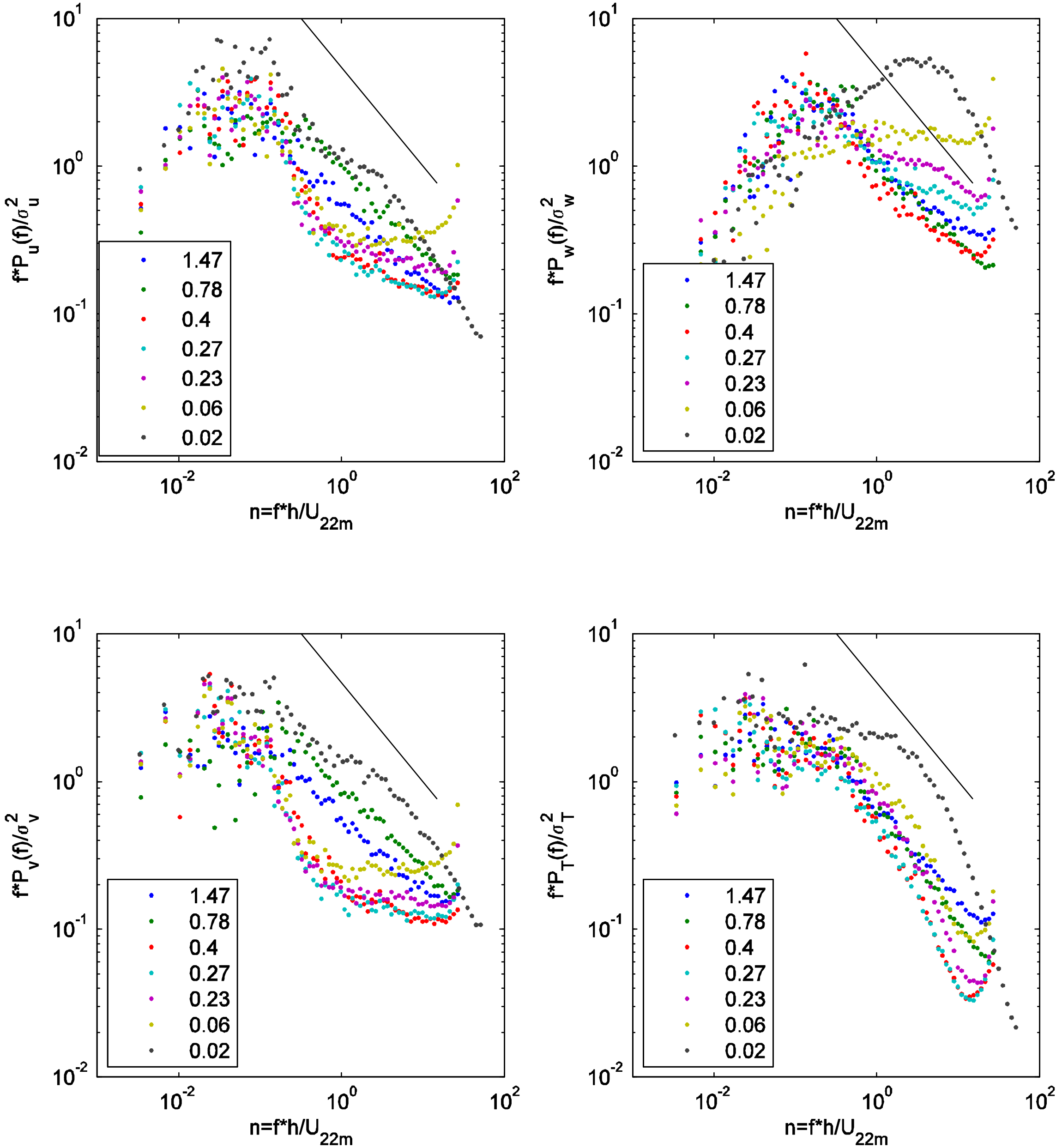
Same as previous but in sub-canopy trunk space (3m above ground)



Note that the slope of u and v components are more than -2/3 in low frequency end and less than -2/3 in high frequency end of the inertial subrange

Leaf area density profile of the intensive measurement site





Spectra at different levels.

von Karman streets
in cylinder wakes

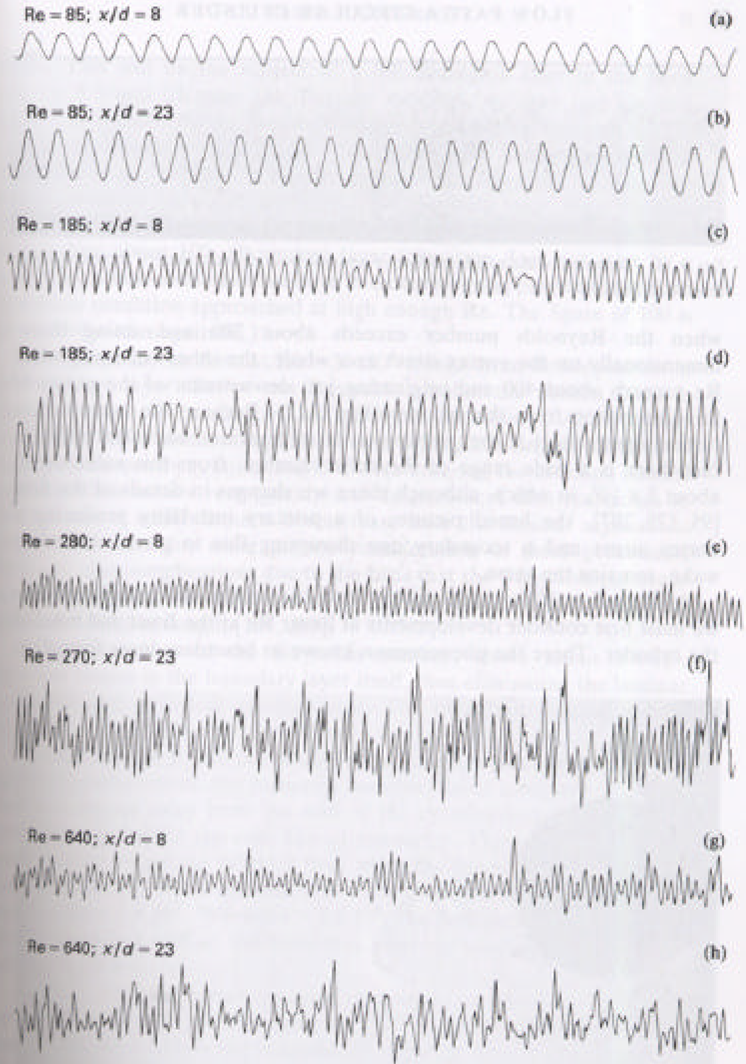


FIG. 3.10 Oscillograms of velocity fluctuations in cylinder wake. Traces are in pairs at same Re, but different distances, x, downstream from cylinder. For both positions, probe was slightly off-centre to be influenced mainly by vortices on one side of street. (Notes: relative velocity amplitudes are arbitrary; time scale is expanded by factor of about 3 in traces (g) and (h).)

