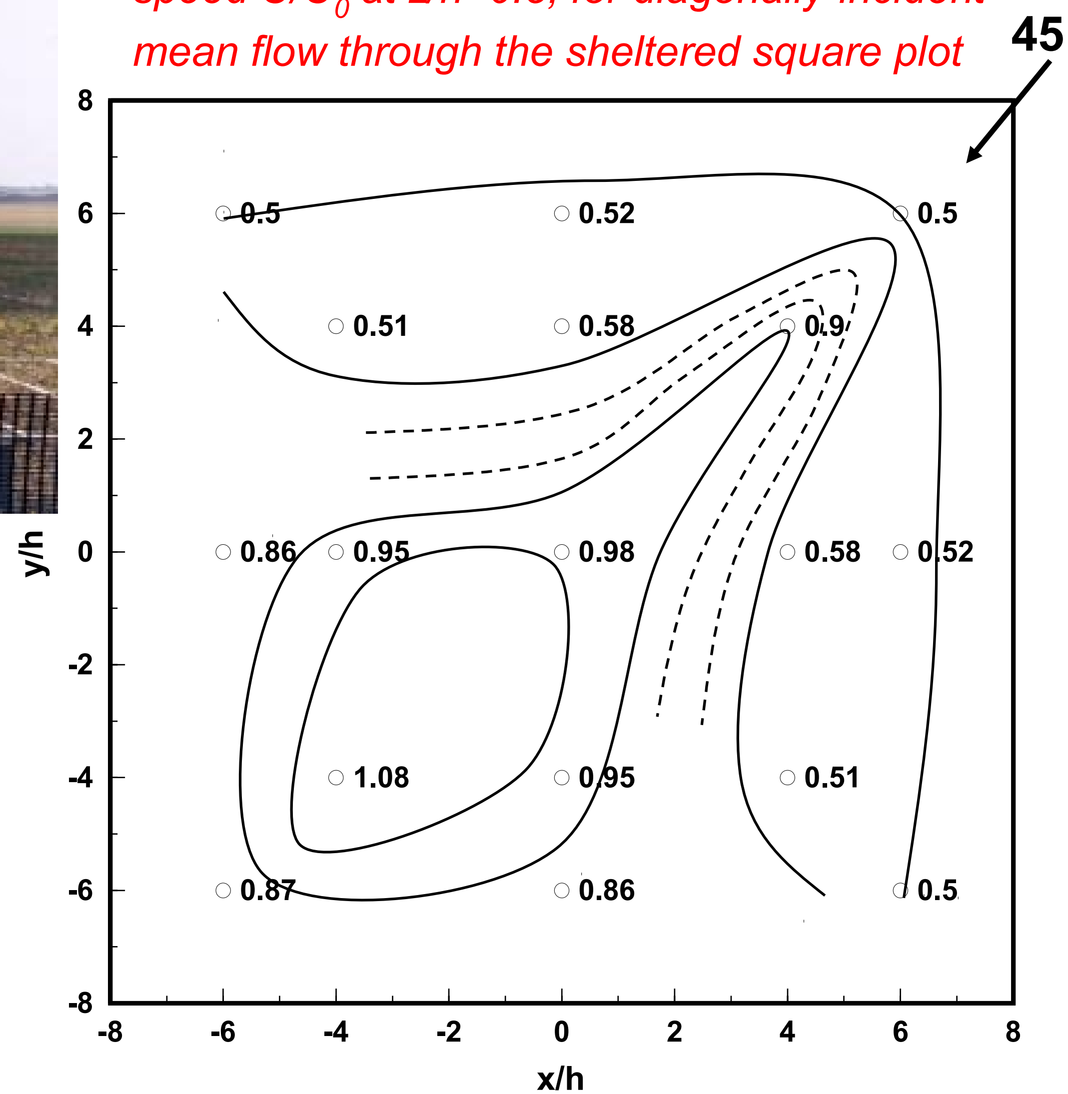
Disturbed micro-meteorological flows (ctd): flow around windbreaks

- basic effects observed
- elements of the theoretical description

Contours of measured relative mean wind speed U/U_0 at $z/h=0.5$, for diagonally-incident mean flow through the sheltered square plot

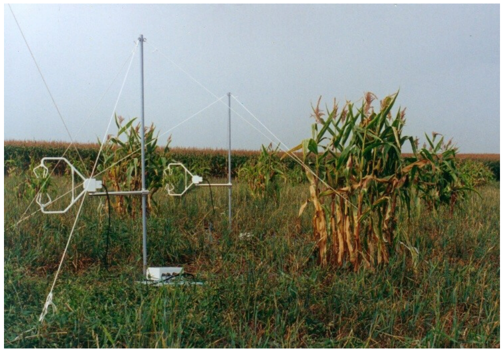


Useful review: pages 17-24 in McNaughton (1988, Agric., Ecosys. & Environ. Vol. 22/23, 17-39)

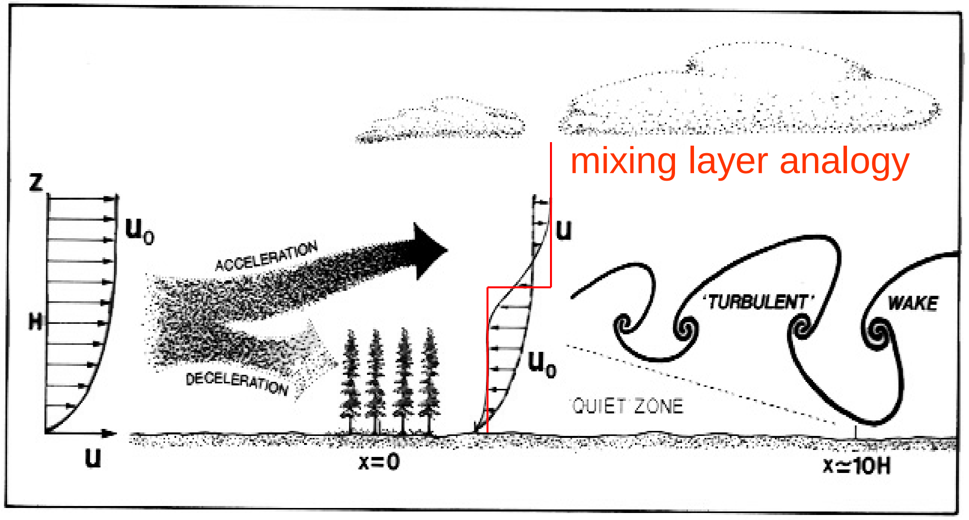
eas572_windbreak.odp

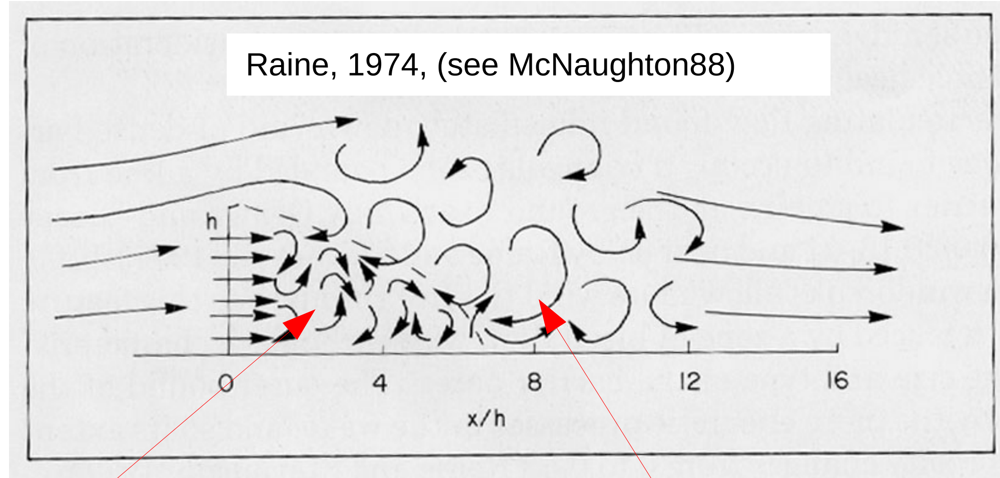
JDW vers. 22 Nov. 2012

Disturbed micro-meteorological flows (ctd): flow around windbreaks



Overview of effects of windbreak – on mean wind, turbulence, temperature...





