"the surface layer over a rough boundary must be considered in two parts: an inertial sublayer in which height above the effective surface provides the only length scale in adiabatic conditions, and in which semi-logarithmic profile laws, and their diabatic extensions, are obeyed; and a sublayer adjoining the surface itself, in which the flow depends explicitly on surface-defined length scales, via the intrusion into the mean flow field of wake or convective motions generated by individual roughness elements. We call this region the roughness sublayer" (Raupach et al., 1980, BLM Vol. 18)

Let's consider the micro-meteorology of a plant canopy layer**. Let the canopy be characterized by its mean height *h* (or *H*), its "leaf area density" $a = a(z)$ [$m^2\ m^{-3}$] whose height integral is the "Leaf Area Index" or LAI (leaf area per unit ground area), and a drag coefficient $c_d(z)$

** optional reading:

Annu. Rev. Fluid Mech. 2000. 32:519–571
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TURBULENCE IN PLANT CANOPIES

John Finnigan
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Arya, Intro to Micrometeo, Sec 15.5

eas572_roughnesssublayer.odp

JDW vers. 18 Oct. 2012

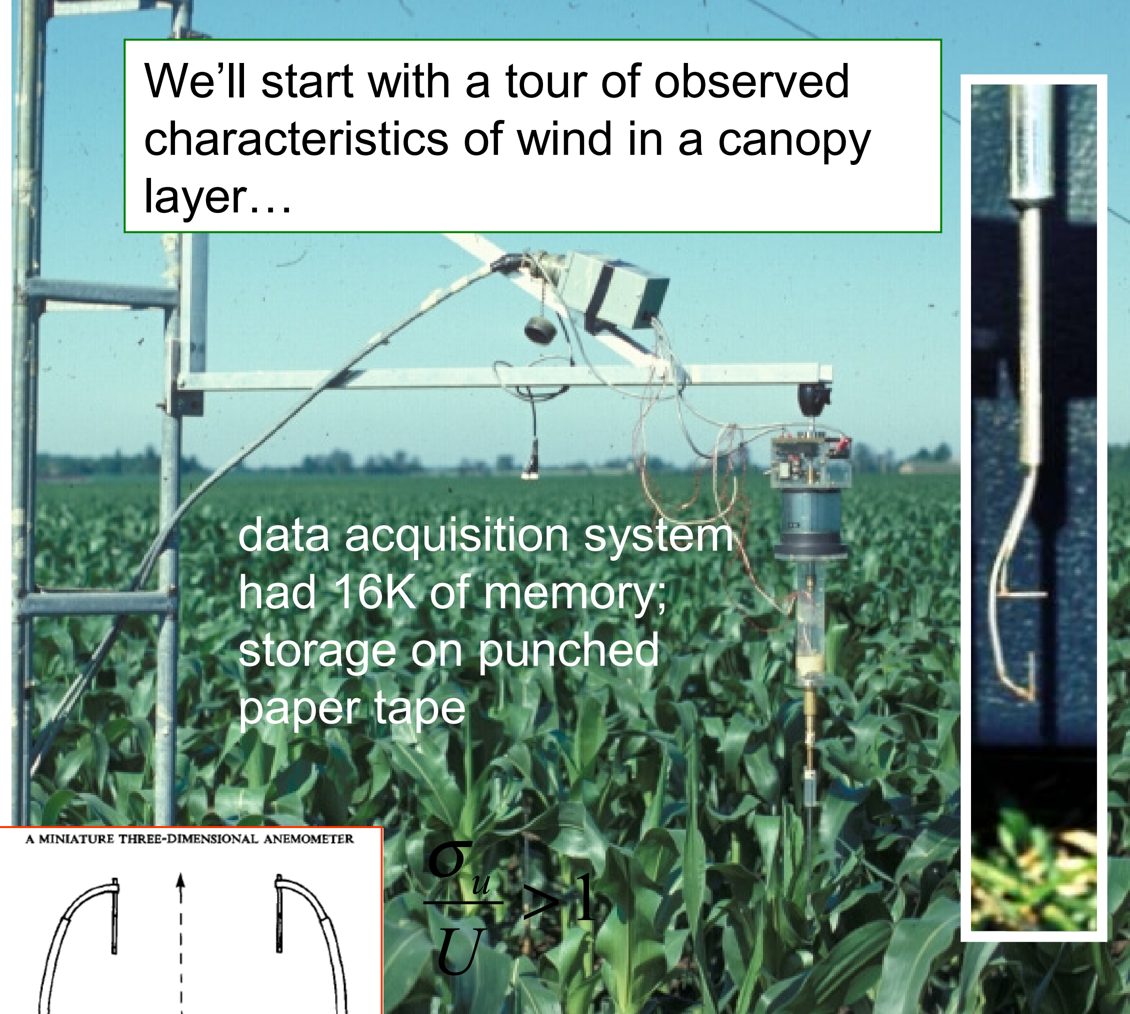
STATISTICS OF ATMOSPHERIC TURBULENCE WITHIN AND ABOVE A CORN CANOPY

J. D. WILSON*, D. P. WARD**, G. W. THURTELL, and G. E. KIDD
Department of Land Resource Science, University of Guelph, Guelph, Ontario, Canada

Boundary-Layer Meteorology **24** (1982) 495–519.

- need small, fast sensors capable of response to winds over entire solid angle (turbulence intensity σ_u / U is large)

- here showing servo-driven, split-film heat transfer anemometers, running at 20 Hz (Elora, Ontario)



A MINIATURE THREE-DIMENSIONAL ANEMOMETER FOR USE WITHIN AND ABOVE PLANT CANOPIES

R. H. SHAW, G. KIDD, and G. W. THURTELL
Dept. of Land Resource Science, University of Guelph, Guelph, Ont., Canada

Boundary-Layer Meteorology **3** (1973) 359–380.

- latest instrument is a 3-D sonic with 10 cm pathlength, suitable within tall forests

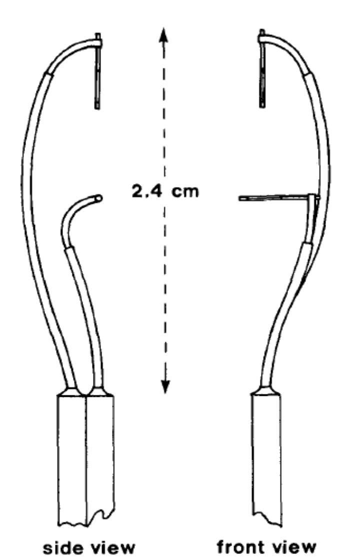


Fig. 2. Dual split-film anemometer sensor.

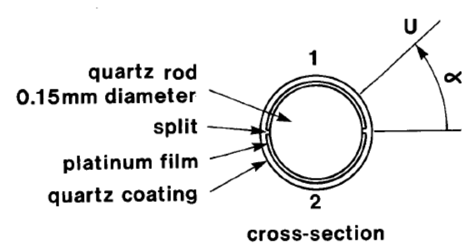


Fig. 1. Split-film anemometer element.

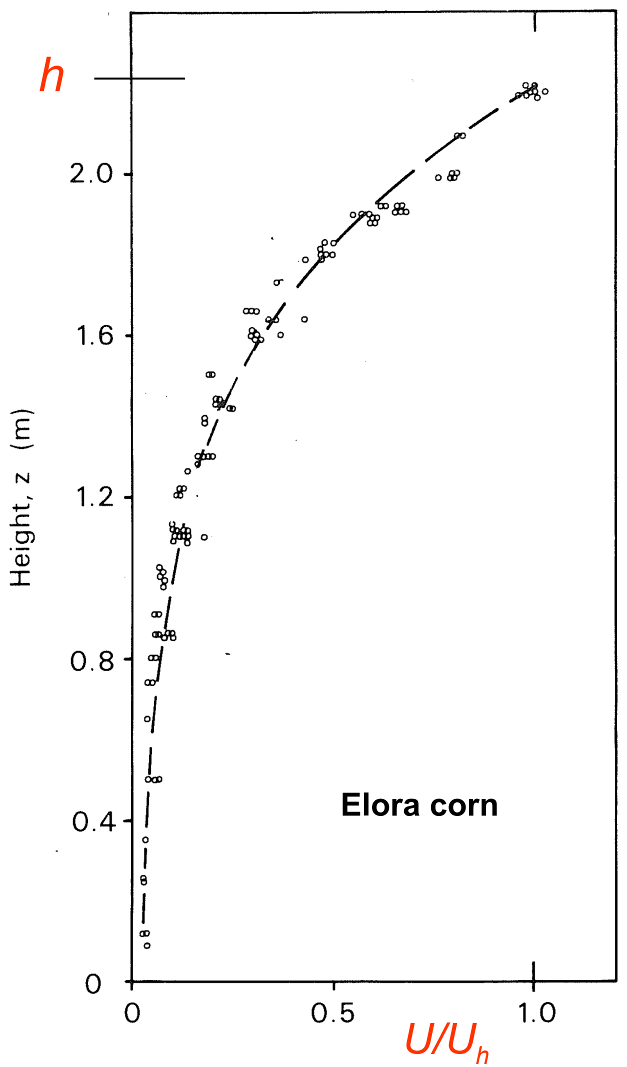
Mean windspeed:

- profile is concave down; well fitted by exponential decay

$$U = U_h \exp[\beta(z/h - 1)]$$

- curvature changes sign near $z = h$… inflexion point instability
- CSIRO (Aust.) group (Finnigan, Raupach, Harman...) take coherent structures view and explain obsvd. charact.