G. Katul

Secondary peaks in w spectrum at Strouhal number fd/U = 0.2.

In the forest, inverting peak frequencies using the measured velocity produces d of the order of tree diameter.

VOLUME AVERAGING

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

$$\langle\phi_j\rangle(\vec{x},t) = \frac{1}{V}\iiint\limits_V \phi_j(\vec{x}+\vec{r},t)d^3r \qquad (2)$$

where the averaging volume V

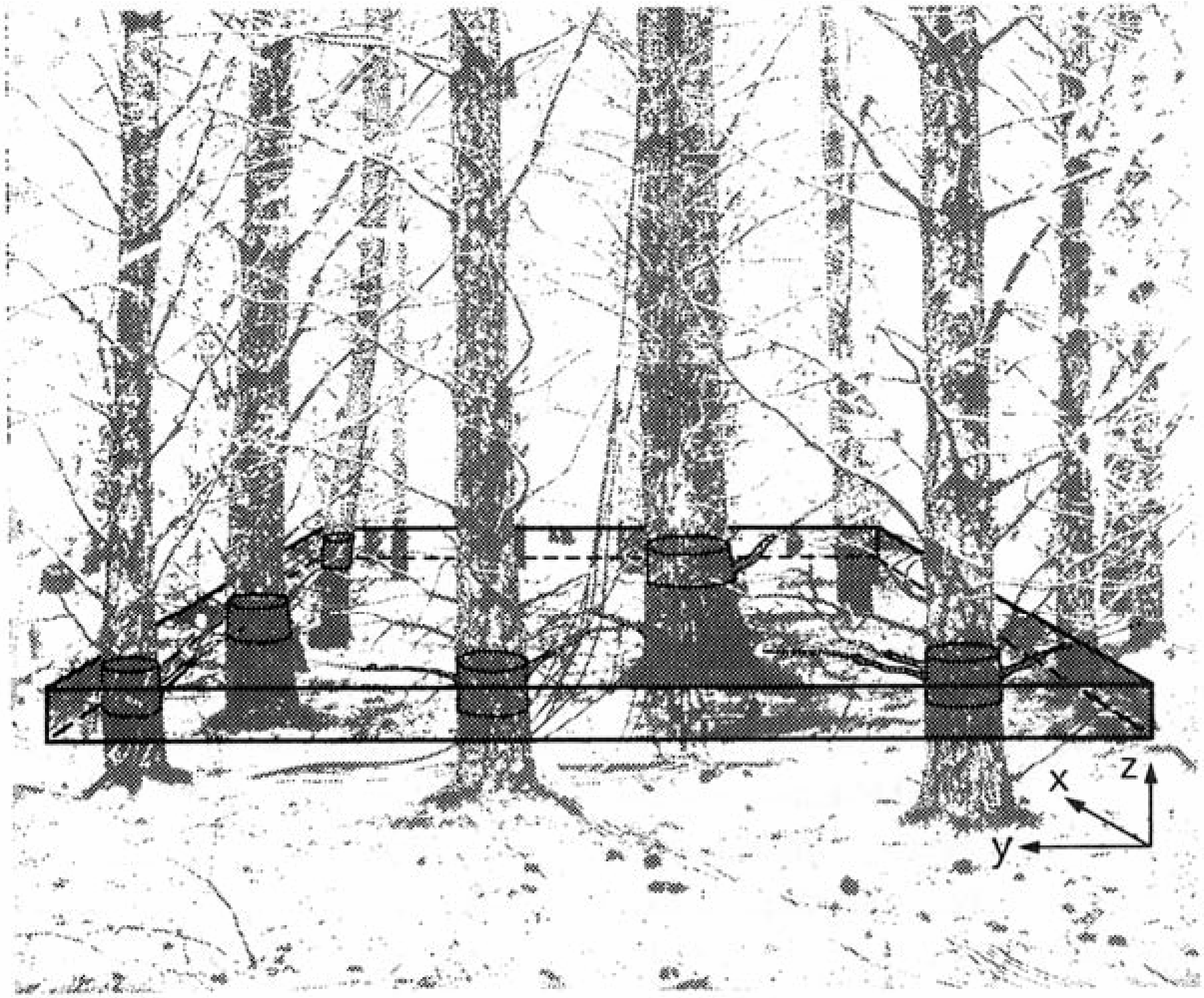


Fig. 3.7. Schematic view of an averaging volume V in a forest. The solid plant parts are excluded from the average, causing V to be a "multiply connected" space.

Thus, a variable ϕ_j can be divided into 3 terms: 1. time- and volume averaged component $\langle\overline{\phi_j}\rangle$ 2. time averaged local deviation from the volume average $\overline{\phi_j}''$ and 3. local deviation from time average ϕ_j' :

$$\phi_j = \langle\overline{\phi_j}\rangle + \overline{\phi_j}'' + \phi_j' \tag{3}$$

For meteorologists this is analogous to taking e.g. time and zonal averages of some quantity s; there will be regions where $\overline{s}$ differs from $\langle\overline{s}\rangle$. The origin of term s'' is in these local deviations. Fluctuations in time s' are "moving, transient disturbances" in this case. (see e.g.Yleinen kiertoliike 1 lecture notes)

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

The second term of τ_{ij} describes the dispersive momentum 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.

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

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

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

TKE budget equation in the canopy

$$0 = -\left\langle \overline{u'w'} \right\rangle \frac{\partial \left\langle \overline{u} \right\rangle}{\partial z} - \left\langle \overline{u_i'u_j'}'' \frac{\partial \overline{u_i}''}{\partial x_j} \right\rangle - \frac{\partial}{\partial z}\left(\frac{\left\langle \overline{p'w'} \right\rangle}{\rho} + \frac{1}{2}\left\langle \overline{w'u_i'u_j'} \right\rangle + \frac{1}{2}\left\langle \overline{w}'' \overline{u_i'u_j'} \right\rangle \right) - \left\langle \varepsilon \right\rangle + \frac{1}{\rho}\left\langle \overline{v_i'd_i'} \right\rangle$$

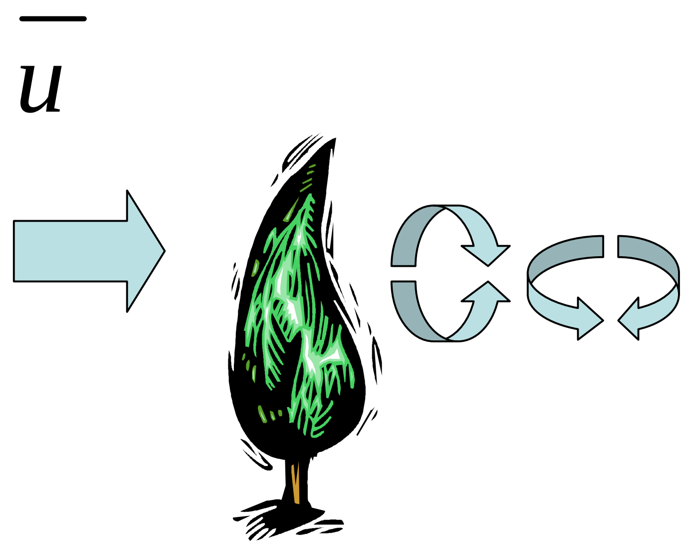
1 2 3 4 5 6 7 (16)