“quiet zone” of reduced TKE

- mean wind reduction, turbulent wake

$$\int_{z_0}^{\infty} \overline{u}(z)\ dz = \int_{z_0}^{\infty} \overline{u}_0(z)\ dz$$

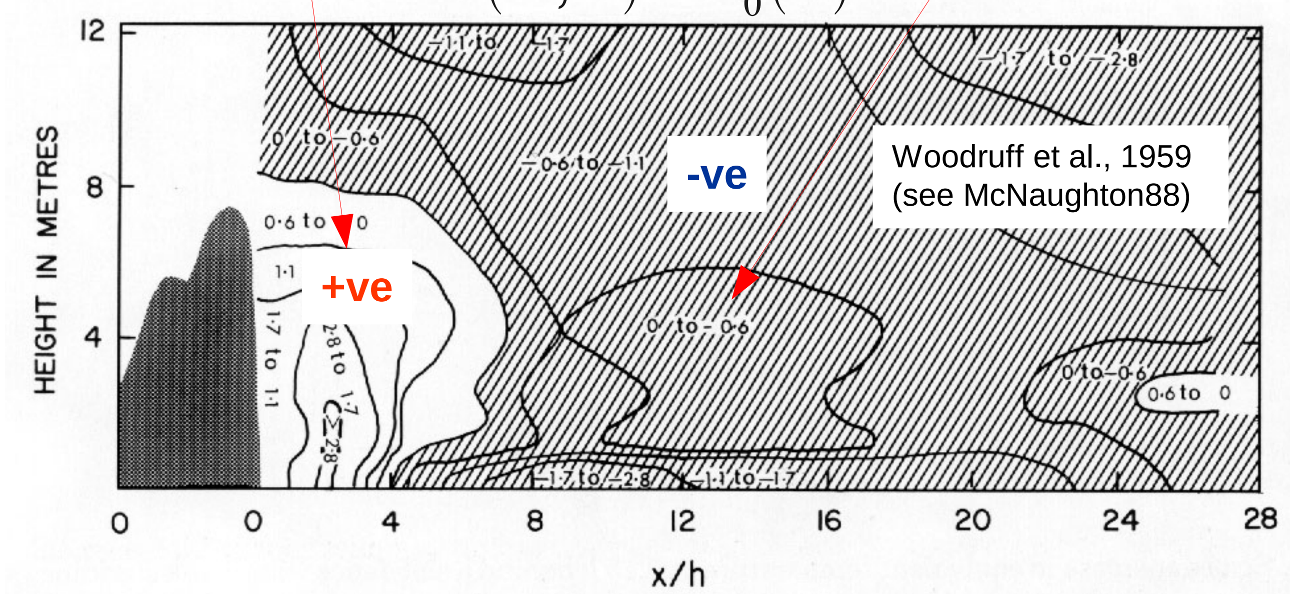
Reduced K_h, so need stronger mean temp gradient to carry Q_H

Enhanced K_h

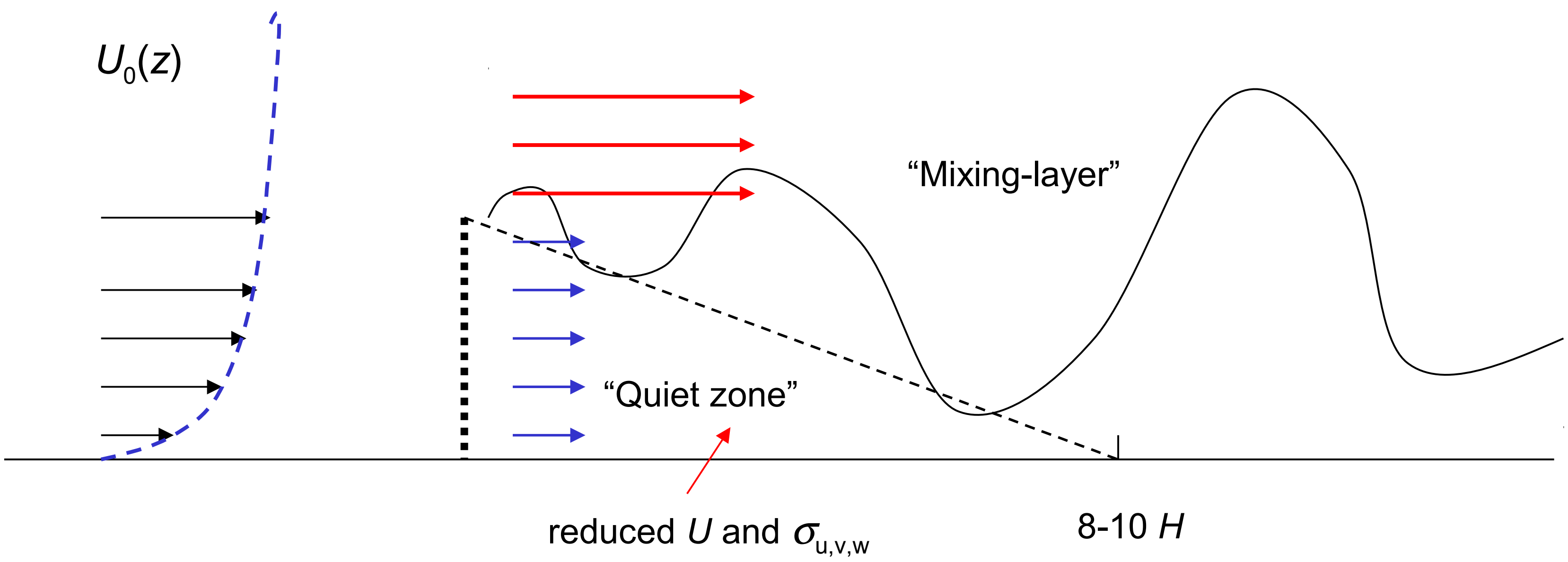
- altered scalar fields

midday summertime anomaly in mean temperature [^{o}C],

$$\overline{T}(x,z) - \overline{T}_0(z)$$

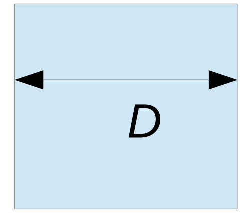


Overview of effects of windbreak – on mean wind, turbulence, temperature...



Overview of effects of windbreak

Agricultural and Forest Meteorology, 48 (1989) 185–199
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands



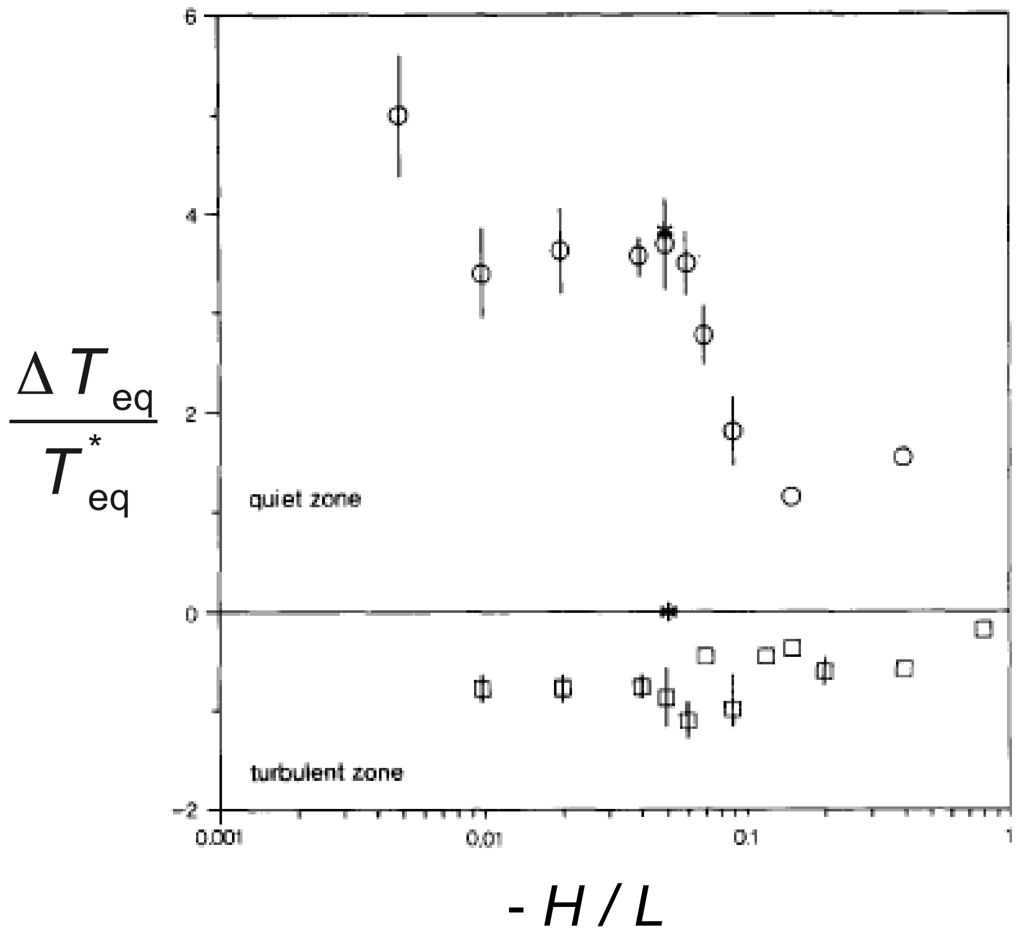
THE MICROCLIMATE IN THE CENTRE OF SMALL SQUARE SHELTERED PLOTS

J.C. ARGETE* and J.D. WILSON

Normalized difference in mean equivalent temperature between plot centre and same height in the open, for plot widths D/H=8 (circles) and D/H=16 (squares)