Boundary-Layer Meteorology 24 (1982) 495–519.



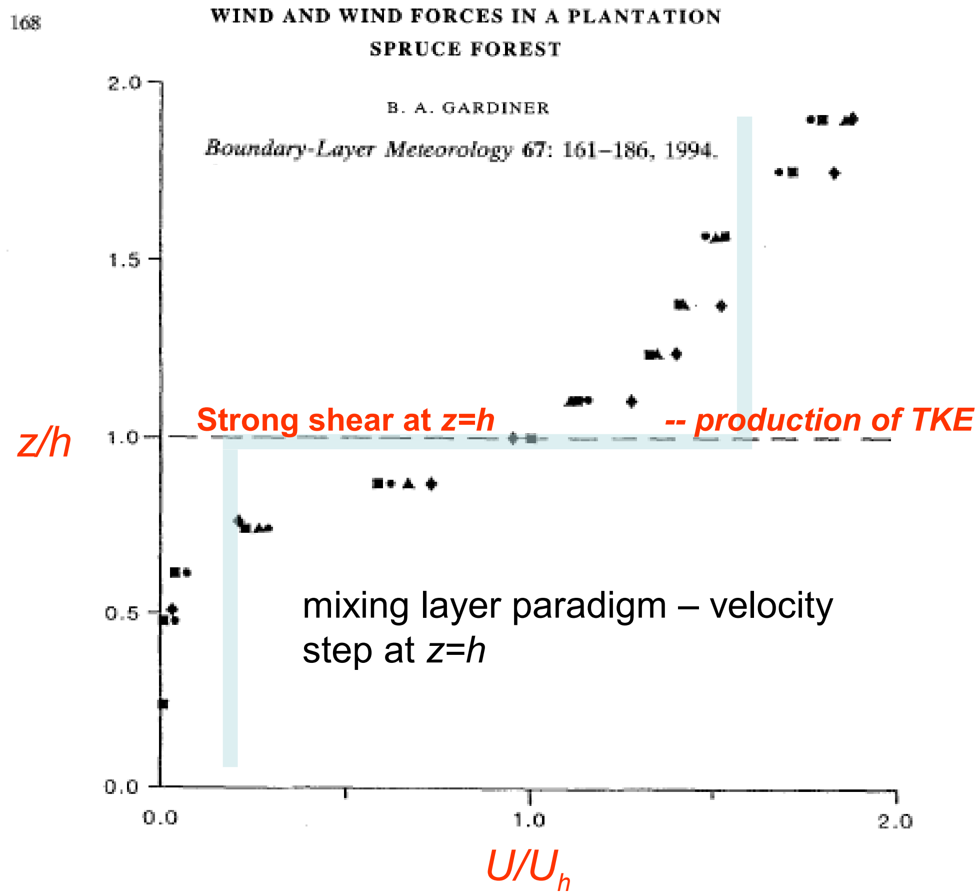


Fig. 2. Profiles of mean windspeed ($\bar{u}$) normalised against u_h. (For Figures 2, 3 and 8, ● = 10 Dec. 88, ■ = 18 Dec. 88, ▲ = 19 Dec. 88 and ◆ = 21 Dec. 88.)

• under a dense canopy one expects there is no mean stress on ground – then τ_h $(= u_{*h}^2)$ equals height integral of drag

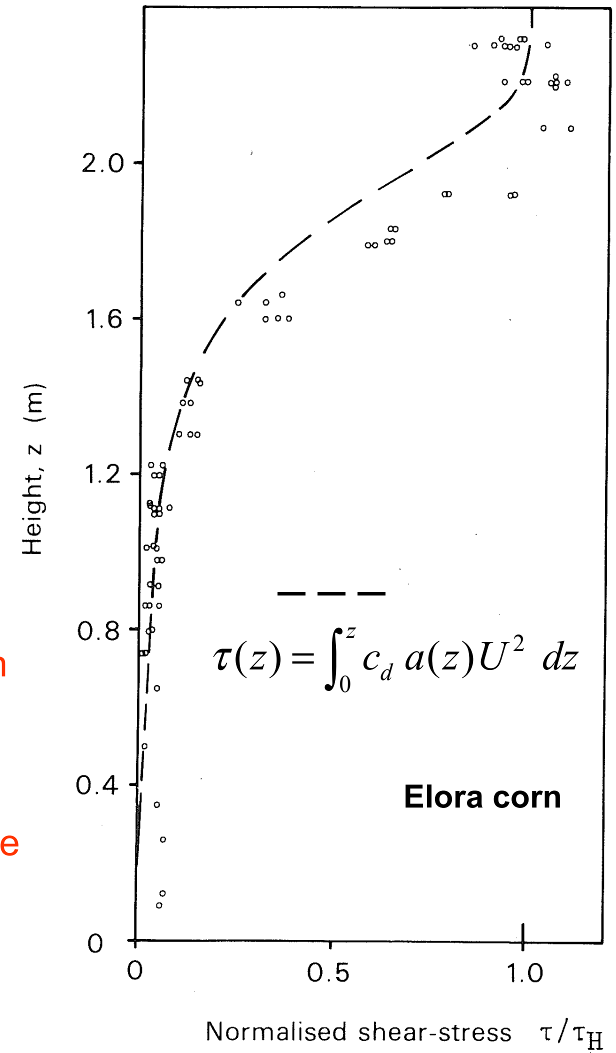
$$\tau(z) = \int_0^z c_d \; a(z) \; U^2 \; dz$$

• above canopy, height gradient of stress balances pressure gradient + Coriolis force (or in wind tunnel, pressure alone)

• stress gradient aloft here attributed to disparity of instrument types (uppermost instrument *u-v-w* propellors; all others sonics) and terrain effects

Shear stress profile:

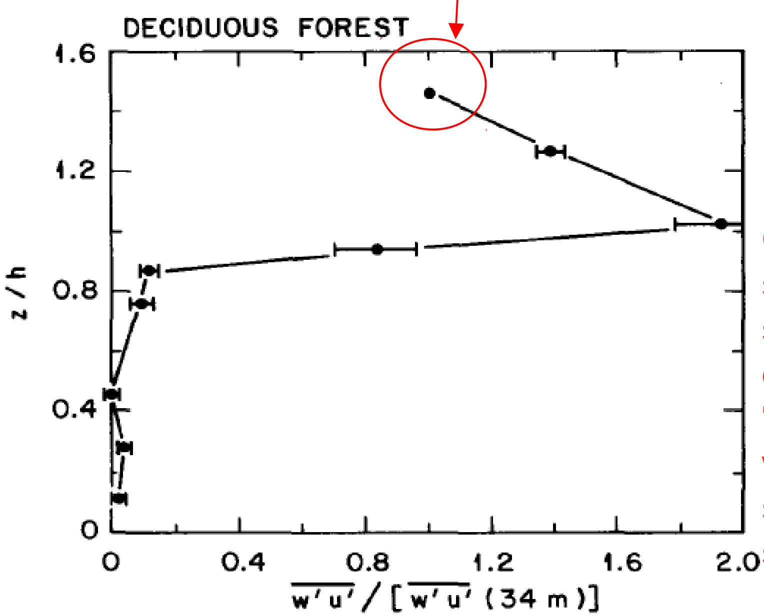
Boundary-Layer Meteorology 24 (1982) 495–519.



TURBULENCE STRUCTURE IN A DECIDUOUS FOREST

DENNIS D. BALDOCCHI and TILDEN P. MEYERS

Boundary-Layer Meteorology 43 (1988) 345–364. 351



Quadrant analysis shows that the mean shear stress is dominated by "sweeps" (gusts), which transfer a large stress fraction in a short time fraction

Fig. 3. Vertical variation in tangential momentum stress, normalized by values measured above the canopy (34 m above the ground). Error bars represent the standard error of the mean.

Mean streamwise momentum balance within the canopy – and the wind profile

$\overline{u'w'}(z+\Delta z)$

$z+\Delta z$

Parameterize vegetation by its leaf area density *a(z)* [m^2 m^{-3}] and effective drag coefficient

To a first approx. mtm balance is

$$\left|\Delta \overline{u'w'}\right| = c_d \, a(z) U^2 \;\; \Delta z$$

z

$\overline{u'w'}(z)$

(discretization of the d.e.)