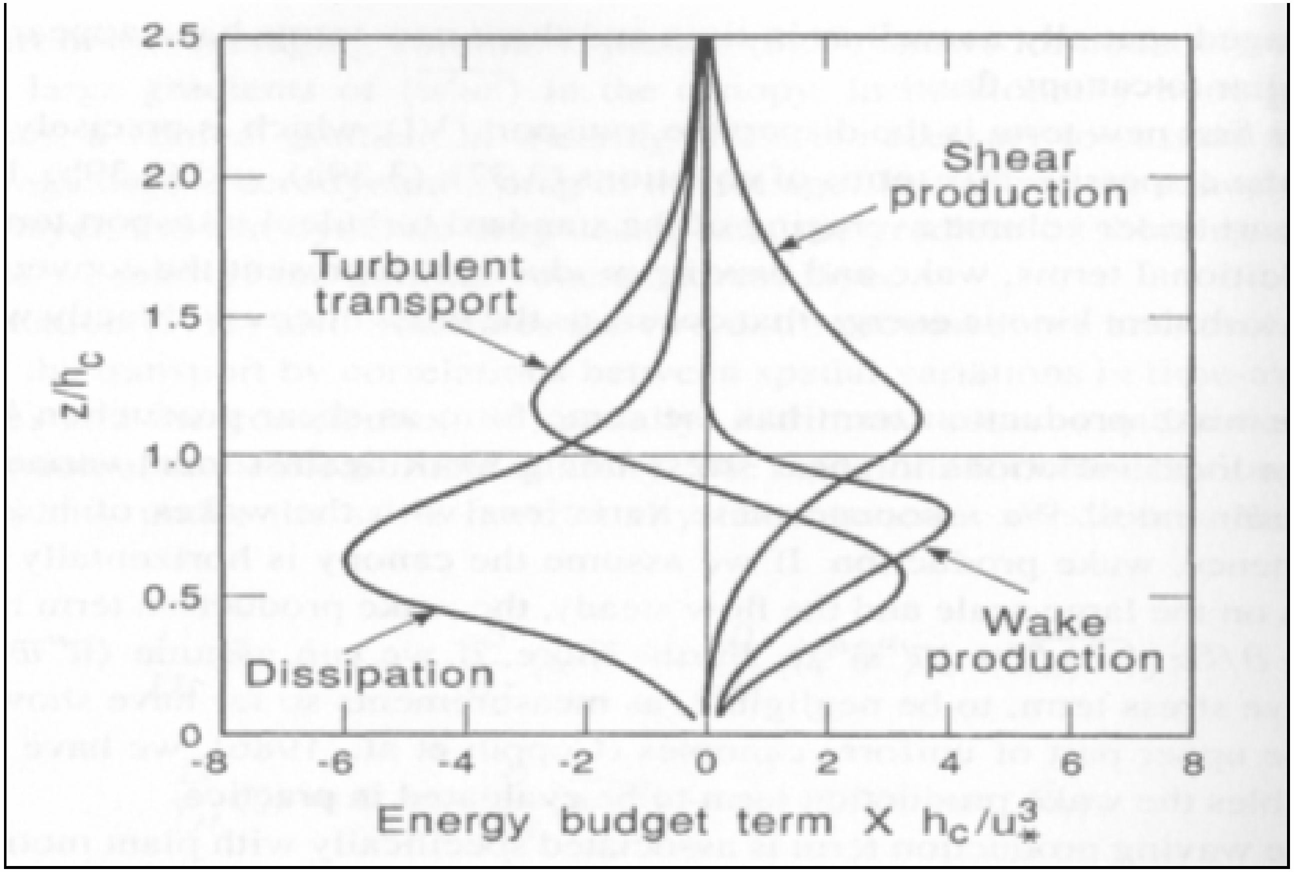
Terms 1,3,4,6 like in the constant flux layer:

Term 2: ”wake production”

Term 5: ”dispersive flux”