- same surface flux of thermodynamic energy $Q_{H0}+Q_{E0}$ ($\equiv - \rho c_p u_* T_{eq}$) along with reduced eddy diffusivity in quiet zone results in higher T_{eq}

- larger plot size *D/H=16* places centre of plot beyond the quiet zone... eddy diffusivity increases in the wake zone



Digression – quality of fluxes inferred from profiles

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THE MICROCLIMATE IN THE CENTRE OF SMALL SQUARE SHELTERED PLOTS

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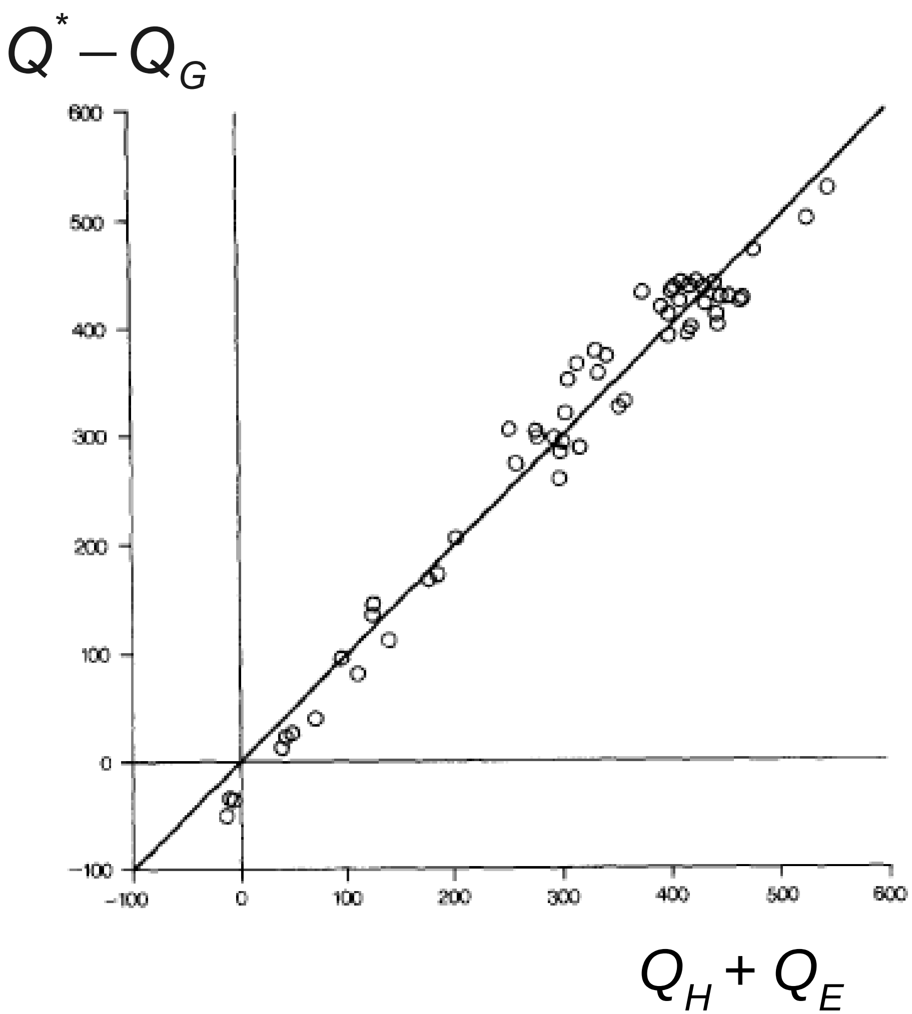


- fitted MO profiles to measured profiles of U, T, Q and inferred u^*, L , and fluxes Q_H, Q_E

- measured net radiation Q^* with net radiometer and Q_G with soil heat flux plate

Windbreak flow: theory & observations regarding an idealized case

– infinitely long but thin porous barrier (height *h or H*, porosity φ), aligned along *y*-axis

– approach flow is neutrally stratified and mean wind direction is normal to the barrier

– by symmetry, $\bar{v} = 0$ and $\partial / \partial y = 0$ for any statistic

– things we'd like to be able to anticipate: spatial patterns in

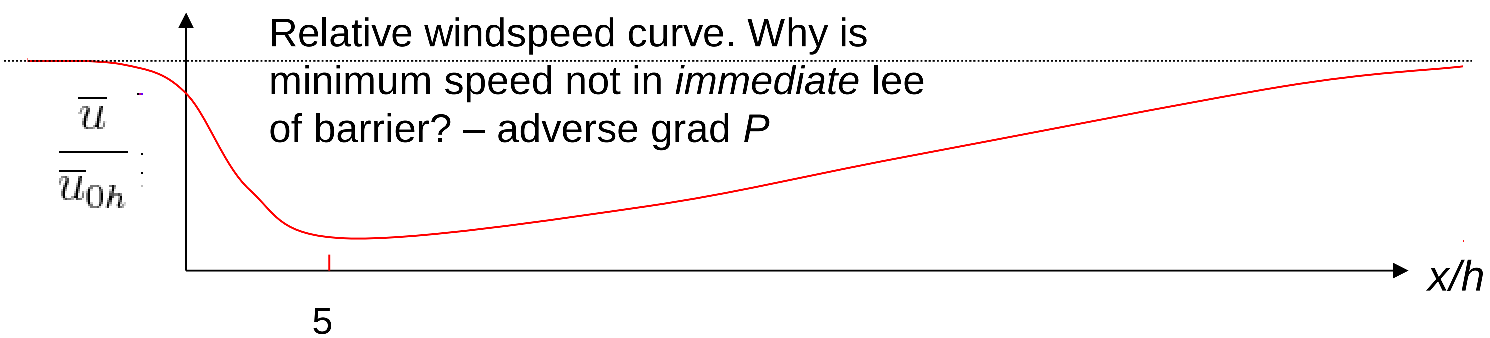
$$\frac{\Delta \overline{u}}{\overline{u}_{0h}} \quad \text{or} \quad \frac{\Delta \overline{u}(x,z)}{\overline{u}_0(z)}$$

(is this strongly height-dependent?)

$$\frac{k}{\overline{u}_{0h}^2} \qquad \frac{k}{u_{*0}^2}$$

"resistance coefficient" (defined over)