The canopy leaf area index (LAI) is height integral of *a(z)*,

$$LAI = \int_0^h a(z)\, dz$$

$$0 = -\frac{\partial \overline{u'w'}}{\partial z} - c_d \, a(z) U^2$$

If one adopts eddy viscosity closure with a constant *K* (typically chosen as $K = c\, h\, u_{*h}$), and treats $c_d a$ as a constant then:

$$0 = K \frac{\partial^2 U}{\partial z^2} - c_d \, a(z) U^2$$

$$U = U(h) \exp\left[\beta (z/h - 1)\right]$$

β (the "extinction coefft") is a function of (K, $c_d a$) but normally treated as a free coefficient

Formal treatment of the horizontal inhomogeneity of a canopy flow

The canopy space is "multiply connected" (vegetation is external to the flow domain). Following NR Wilson & RH Shaw (1977), one introduces spatially-continuous flow variables that are averages in the horizontal plane over distances that are large w.r.t. canopy inhomogenbeity length scales, and so can be regarded as being independent of x,y.

$$g(x, y, z, t) = \langle \overline{g} \rangle + \overline{g}'' + g'$$

instantaneous local value = space-time mean (horiz. avg. of time avg.) + local time-average deviation from the space-time mean + instantaneous local fluctuation from the local time average

Then cross products expand as follows:

$$R_{ij}^{tot} = \langle \overline{u_i u_j} \rangle = U_i \ U_j + \langle \overline{u}_i'' \ \overline{u}_j'' \rangle + \langle \overline{u_i' u_j'} \rangle$$

where $U_i \equiv \langle \overline{u}_i \rangle$

dispersive momentum flux – arises from spatial covariance of local time average departures from the local space-time mean flow.

Dispersive fluxes have rarely been measured – Raupach et al. in wind tunnel canopy flow. Andreas Christen (UBC Geog.) is actively working on this (forest & urban winds) – e.g. Christen et al. (2009; Boundary-Layer Meteorol., 131:193-222)

Std dev of vertical velocity

• normalization renders profiles from corn canopy and from pine forest quite similar

• in base of canopy σ_w only about 1/5th of its value above canopy

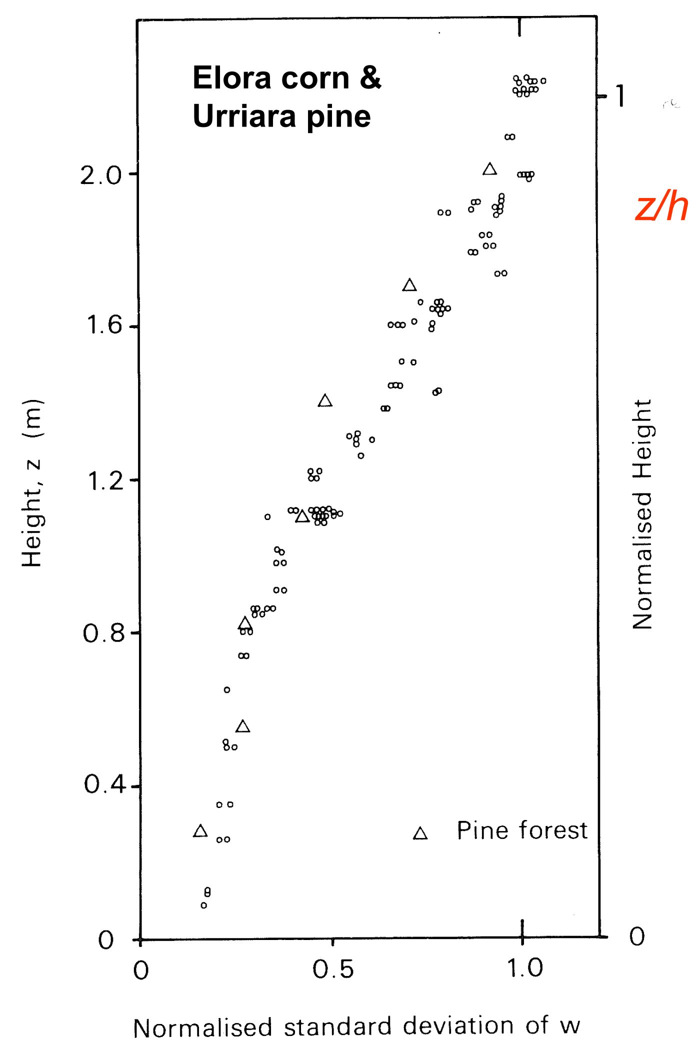
• unless trajectories computed using a well-mixed LS model*, particles accumulate in base of canopy (analog to molecular diffusion where small velocity scale reflects low temperature and – accordingly – high density)

• the budget equation for σ_w^2 contains a turbulent transport term $T_t = -\partial \overline{w'^3}/\partial z$, which measurements show is large near and in the plant canopy – the TKE budget in a canopy is not in local equilibrium

*The unique well-mixed , 1D LS model for vertically-inhomogeneous Gaussian turbulence is (Thomson, 1987):

$$
\begin{aligned}
dW &= a\,dt + b\,d\xi \\
a &= -\frac{C_0\,\epsilon(z)}{2\sigma_w{}^2(z)}\,W + \frac{1}{2}\frac{\partial \sigma_w{}^2}{\partial z}\left(\frac{W^2}{\sigma_w{}^2} + 1\right) \\
b &= \sqrt{C_0\,\epsilon(z)}
\end{aligned}
$$

Boundary-Layer Meteorology 24 (1982) 495–519.



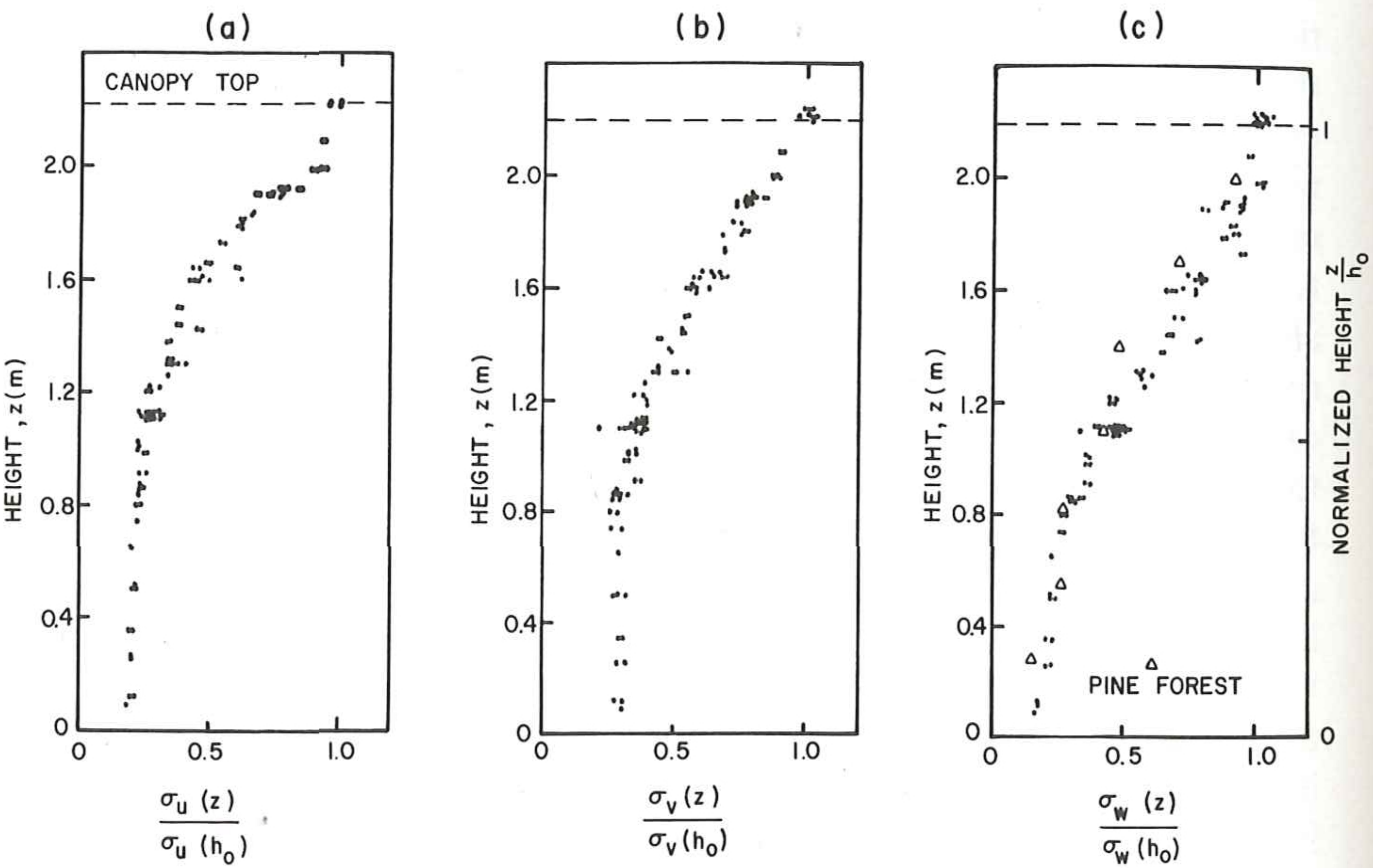
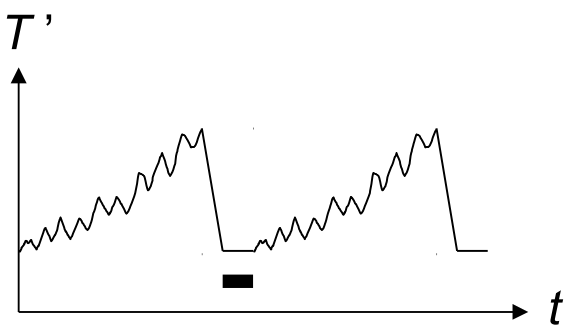