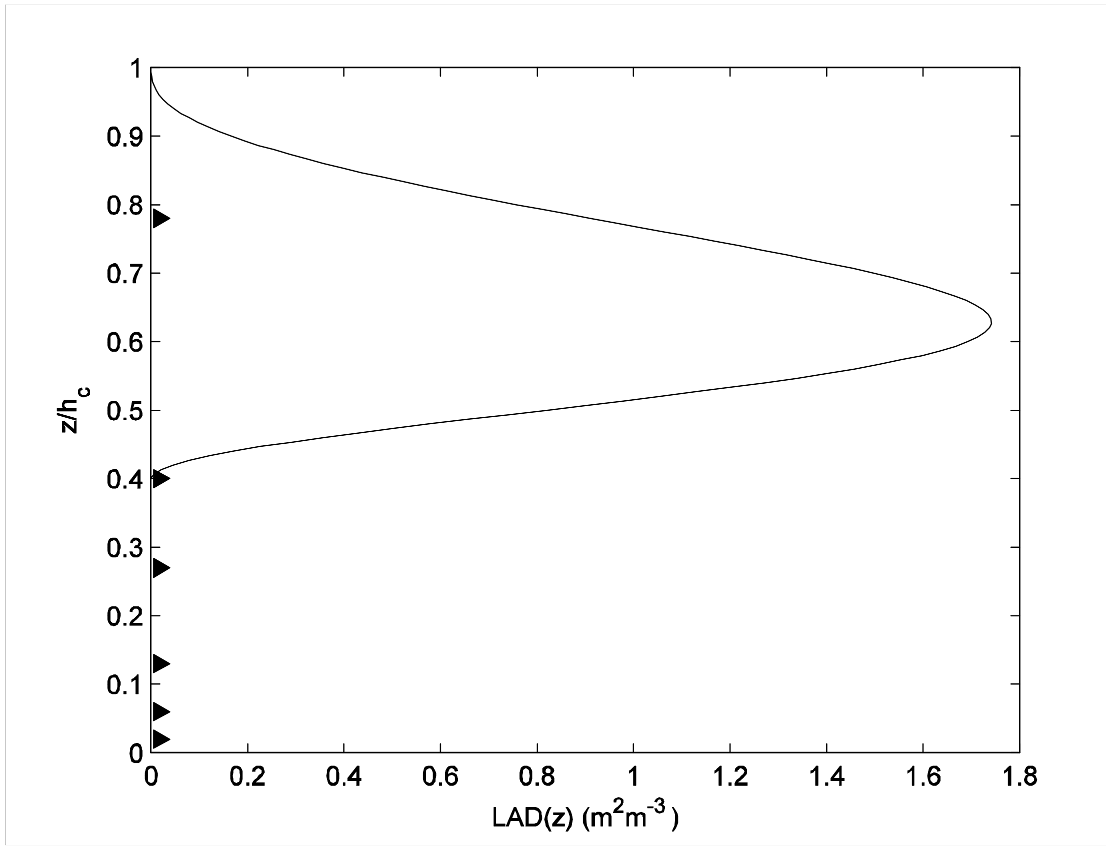
Term 7: waving of leaves



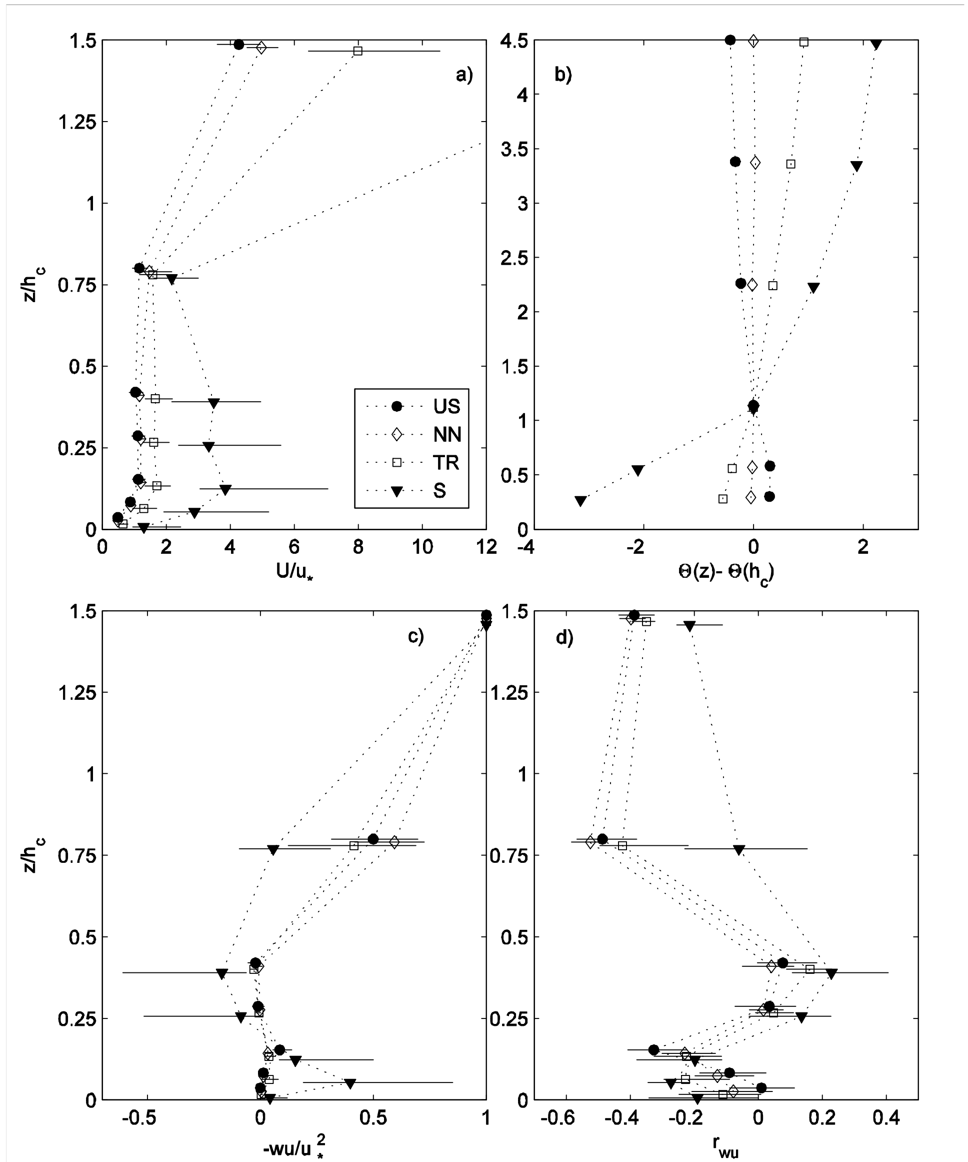


Kuva 3: Turbulenssin kineettisen energian (TKE) taseen suurimpien termien merkitys latvuston sisällä ja yläpuolella. Tuuliväänne (shear production) ja vanavesiefekti (wake production) tuottavat turbulenssin kineettistä energiaa, jota turbulenttinen kuljeustermi (turbulent transport) siirtää latvuston alaosiin, missä dissipaatio on voimakasta. Pystyakseli on normitettu latvuston korkeudella (Kaimal ja Finnigan 1994).