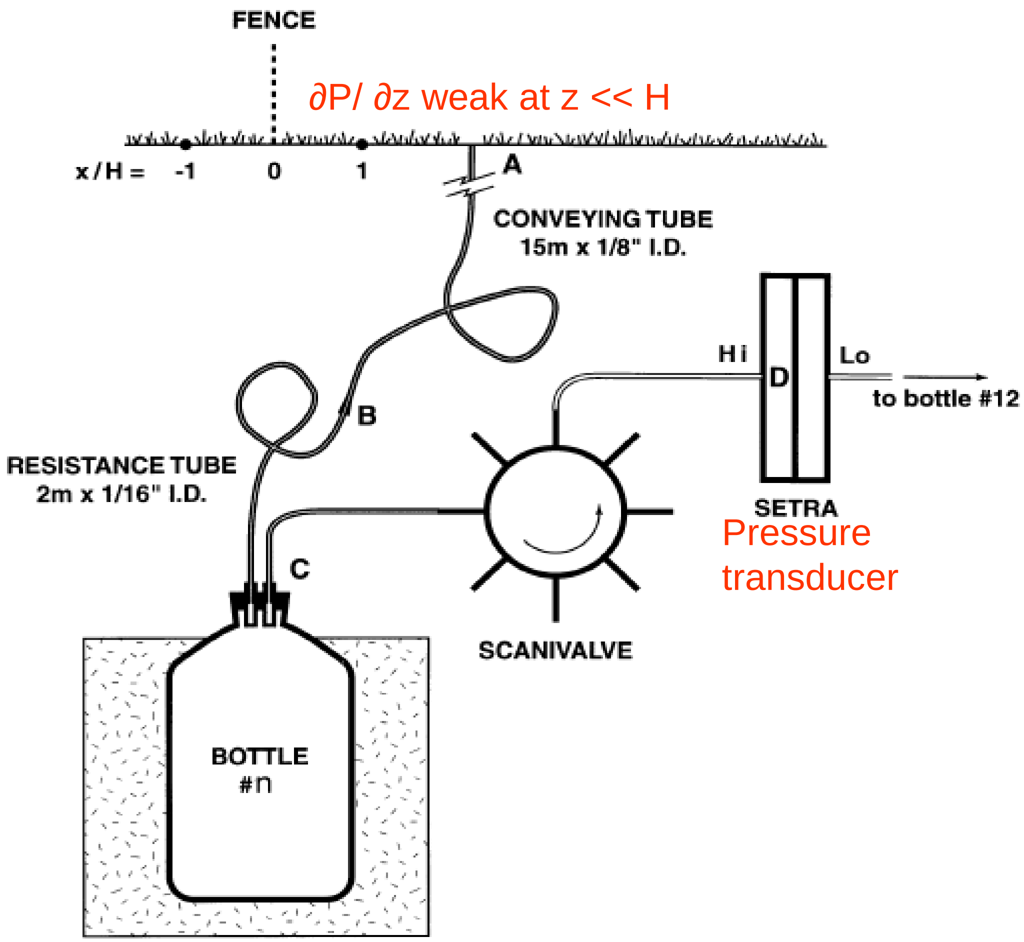
as function of: $\frac{x}{h}, \ \frac{z}{h}, \ \frac{h}{L}, \ \frac{L}{\delta}, \ \frac{h}{z_0}, \ \phi, \ k_r, \ \frac{\overline{u}_{0h}\, h}{\nu}, \ \ldots$?



Why the "recovery"? – downward turbulent transfer of *u*-momentum from the jet aloft, i.e. due to

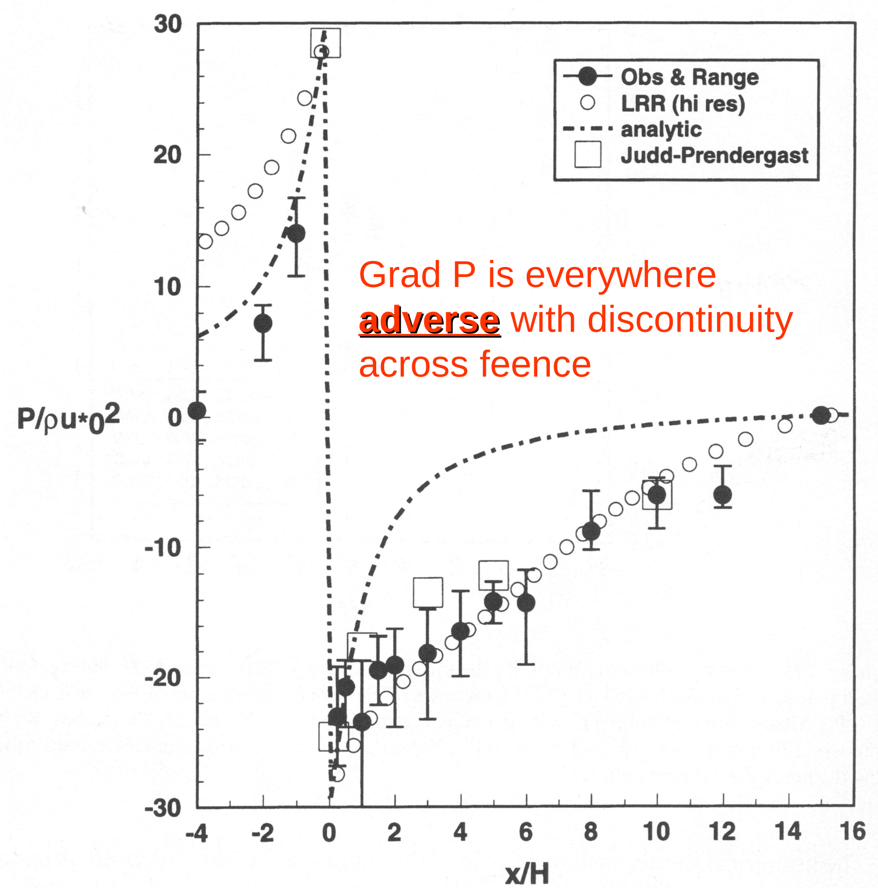
$$\frac{\partial\, \overline{u'w'}}{\partial z}$$

 Wilson, *Boundary-Layer Meteorology* **85:** 327–358, 1997.



Mean pressure jump across windbreak:

$$\Delta P \sim 50\ \rho\ u_{*0}^2$$



4. Numerical Simulations

In Section 4 the field observations of pressure and windspeed will be compared with numerical simulations, i.e., solutions of the mean momentum equations (plus the continuity equation, and a turbulence closure). For example the $\bar{u}$-momentum equation is:

$$\frac{\partial}{\partial x}\left(\overline{u}^2 + \overline{u'^2} + \overline{p}\right) + \frac{\partial}{\partial z}\left(\overline{u}\ \overline{w} + \overline{u'w'}\right) = \underbrace{-k_r\ \overline{u}^2\ \delta(x-0)\ s(z,H)}$$

Localized momentum sink at $x = 0$, $z \leq H$. Proportional to square of speed at barrier, and resistance coefficient k_r

Governing equations – barrier parameterized as momentum sink

- presence of the barrier implies multiply-connected space; formally, need to define flow variables as a suitable area- or volume-average

- interaction of the flow with barrier is not resolved; momentum loss has to be parameterized

$$\frac{\partial}{\partial x}\left(\overline{u}^2+\overline{u'^2}+\overline{p}\right)+\frac{\partial}{\partial z}\left(\overline{u}\,\overline{w}+\overline{u'w'}\right)=S_u$$

For a natural windbreak, let $a(x,z)$ be the "drag area density" (m^{-1}) and c_d the drag coefficient

$$S_u=-c_d\,a(x,z)\,\overline{u}\,\sqrt{\overline{u}^2+\overline{v}^2+\overline{w}^2}$$

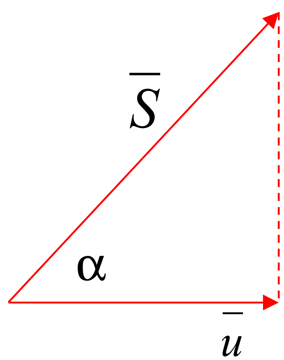
zero by symmetry restriction

of minor importance

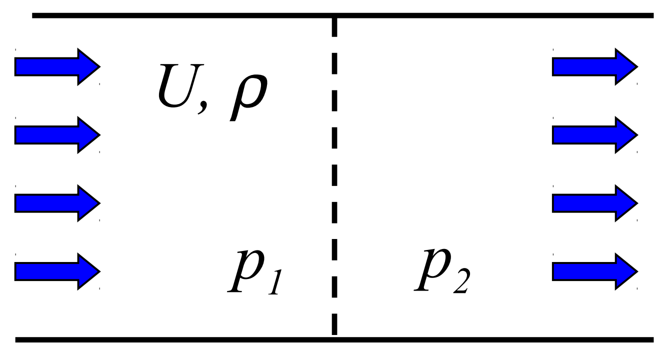
Drag is proportional to projection of $\left(\overline{S}\right)^2$ onto x-axis, where

$$\overline{S}\equiv\sqrt{\overline{u}^2+\overline{v}^2+\overline{w}^2}$$

$$\left(\overline{S}\right)^2\cos\alpha=\left(\overline{S}\right)^2\left(\overline{u}/\overline{S}\right)=\overline{u}\;\overline{S}$$



Definition of "resistance coefficient" with respect to a uniform stream forced through blocking porous screen



$$k_r=\frac{p_1-p_2}{\rho\,U^2}$$

(indep of U for large U)

$$S_u=-k_r\,\overline{u}\,\left|\overline{u}\right|\,\delta(x-0)\;s(z-h)$$

Step fnctn

Earliest attempts to apply fluid mechanics to windbreak (Tani, 1958; Kaiser, 1959)