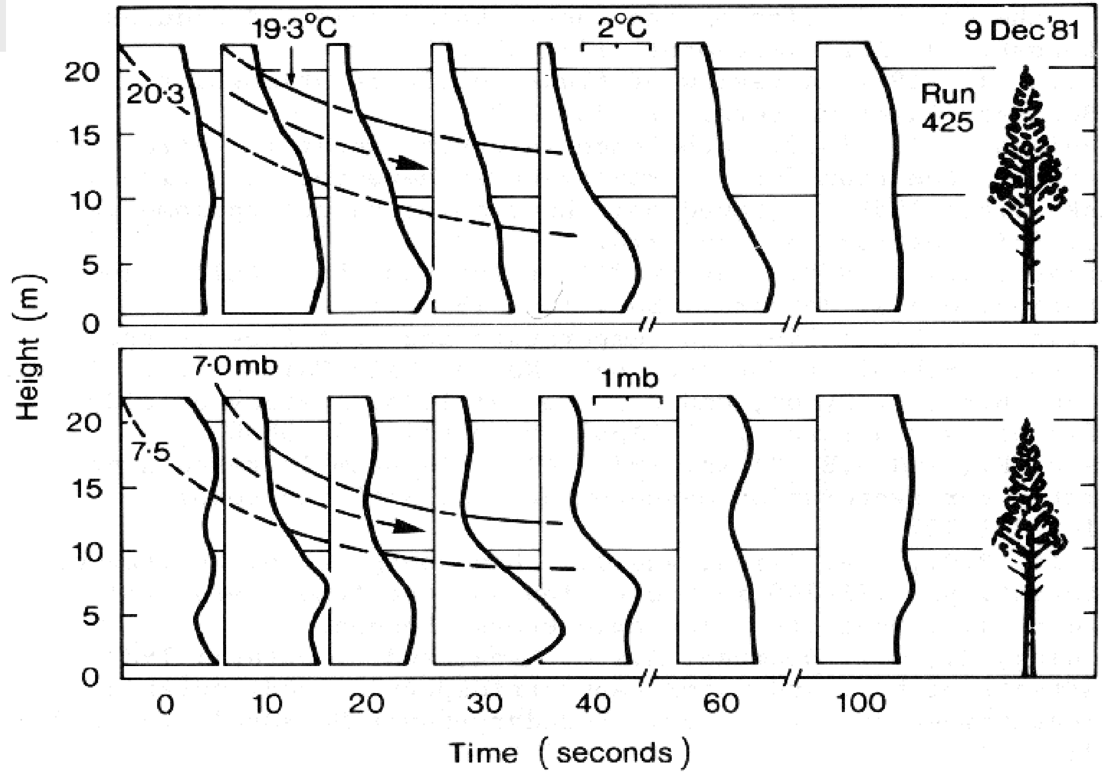
Fig. 15.10 Observed profiles of the normalized standard deviations of (a) longitudinal, (b) lateral, and (c) vertical velocity fluctuations in a corn canopy. [After Wilson *et al*. Copyright © (1982) by D. Reidel Publishing Company. Reprinted by permission.]

Intermittency:

O.T. Denmead and E.F. Bradley, 1985, Flux-gradient relationships in a forest canopy, 421-442 in *The forest-atmosphere interaction*, eds. Hutchison & Hicks, D. Reidel Pub. Co.



Schematic "temperature ramp" – during quiescent periods temperature slowly increases, then suddenly drops to a cooler baseline value as a gust penetrates the canopy...



Here we see a "sweep" (also known as a "gust")

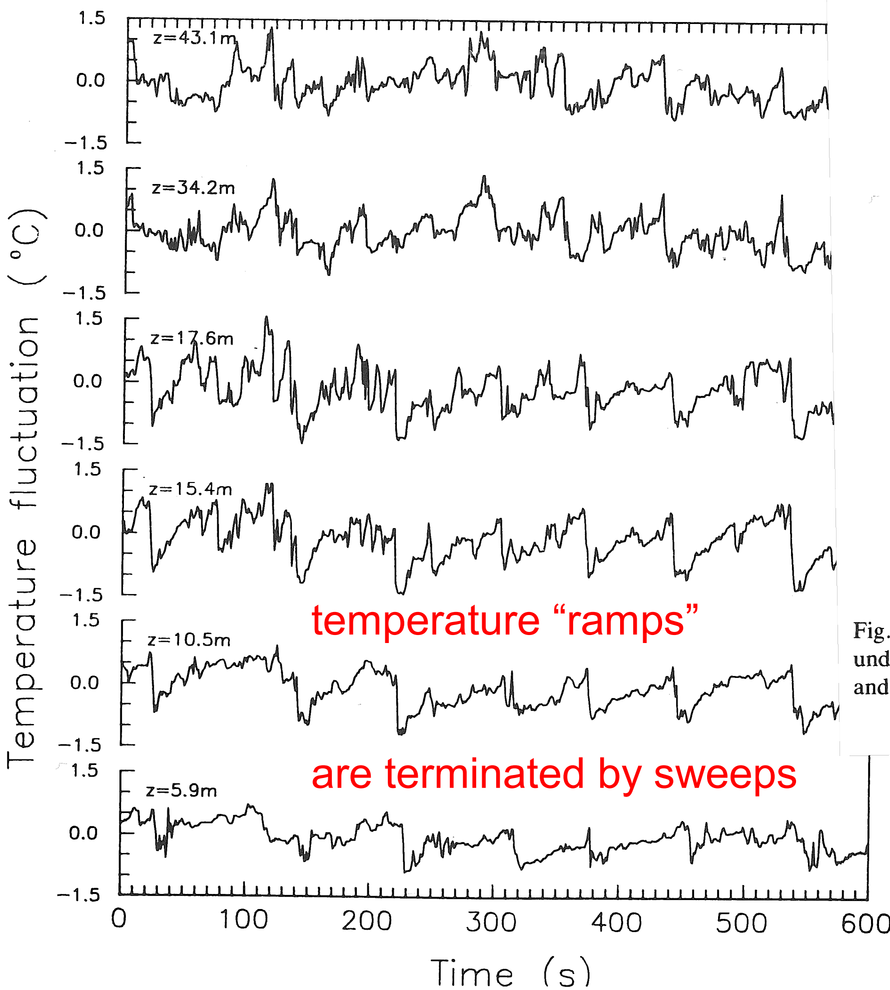
Time sequence of temperature (top) and humidity (below) during the "flushing" of the Urriara pine canopy by a gust of cooler, drier air from above. Long after the gust, local redistribution of the heat shed from the sunlit foliage, and of transpired vapour, have re-established the pre-gust situation of a (relatively) warm, moist, quiescent canopy airstream somewhat decoupled from the boundary-layer overhead. From Denmead and Bradley (1985)

Structure of the “sweeps” (“gusts”)

OBSERVATION OF ORGANIZED STRUCTURE IN TURBULENT FLOW WITHIN AND ABOVE A FOREST CANOPY

W. GAO, R. H. SHAW, and K. T. PAW U

Boundary-Layer Meteorology **47**: 349–377, 1989.