TURBULENCE CHARACTERISTICS

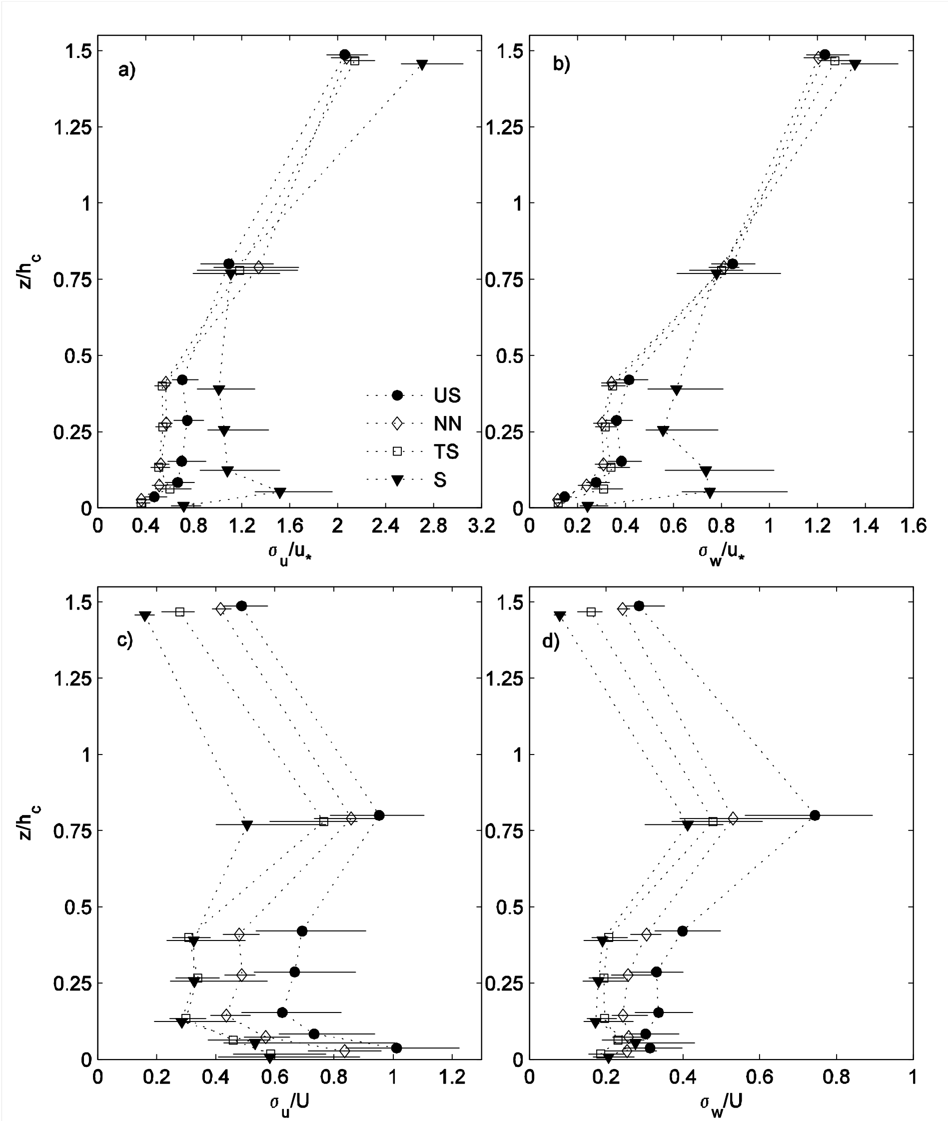


Turbulence characteristic: vertical variability



Launianen et al., 2007. (submitted to Tellus B)

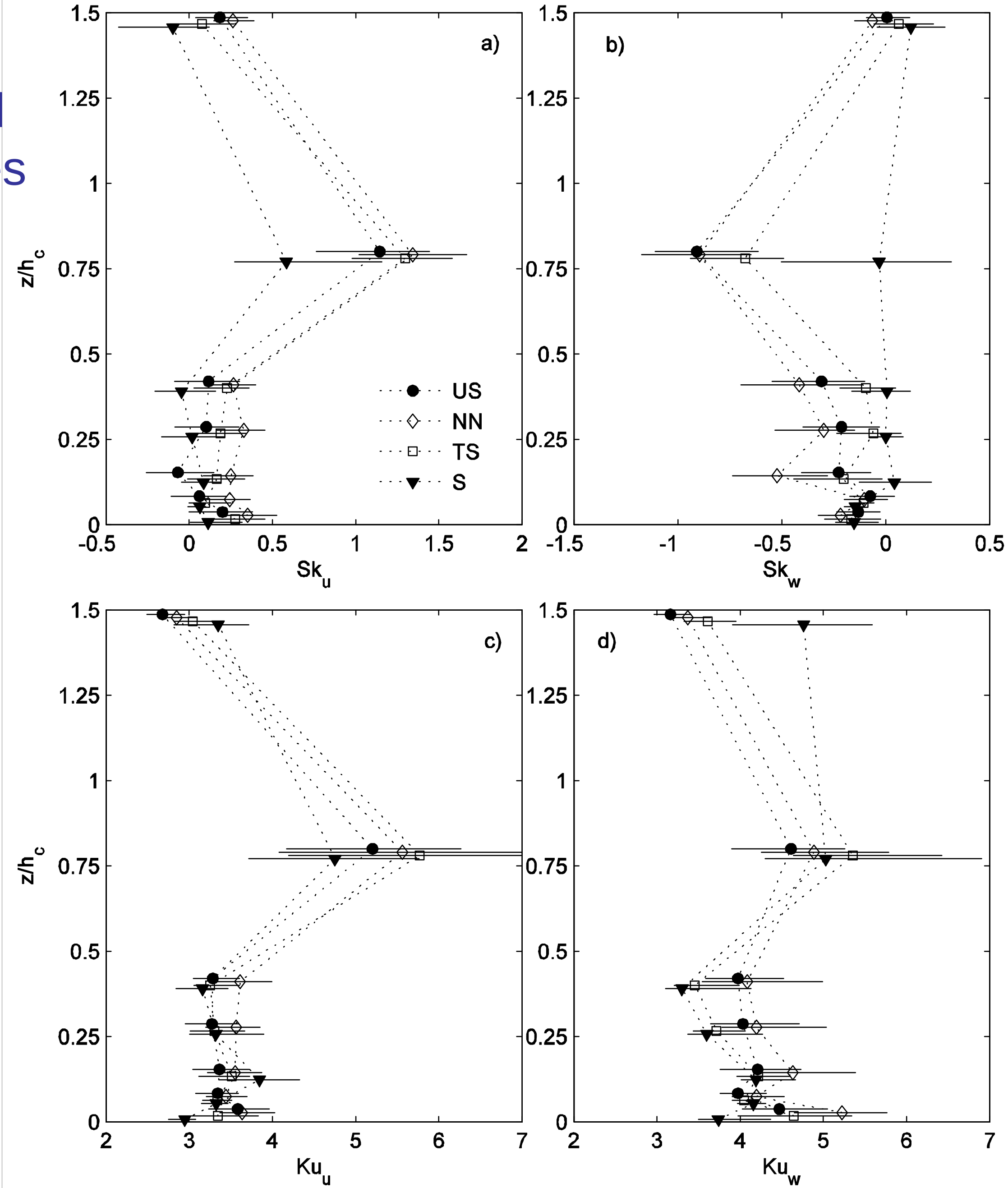
a and b: Normalized standard deviations (s$_u$/u* and s$_w$/u*)



c and d: turbulence intensities (s$_u$/U and s$_v$/U)

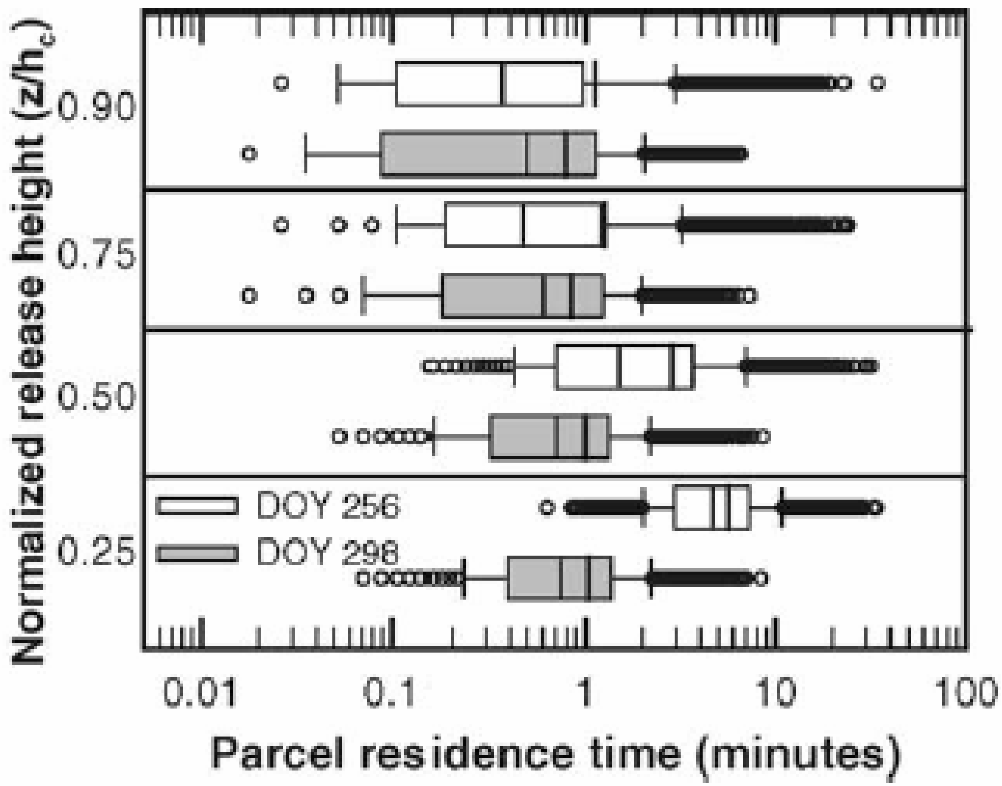
Launianen et al., 2007. (submitted to Tellus B)

Skewness and kurtosis profiles



Launianen et al., 2007.