- treat windbreak as a source of mean velocity deficit $\Delta\overline{u}$

- treat the velocity deficit as a passive scalar that is advected by the undisturbed wind ($\overline{u}_0$) and diffused by the turbulence (eddy diffusivity K_0)

(kinematic pressure)

$$\frac{\partial}{\partial x}\left(\overline{u}^2+\cancel{\overline{u'^2}}+\overline{p}\right)+\frac{\partial}{\partial z}\left(\overline{u}\,\overline{w}+\overline{u'w'}\right)=\cancel{S_u}$$

neglect

Solve eqn only in downwind region. Solution is “driven” not by this inhomogeneity (ie. source term), but by an inflow boundary condition

Substitute

$$\begin{aligned}\overline{u} &= \overline{u}_0+k_r\,\Delta\overline{u}\\ \overline{w} &= k_r\Delta\overline{w}\\ \overline{p} &= k_r\,\Delta\overline{p}\end{aligned}$$

“Perturbation expansion” in small parameter k_r

Neglect terms in k_r^2 (i.e. linearize) and write $\overline{u'w'} = -K\dfrac{\partial\Delta\overline{u}}{\partial z}$

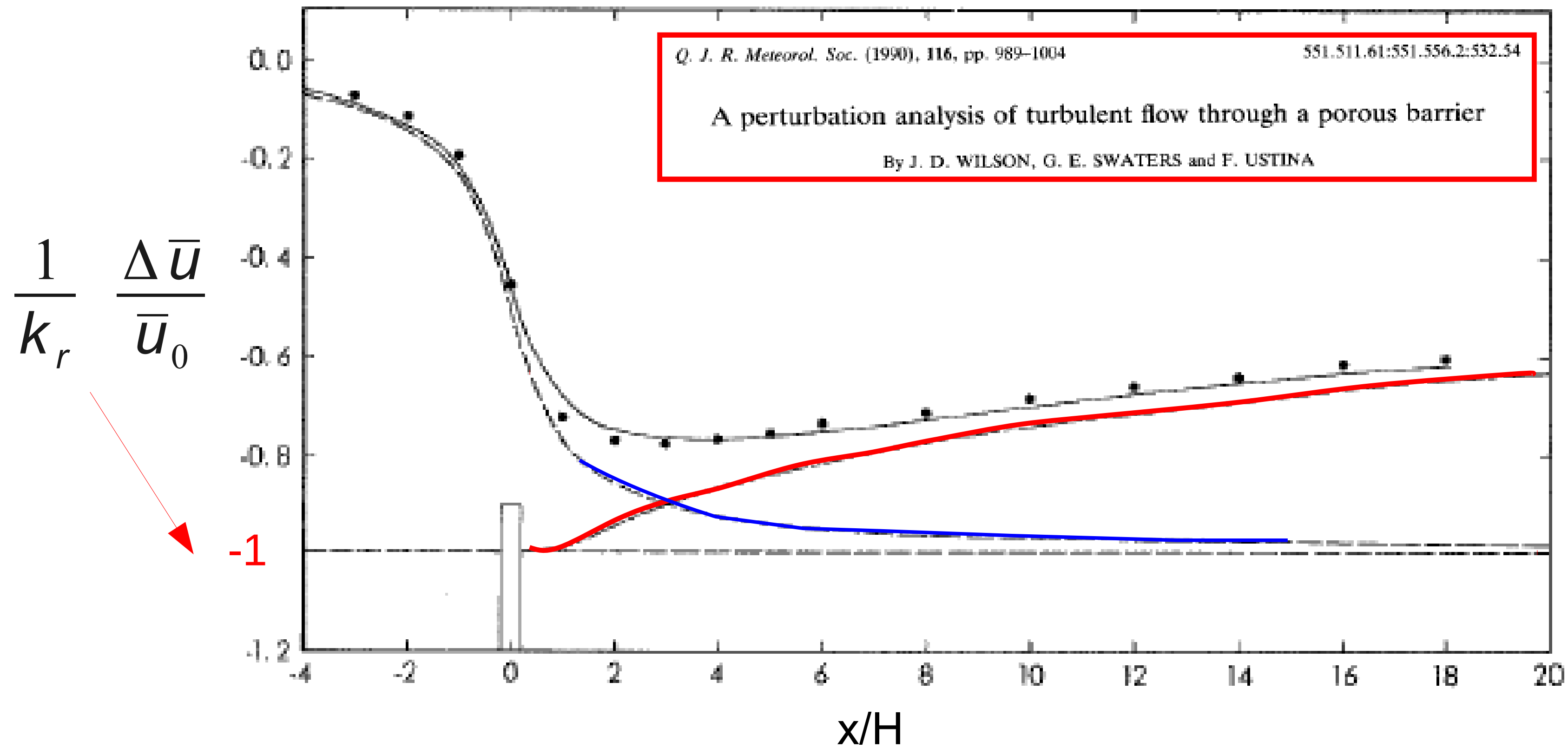
$$\overline{u}_0\frac{\partial\Delta\overline{u}}{\partial x}+\Delta\overline{w}\frac{\partial\overline{u}_0}{\partial z}=-\frac{\partial\Delta\overline{p}}{\partial x}+\frac{\partial}{\partial z}K\frac{\partial\Delta\overline{u}}{\partial z}$$

Further simplifications: $\Delta\overline{w}=0,\ \partial\overline{p}/\partial x=0,\ K=K_0=\text{const.},\ \overline{u}_0=\text{const.}$

Kaiser's analytical solution for mean wind speed *downwind* (only) of barrier

– windbreak of height h represented as collection of strip sources of momentum deficit, each strip of width dz having strength $dQ=k_r\, u_0^2\, dz$

$$\frac{1}{k_r}\,\frac{\Delta\overline{u}}{\overline{u}_0} = -\,\frac{1}{2}\left[\, erf\left(\frac{h+z}{2\sqrt{x\,K_0\,/\,\overline{u}_0}}\right) + erf\left(\frac{h-z}{2\sqrt{x\,K_0\,/\,\overline{u}_0}}\right)\right]$$



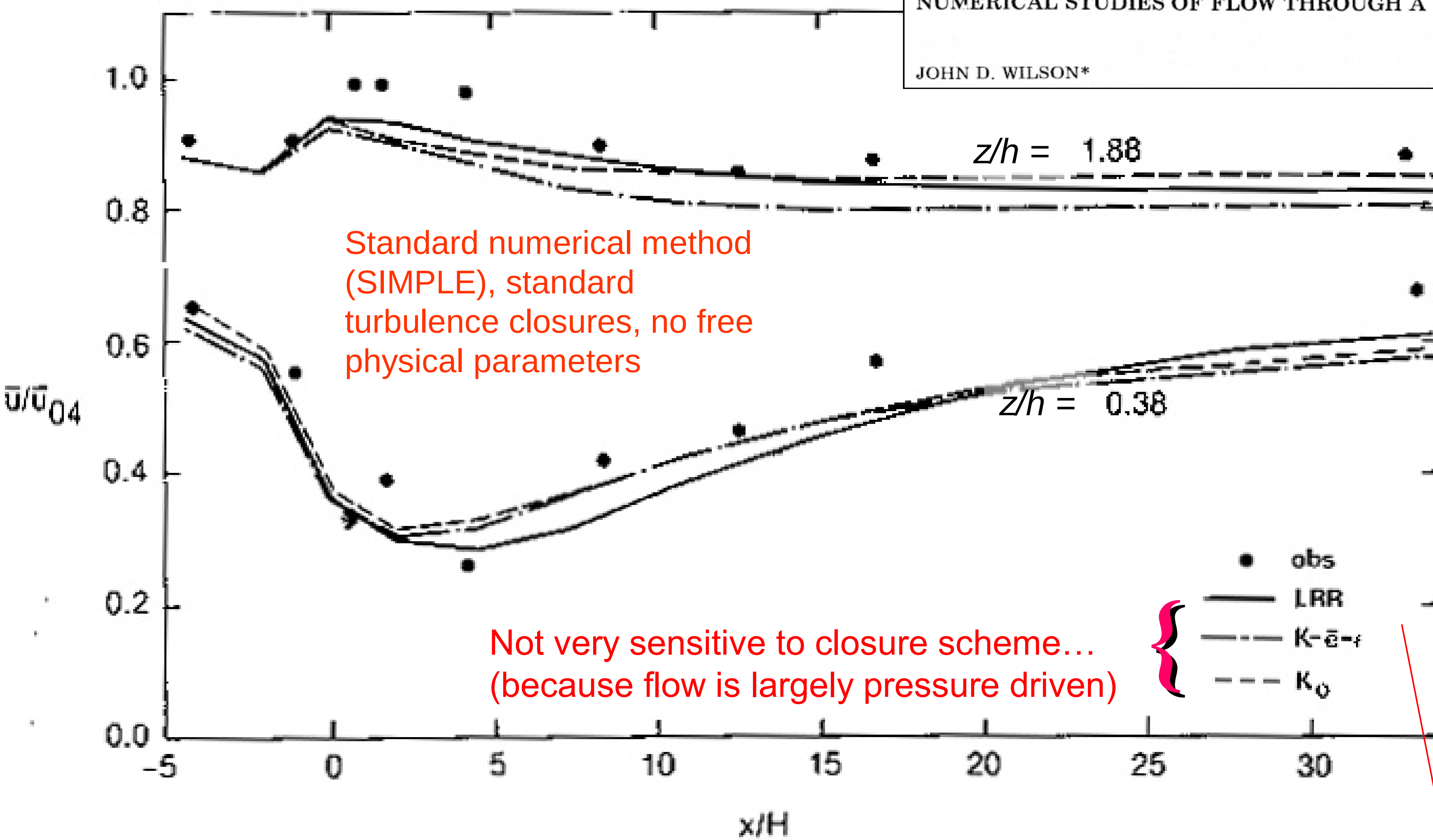
Kaiser’s solution necessarily places minimum velocity at the barrier (source of momentum deficit) – unrealistic. Contrast with later analytic solutions that retain grad P. The dashed line – no recovery – neglects $\partial\overline{u'w'}/\partial z$