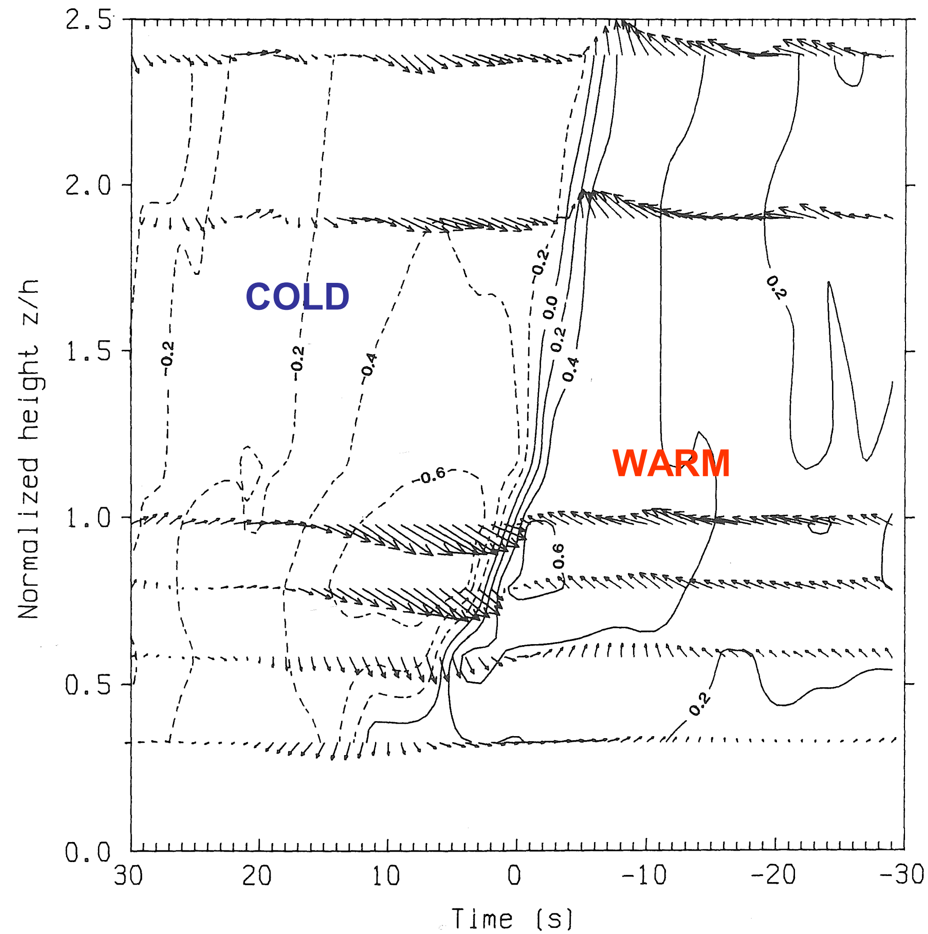


Fig. 6a. Vertical cross-section of ensemble-averaged temperature and fluctuating velocity fields, under unstable conditions ($L = -138$ m), during Run A. Dashed lines are isotherms below the mean, and solid lines are isotherms above the mean. Contour interval is 0.2 °C and the maximum arrow length represents a wind magnitude of 1.9 m/s.

Structure of the "sweeps" ("gusts")

WIND AND WIND FORCES IN A PLANTATION SPRUCE FOREST

B. A. GARDINER

Boundary-Layer Meteorology 67: 161–186, 1994.

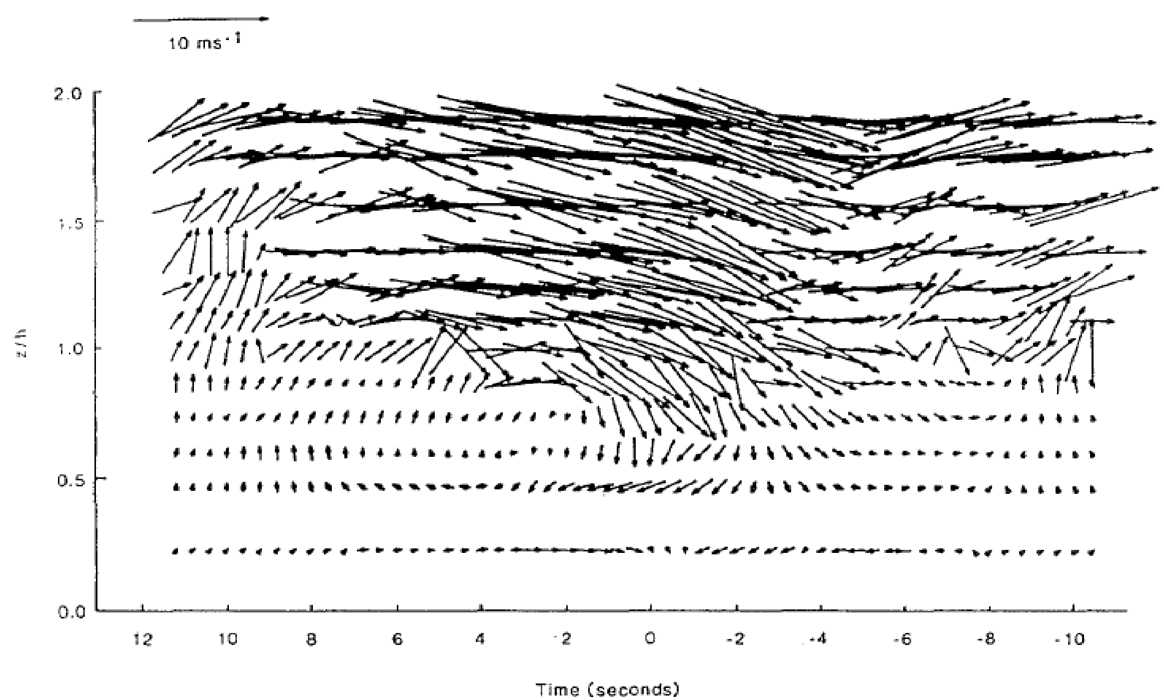


Fig. 6. Vertical cross-section of the velocity field for a single sweep event with time going from right to left. Arrows represent the two dimensional (u, w) wind velocities over a 0.4 s period.

Quadrant analysis of the shear stress

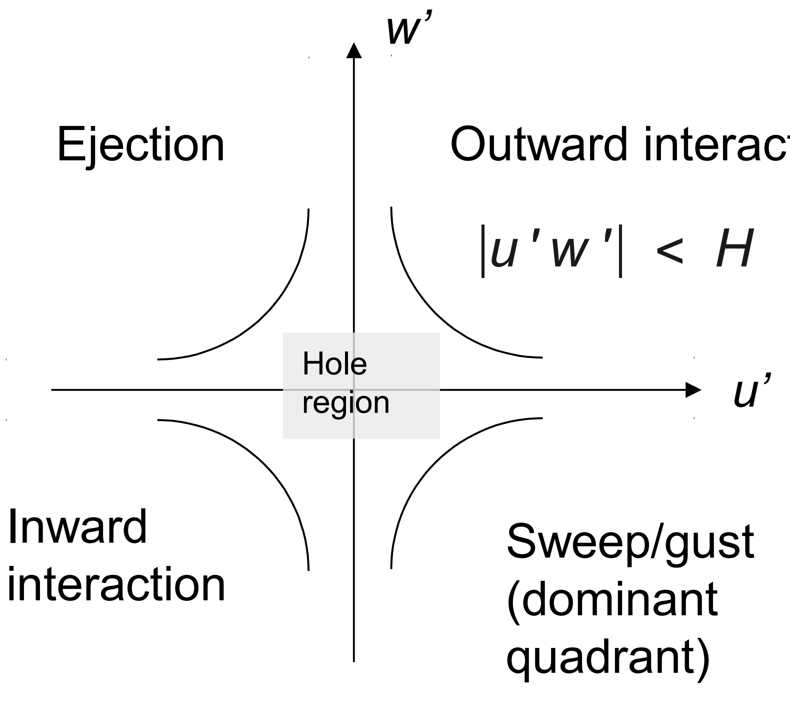
Stress contribution from quadrant α

$$(\overline{u'w'})_\alpha = \frac{1}{N}\sum_{i=1}^{N} I_\alpha(u_i', w_i')\; u_i' \; w_i'$$