Parcel residence times from Lagrangian simulations



Strong et al., 2004

TRANSPORT OF SCALARS

Counter-gradient transport

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 (”K-theory) may be seriously in error in the canopy environment.

- 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

- inside canopy this is not valid since large coherent eddies are responsible for most of the transport. The concentration gradient on the other hand is determined by much more local (smaller scale) processes, sources and sinks

Quadrant analysis

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

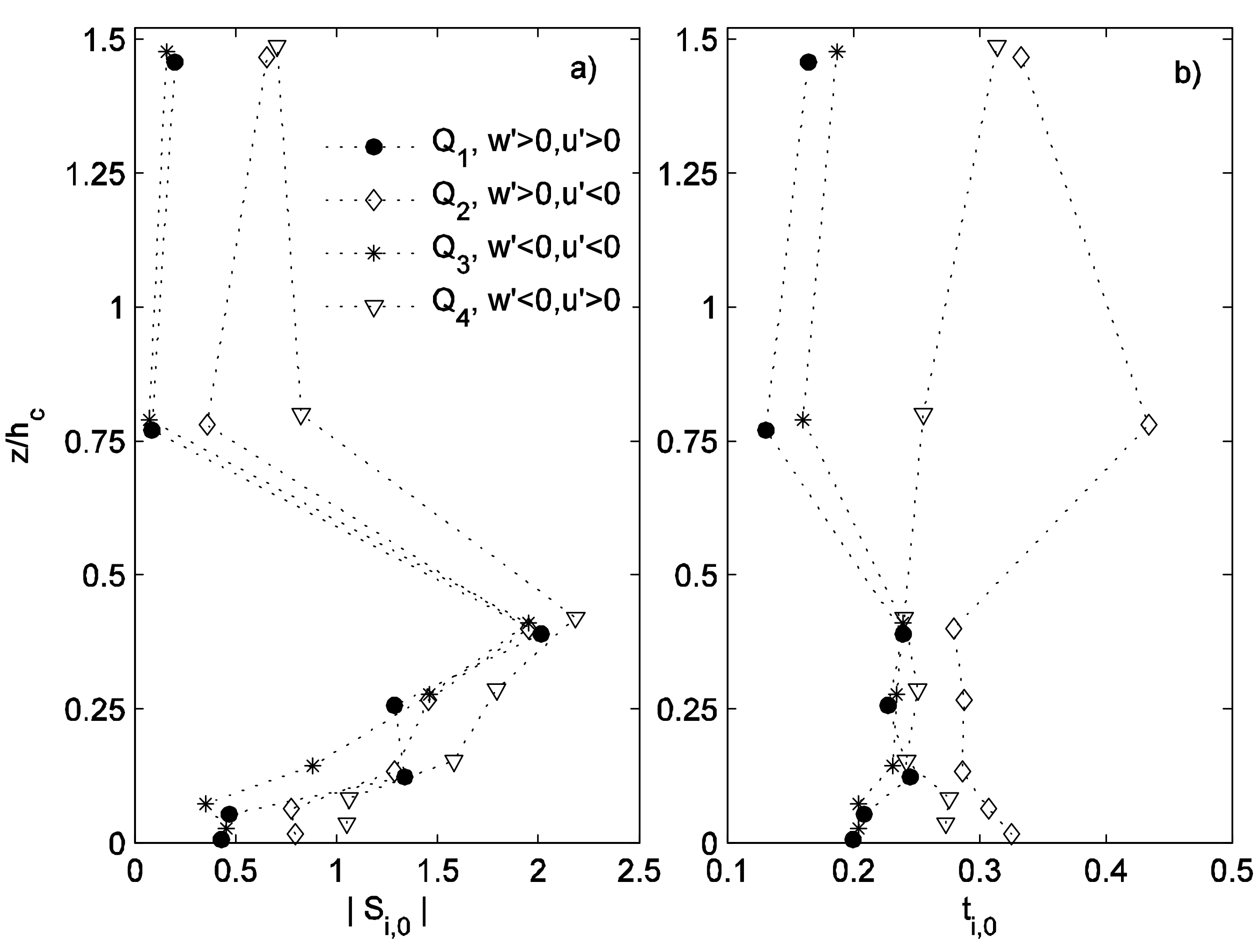
Quadrant 2: $u' > 0$; $w' < 0$; sweep

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

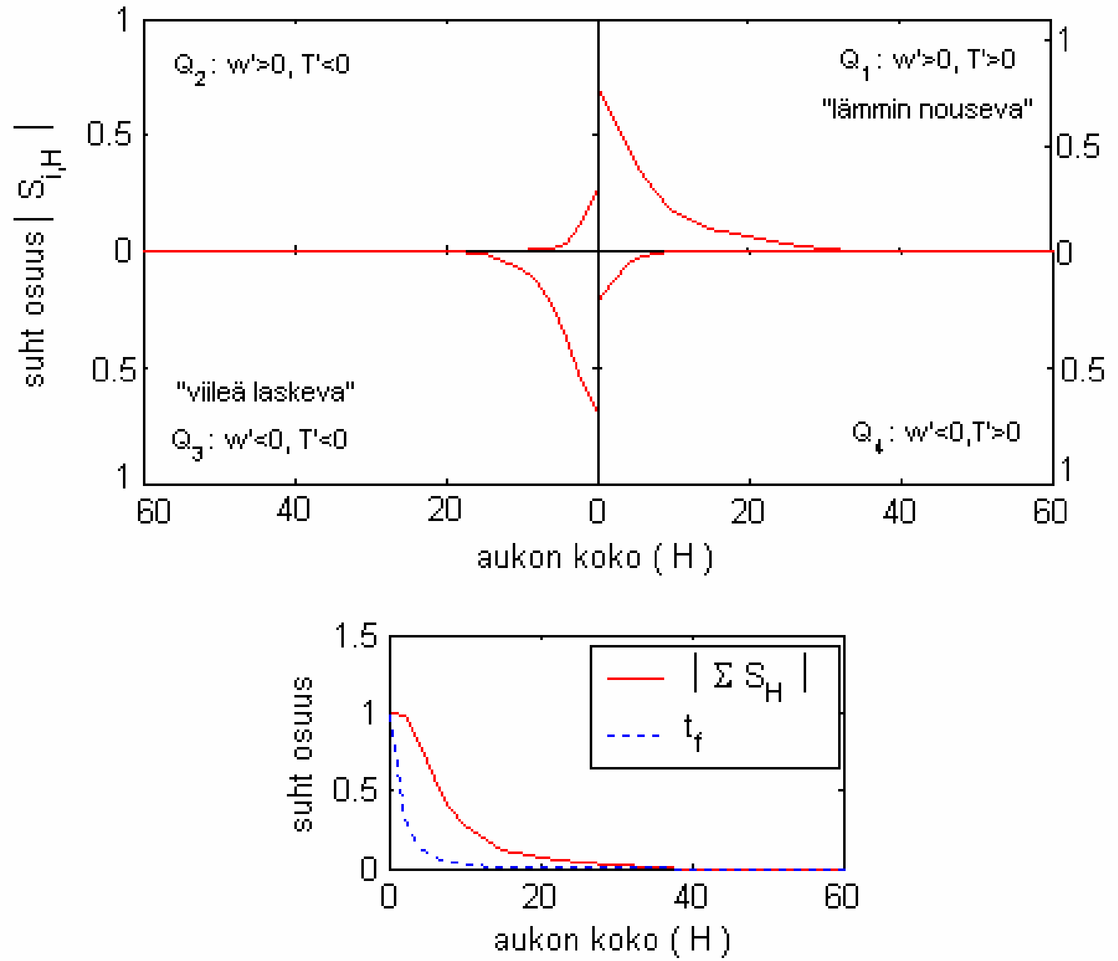
Quadrant 4: $u' < 0$; $w' > 0$; ejection