Numerical solution – various closures

Journal of Wind Engineering and Industrial Aerodynamics, 21 (1985) 119—154
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

NUMERICAL STUDIES OF FLOW THROUGH A WINDBREAK

JOHN D. WILSON*



Bradley-Mulhearn (1983, J. Wind Eng. Indust. Aerodyn., Vol. 15, 145 -156)

$$k_r = 2, \quad h/z_0 = 600, \quad |L| = \infty$$

$$(h = 1.2 \text{ m}, \quad z_0 = 0.002 \text{ m})$$

Closures :

(1) $K_0 = k_v u_{*0} z$,

(2) $k - \epsilon$

(3) LRR second order closure

Numerical solution of mtm eqns

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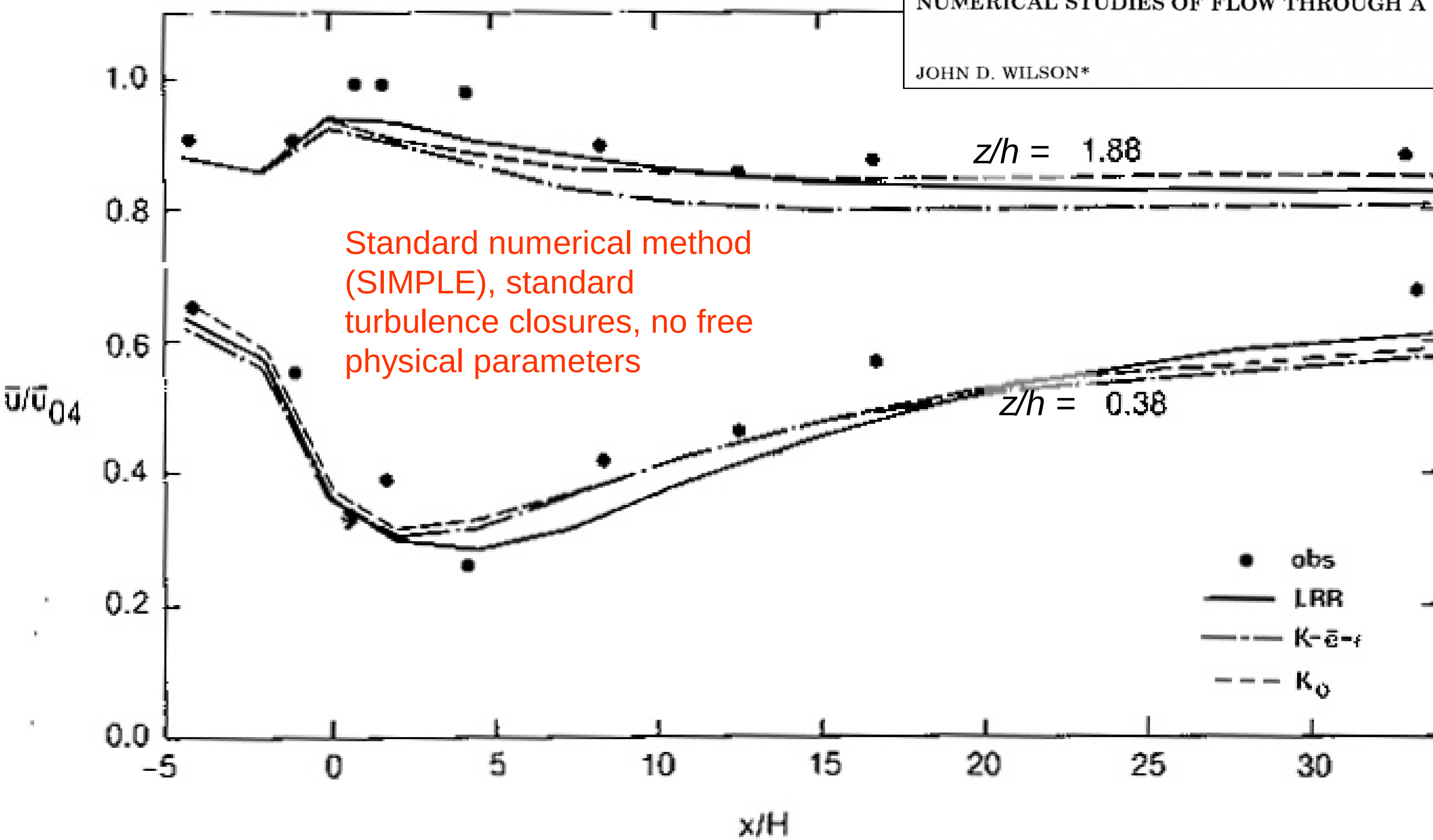
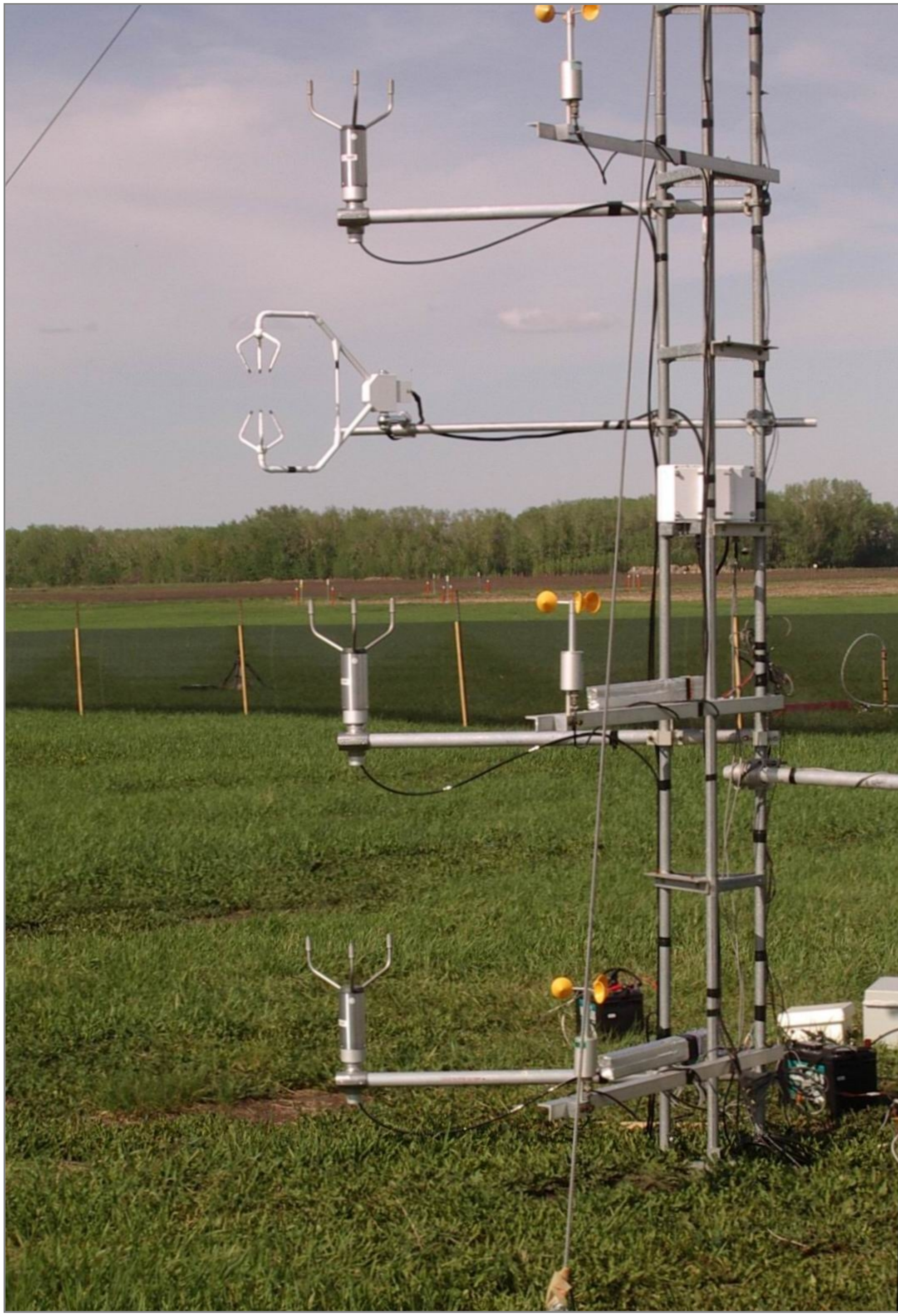