Indicator function for quadrant 1 with hole size H

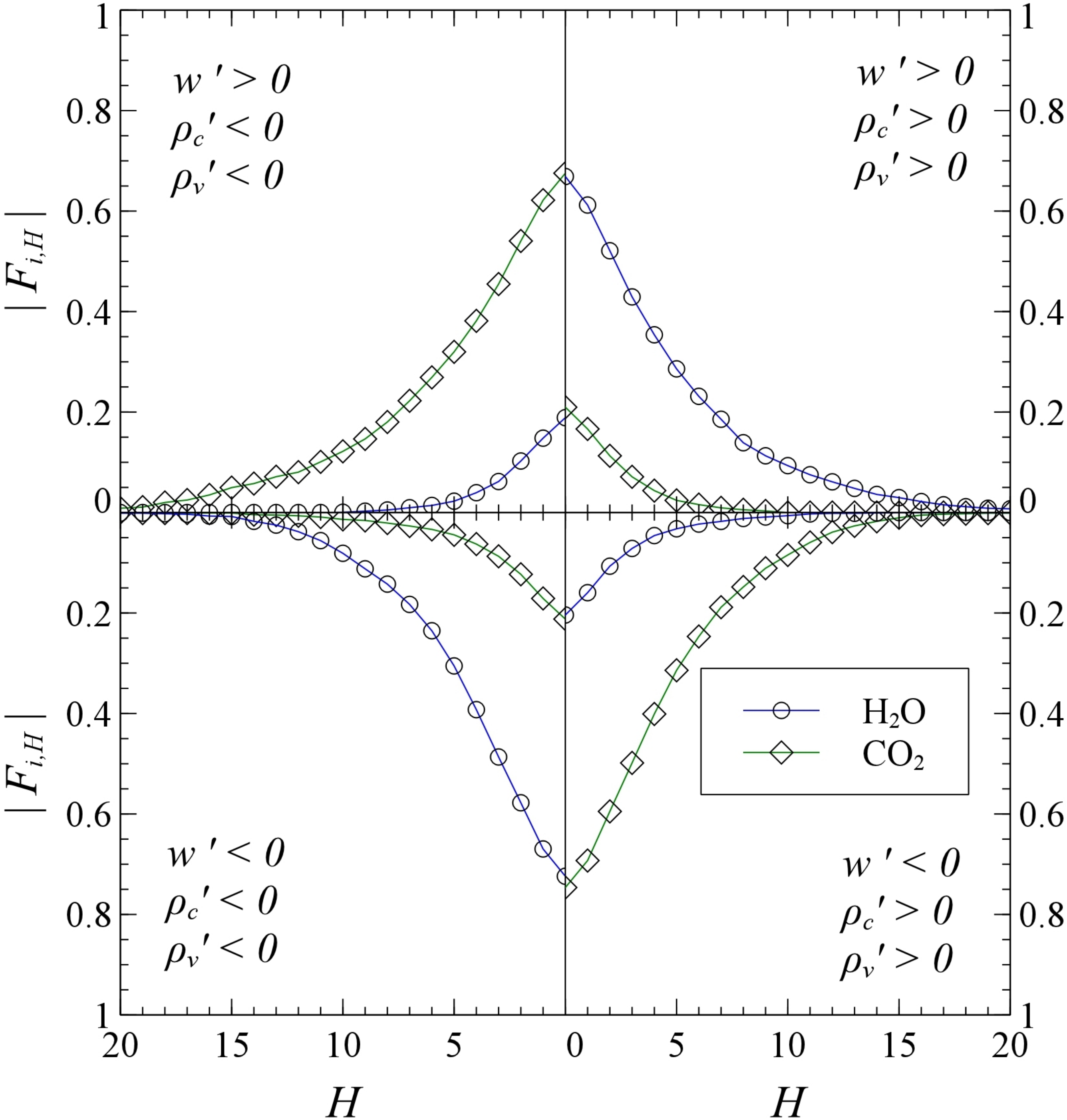
$$I_1 = 1 \text{ if } u'>0, w'>0, |u'w'| \geq H \; |\overline{u'w'}|$$

One computes the stress fraction from each quadrant and associated time fraction



Stress fraction from quadrant α

$$F_\alpha = \frac{(\overline{u'w'})_\alpha}{\overline{u'w'}}$$

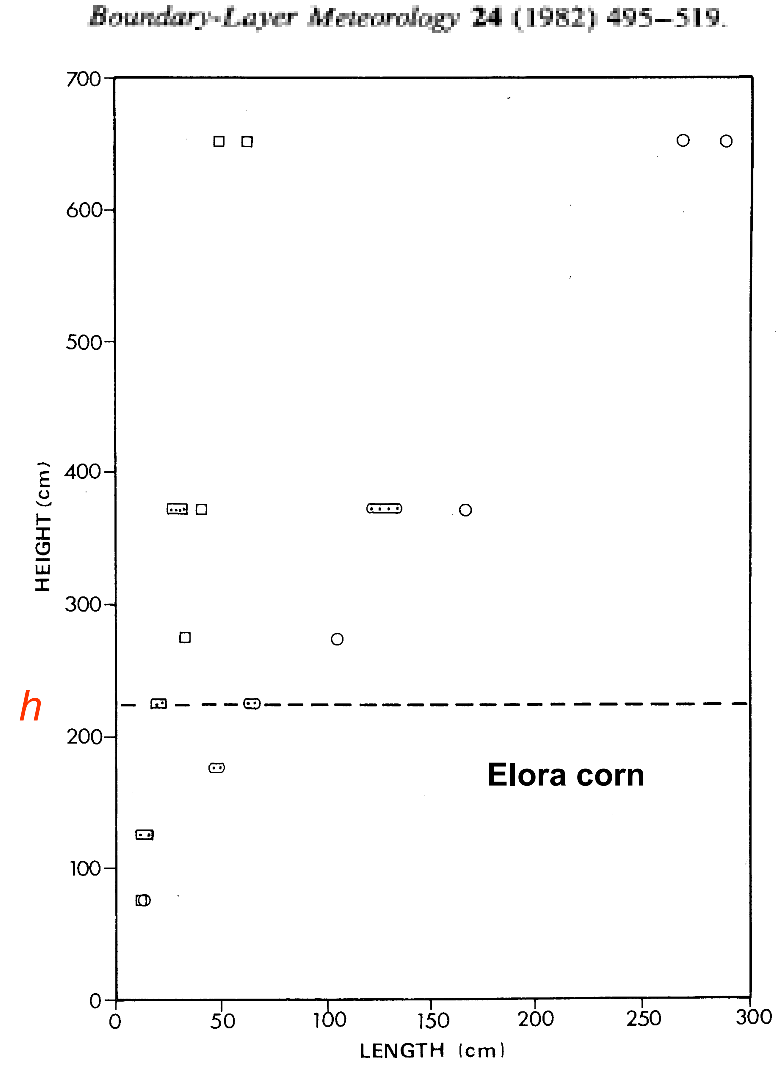


Quadrant analysis applied to the eddy fluxes of water vapour and carbon dioxide above a wheat crop (St. Albert, 16 Aug. 2011)

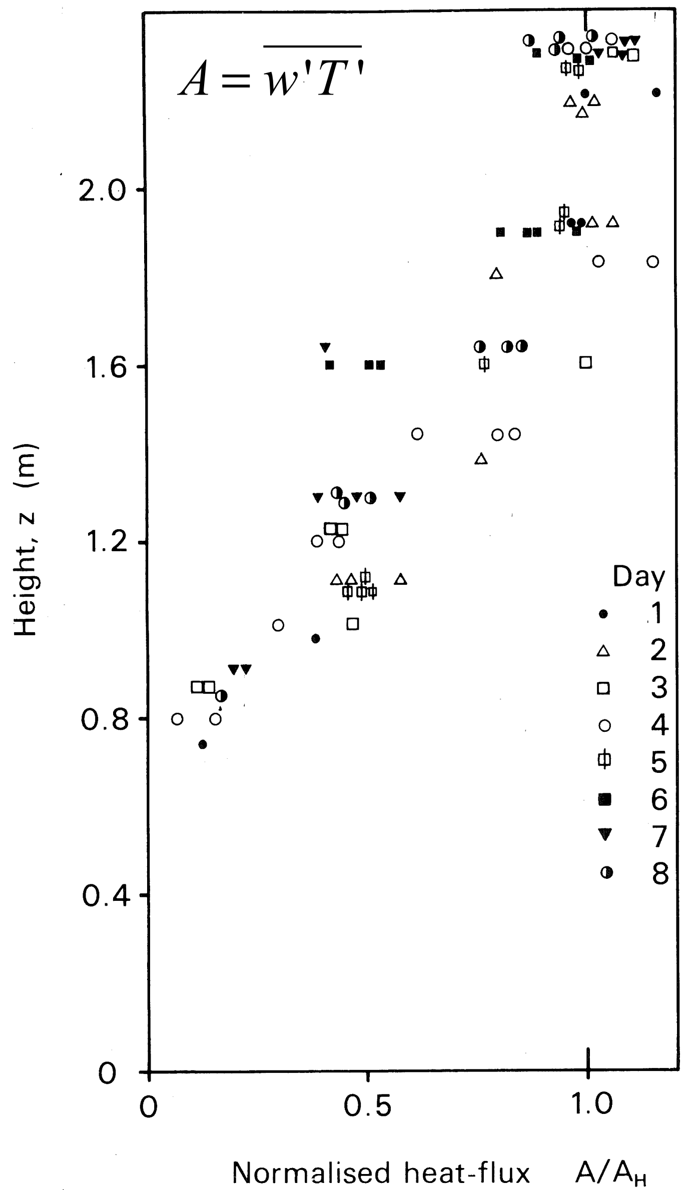
/clang/quadrant/veusz

Squares: $L_w = \sigma_w \Gamma_w$

where $\Gamma_w = \int_0^\infty R_{ww}(\zeta)\, d\zeta$ is the Eulerian integral time scale



Heat flux density



More scatter than in the stress profile – why?