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

Contributions of different quadrants



Quadrant analysis: *H* on a sunny summer day



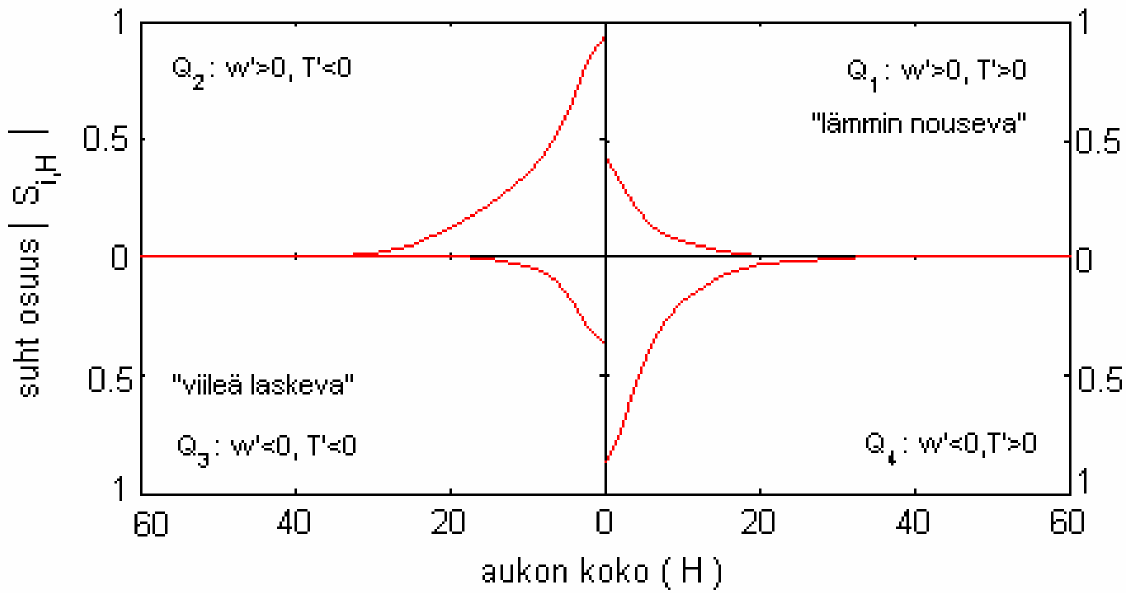
Q_1 and Q_3: upward flux

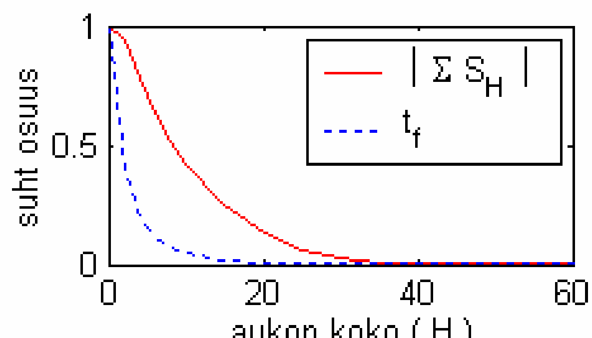
Q_2 and Q_4: downward flux

TOTAL flux is sum of these!

The formation of sensible heat flux from different quadrants (instant products w'T')

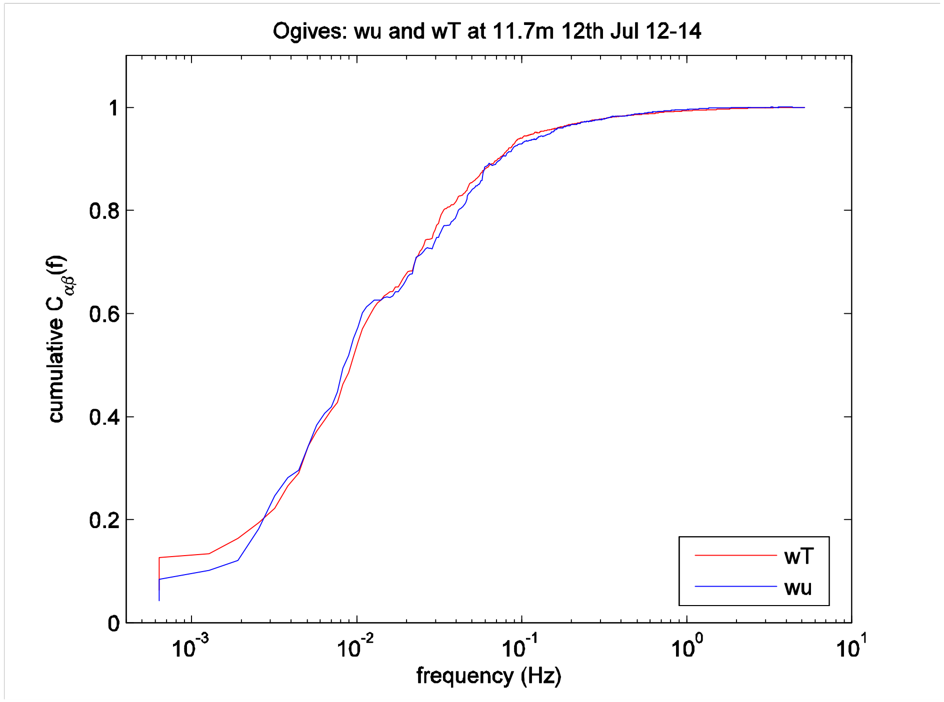
Quadrant analysis: *H* on a clear stable night