Minimum mean wind speed occurs at about *5H* downwind of the barrier, and the fractional reduction in wind speed at that point is:

$$\frac{\Delta \bar{u}}{\bar{u}_0} \approx \frac{k_r}{\left(1+2\,k_r\right)^{0.8}}$$

Windbreak experiment at Ellerslie



11 cup anemometers
8 two-D sonic anemometers
2 three-D sonic anem/thermometers (16 Hz)
wind vane
2 thermocouple Δ*T*s

34 wind signals, 4 *T* signals, 3 dataloggers

Mean speed… effect of stratification (L) in perpendicular flow

1392 JOURNAL OF APPLIED METEOROLOGY VOLUME 43

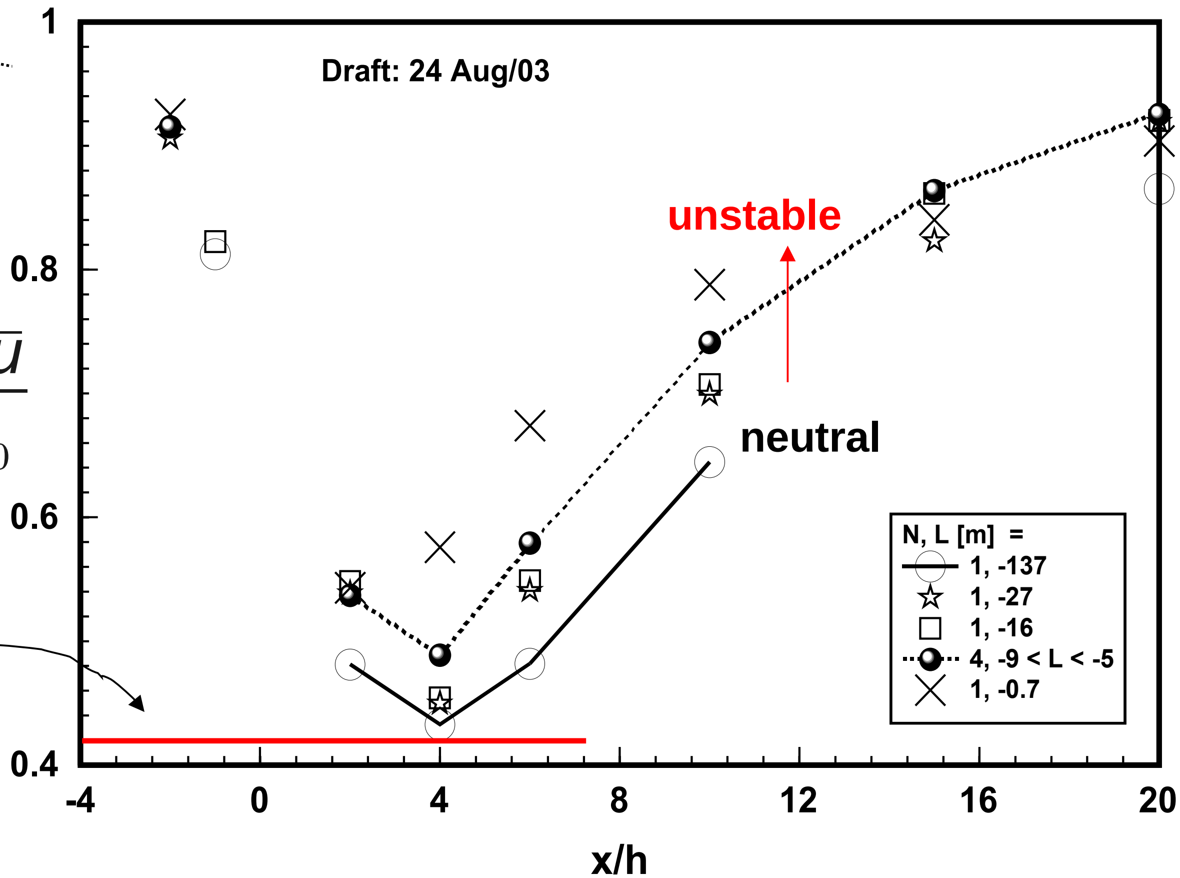
Oblique, Stratified Winds about a Shelter Fence. Part II: Comparison of Measurements with Numerical Models

JOHN D. WILSON

- neutral, L < - 50 m
- mod. instability, -50 < L < -20 m
- extrm. instability, -5 < L < 0 m

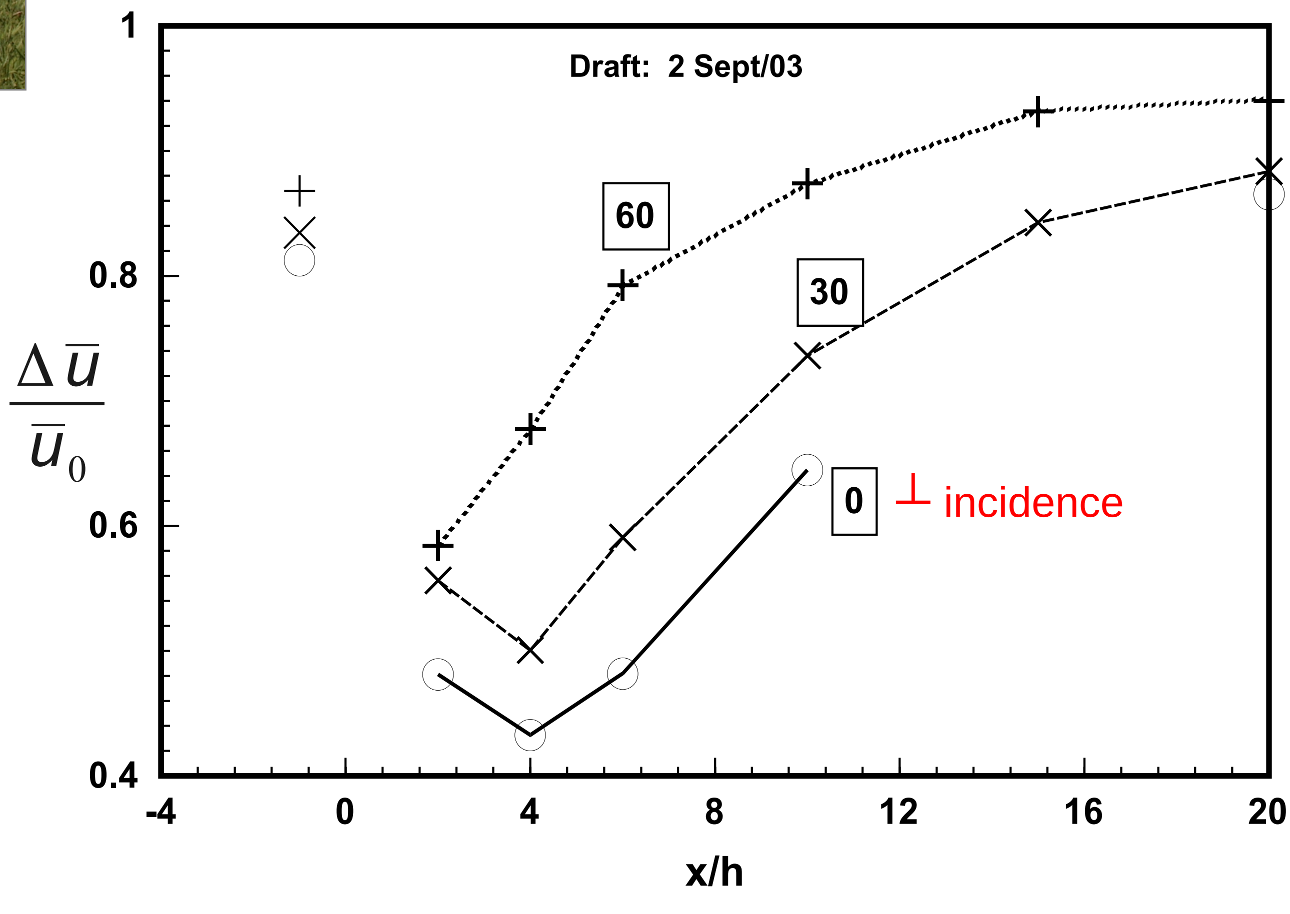
"relative windspeed"

$$\frac{\Delta \overline{u}}{\overline{u}_0}$$



$$\frac{\Delta \overline{u}}{\overline{u}_0} = \frac{k_r}{\left(1+2\,k_r\right)^{0.8}}$$