$\overline{w'T'}(z+\Delta z)$

$z+\Delta z$

Assuming stationarity & horiz homogeneity the layer heat budget is:

$$\left|\Delta \overline{w'T'}\right| = a(z)\, \Delta z\, \frac{Q_{H,leaf}}{\rho\, c_p}$$

$\overline{w'T'}(z)$

z

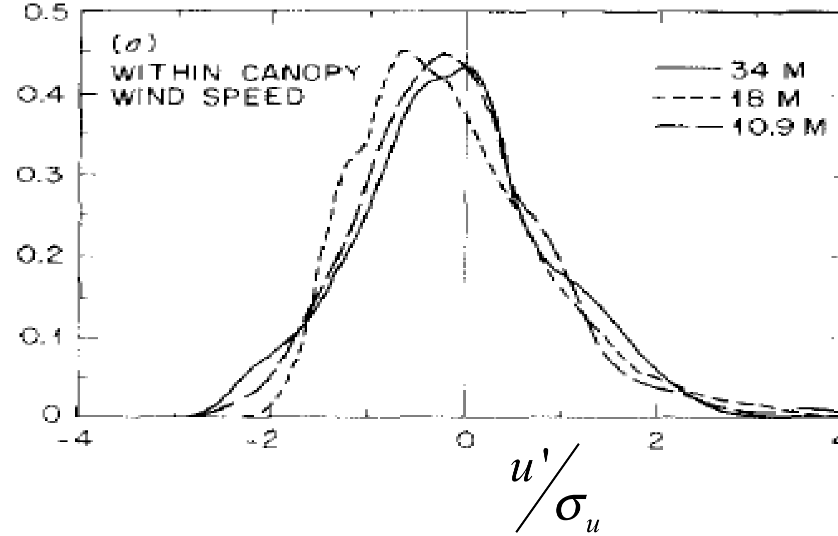
$Q_{H,leaf}$ is the mean rate at which a leaf at z+Δz/2 is shedding heat to the airstream; a function of its energy balance – the radiation load, vapour pressure deficit, stomatal conductance… If we introduce the Bowen ratio β_{br} as ratio of the leaf sensible heat flux to leaf latent heat flux, then the differential equation for the heat budget is

$$\rho c_p \frac{\partial \overline{w'T'}}{\partial z} = a(z) Q_{H,leaf}(z) = \frac{\beta_{br}(z)}{1+\beta_{br}(z)} \frac{\partial Q^*}{\partial z}$$

Note that this involves the divergence of the net radiative energy flux density *Q*(z)*, which in turn will surely depend on such factors as solar elevation (shortwave) and the canopy temperature profiles (longwave)… this explains the *non-universality* of the heat flux profile.

A version of the Penman-Monteith equation provides the Bowen ratio

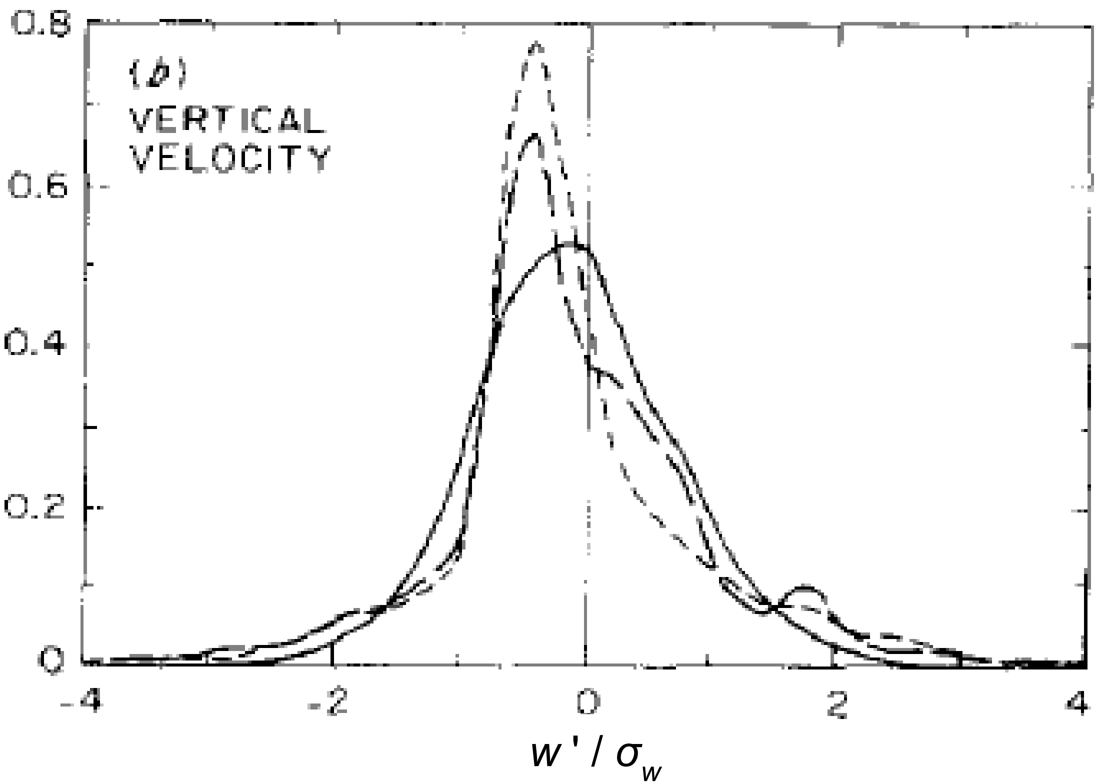
Probability density functions for velocity:



TURBULENCE STRUCTURE IN A DECIDUOUS FOREST

DENNIS D. BALDOCCHI and TILDEN P. MEYERS

Boundary-Layer Meteorology **43** (1988) 345–364.

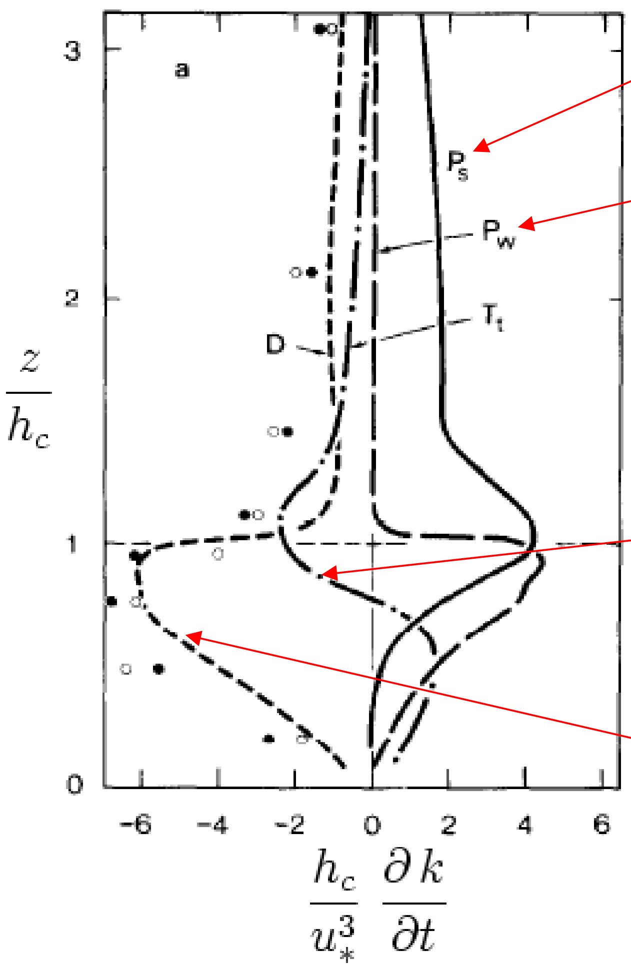


- clearly these are not Gaussian distributions
- deep in the canopy the most probable velocity is a weak downdraft

Non-local TKE balance:

M. R. RAUPACH, P. A COPPIN, and B. J. LEGG[1]

Boundary-Layer Meteorology **35** (1986) 21–52.



$$P_s = -\overline{u'w'}\,\frac{\partial U}{\partial z}$$ rate of shear production

$$P_w = c_d\,a\,U^2 \times U$$ rate of working by the canopy drag force

$$T_t = -\frac{\partial}{\partial z}\overline{w'\left(u'^2 + v'^2 + w'^2\right)/2}$$ turbulent transport**

D (= ε) viscous conversion to heat

**The transport term in the σ_w^2 budget is $T_t = -\frac{\partial\,\overline{w'^3}}{\partial z}$ and would vanish if the vertical velocity skewness $Sk_w = \overline{w'^3}/\sigma_w^3$ vanished – which it does not.