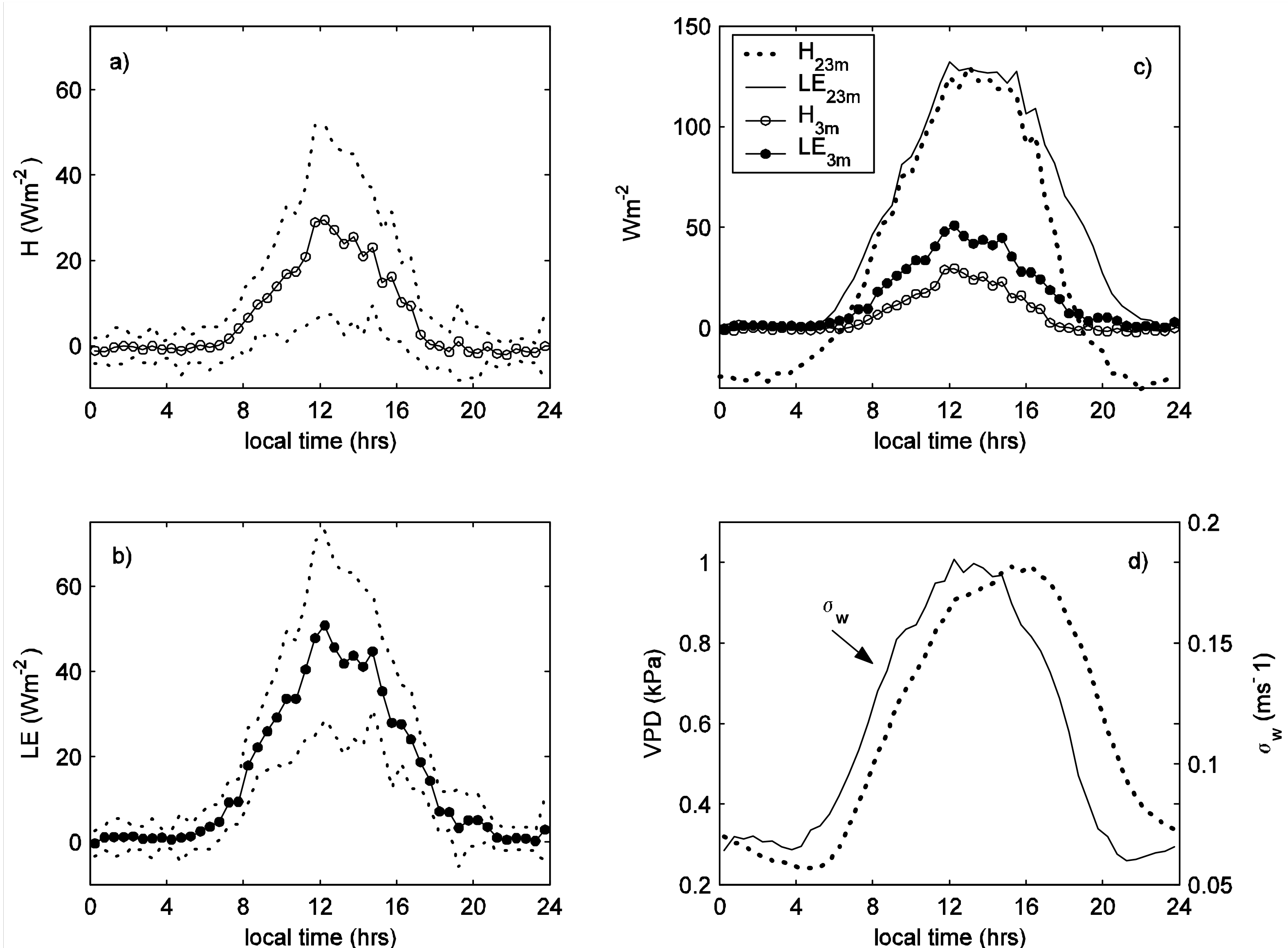
The formation of sensible heat flux from different quadrants (instant products w'T')

Ogive (cumulative frequency) curves



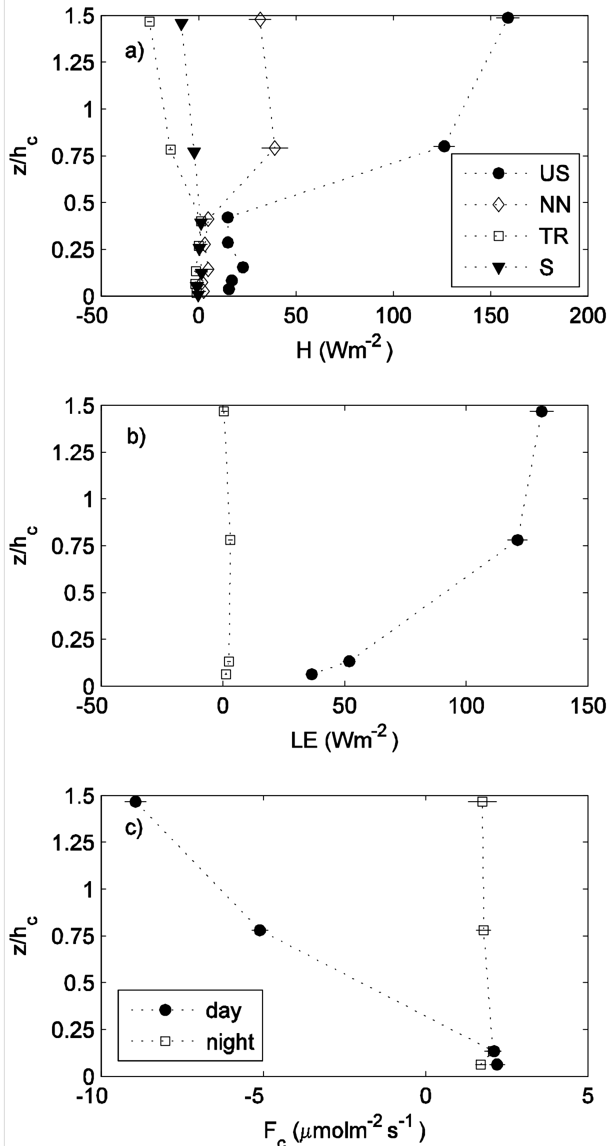
Dominating time-scale in turbulent transport?
200...10 s, low and high frequencies have small effect

Sub-canopy and above-canopy heat fluxes



Launiainen et al., 2005. Bor. Env. Res

Profiles of heat and CO2 fluxes.



Launianen et al., 2007. (submitted to Tellus B)

TAKE HOME

General features of turbulence in plant canopies

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

- mean wind profile inflected
- second moments (fluxes and variances) inhomogeneous with height
- 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

- skewness and kurtosis large

- 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

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

URBAN CANOPIES