Flux- gradient relationship:

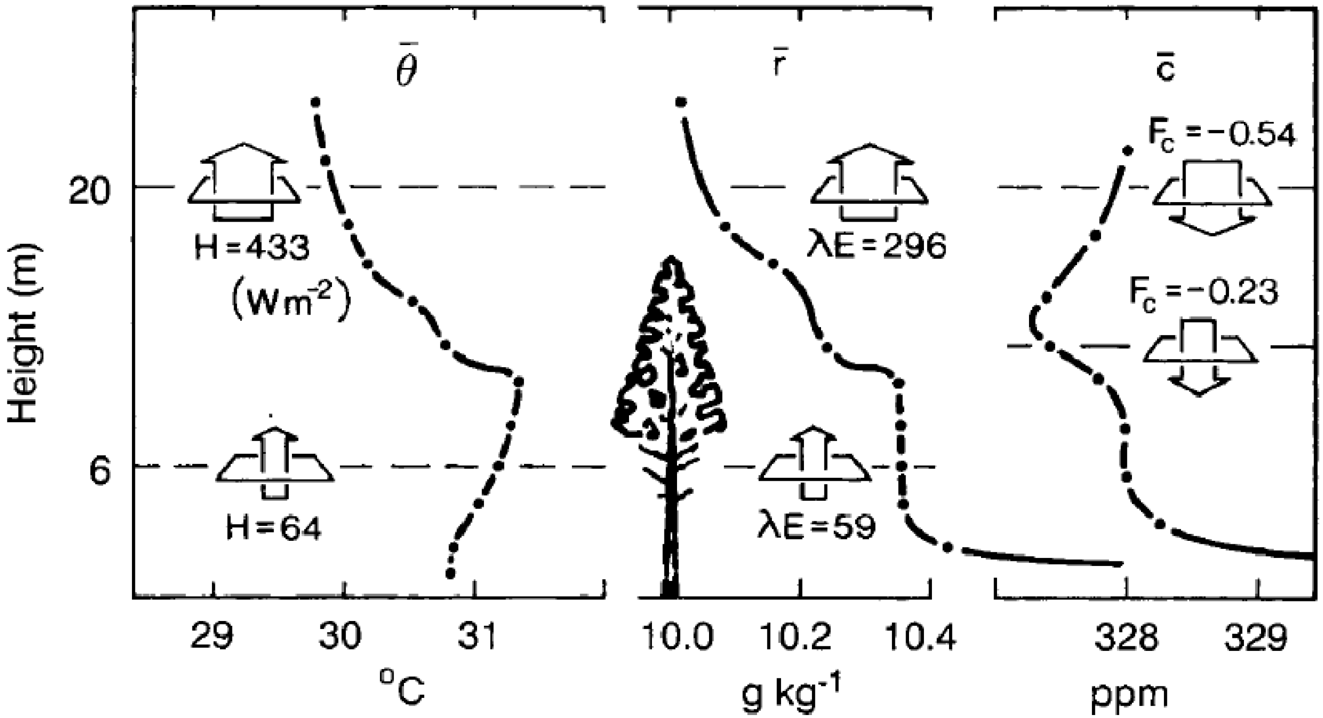
The distinct crown of the canopy and the underlying ground are separated by a very open trunk space. The crown and the ground are strong sinks/sources, whereas the trunk space absorbs little radiation so produces little sensible or latent heat, and no carbon dioxide.

Counter-gradient fluxes in this forest are a consequence of the widely separated sources and sinks in presence of very large eddies (length scale *h*).

Corrsin (Adv. Geophys. 1974, Vol. 18A): *K*-theory valid when the transport process is "fine grained" relative to the length scale of the tracer distribution

Lagrangian model correctly handles the problem

Simplified analytical Lagrangian treatment provided by Raupach ("Localized Near Field" theory) and a variant by Warland and Thurtell



From: O.T. Denmead and E.F. Bradley, 1985, Flux-gradient relationships in a forest canopy, 421- 442 in *The forest-atmosphere interaction*, eds. Hutchison & Hicks, D. Reidel Pub. Co.

J. Fluid Mech. (2009), vol. 637, pp. 387–424. © Cambridge University Press 2009

doi:10.1017/S0022112009990589

Turbulence structure above a vegetation canopy

JOHN J. FINNIGAN[1]†, ROGER H. SHAW[2] AND EDWARD G. PATTON[3]

The characteristic eddy consists of an upstream head-down sweep-generating hairpin vortex superimposed on a downstream head-up ejection-generating hairpin. The conjunction of the sweep and ejection produces the pressure maximum between the hairpins, and this is also the location of a coherent scalar microfront

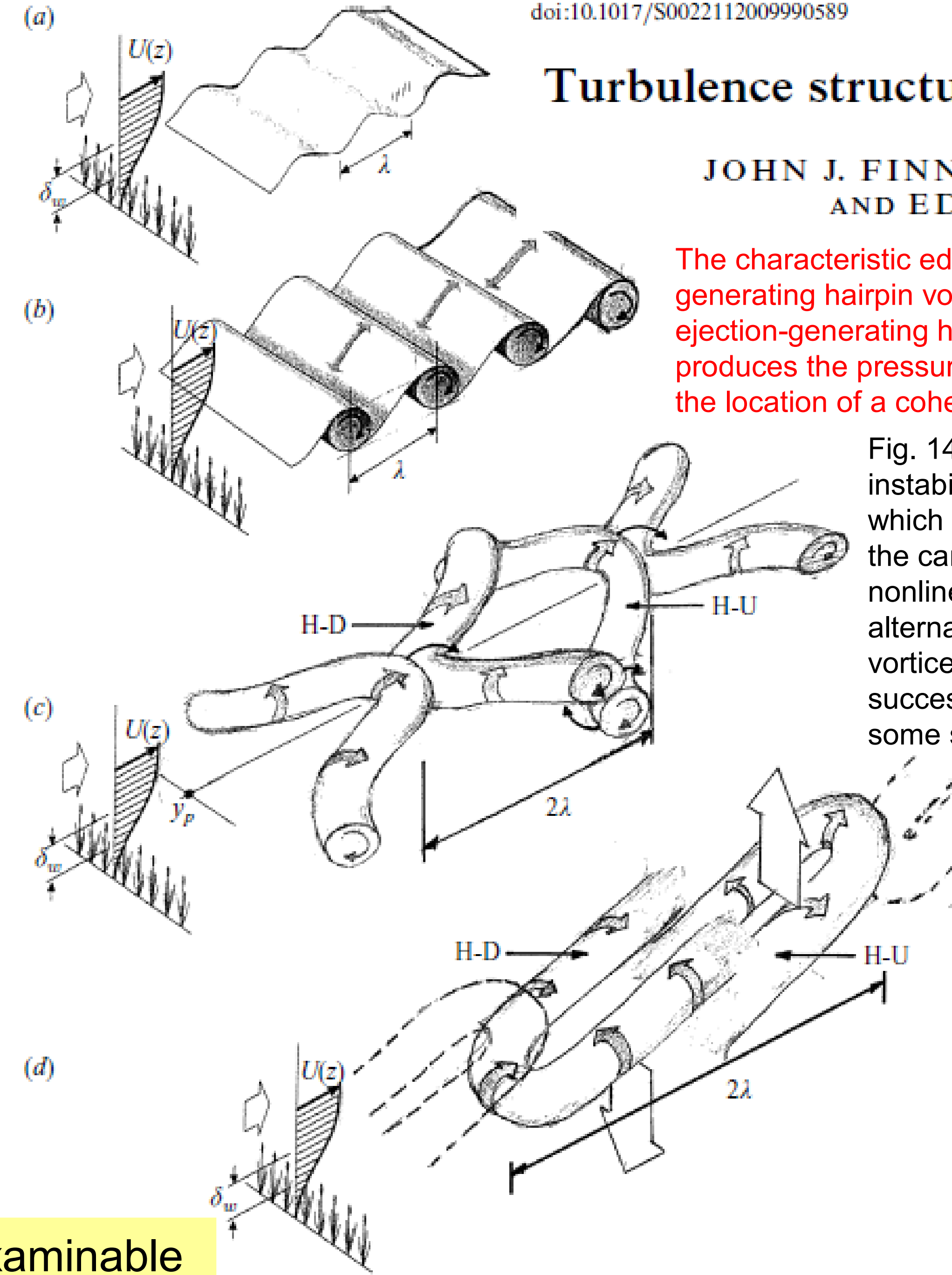


Fig. 14. Formation of dual-hairpin eddy. (a) The initial instability is a Kelvin–Helmholtz wave of wavelength λ, which develops on the inflected mean-velocity profile at the canopy top. (b) The resulting velocity field is nonlinearly unstable, and successive regions of alternating spanwise vorticity clump into coherent 'Stuart' vortices, which retain the wavelength, λ. (c) Two successive Stuart vortices are moved closer together at some spanwise location y_p by the ambient turbulence.

The mutual induction of their vorticity fields causes them to approach more closely and rotate around each other. Vortex pairing doubles the wavelength of the disturbance to 2λ. Note that this disturbance of the streamwise symmetry of the induced velocity fields of successive vortices will propagate upwind and downwind at the same y location. (d) As the initial hairpins are strained by the mean shear, most of the vorticity accumulates in the legs, and self-induction by the vortex legs dominates the motion of the hairpins. As a result, the head-down hairpin moves down, while the head-up hairpin moves up....

Not examinable