Mean speed… effect of obliquity in neutrally-stratified winds

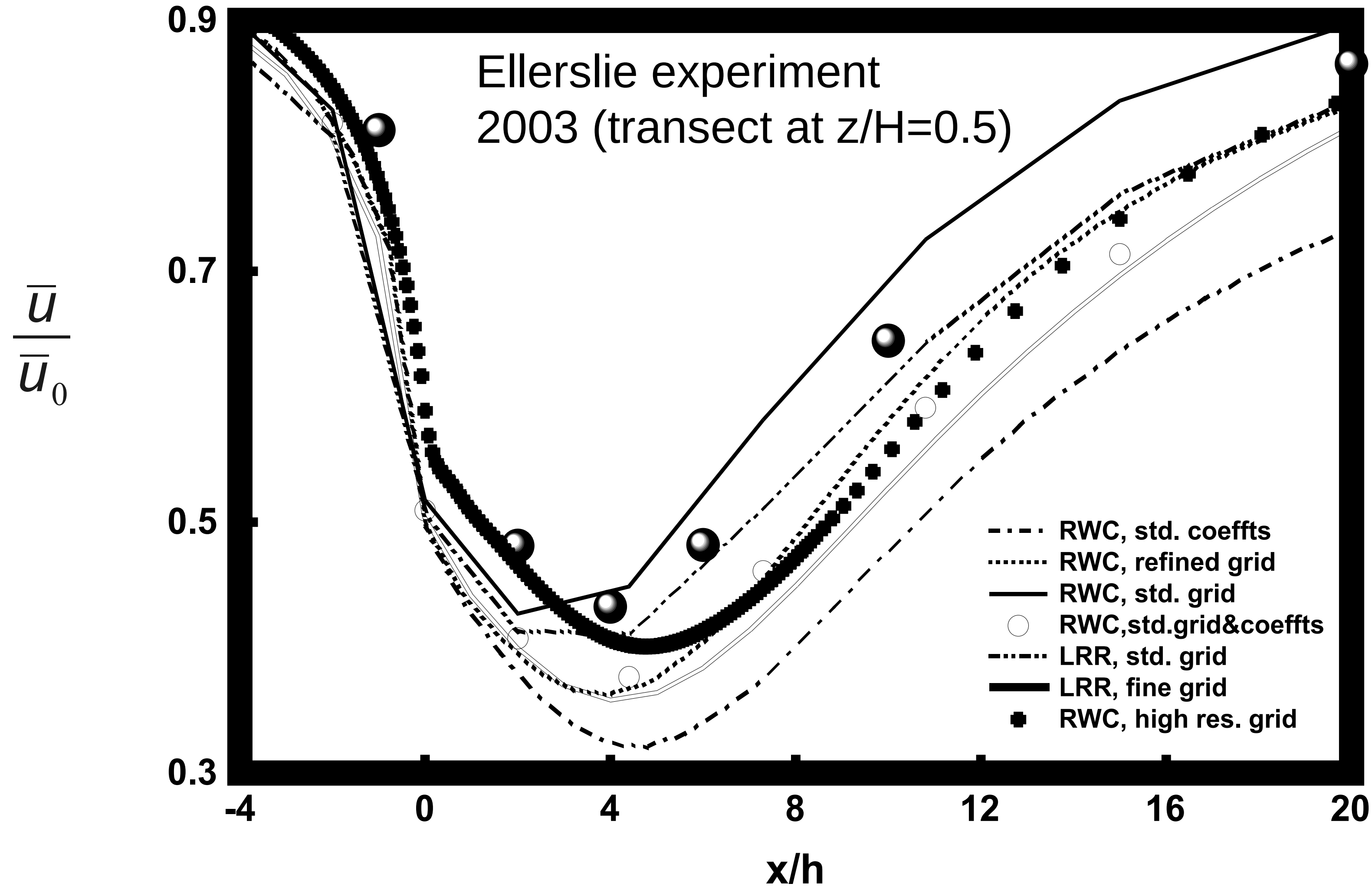


Computed vs. observed transect - neutral, perpendicular flow...

Domain covers: $-20 \le x/h \le 120$, $z/h \le 50$

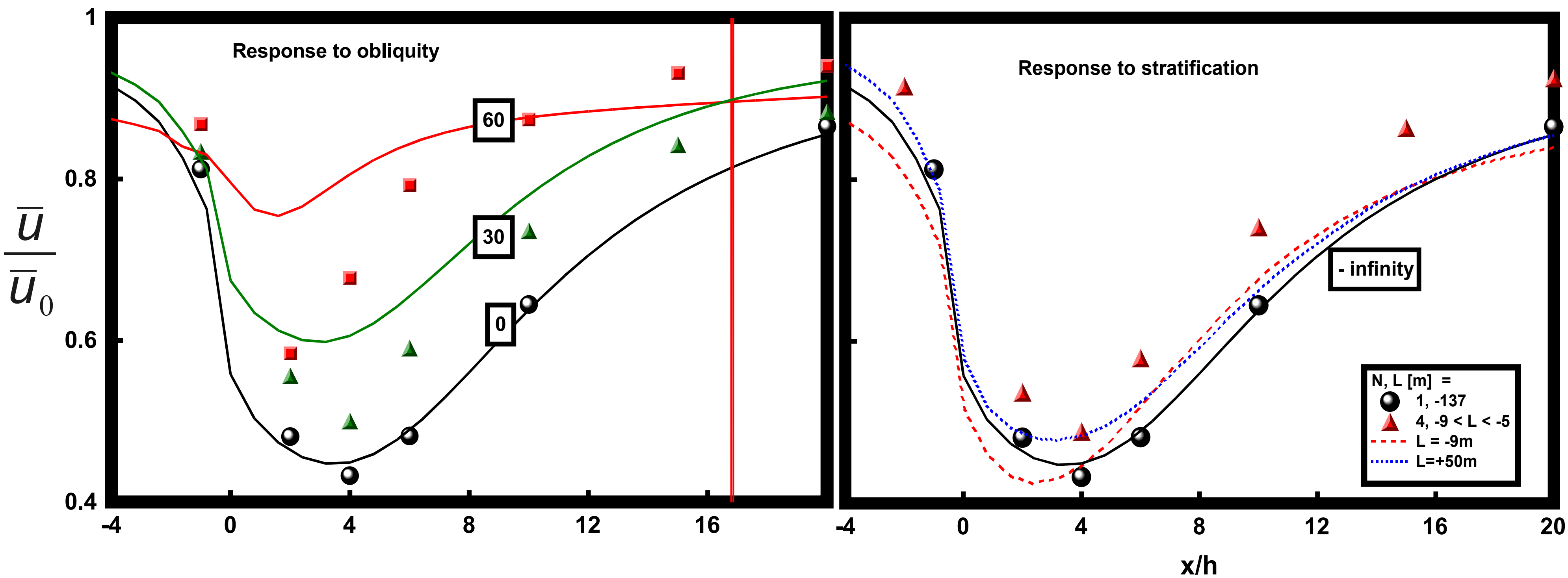
Resolution: . $\Delta x/h \le 2$, $\Delta z/h \le 0.25$

Closure: Launder-Reece-Rodi <u>or</u> Rao-Wyngaard-Coté



Computed vs. observed transects - responses to influence of obliquity and stratification...

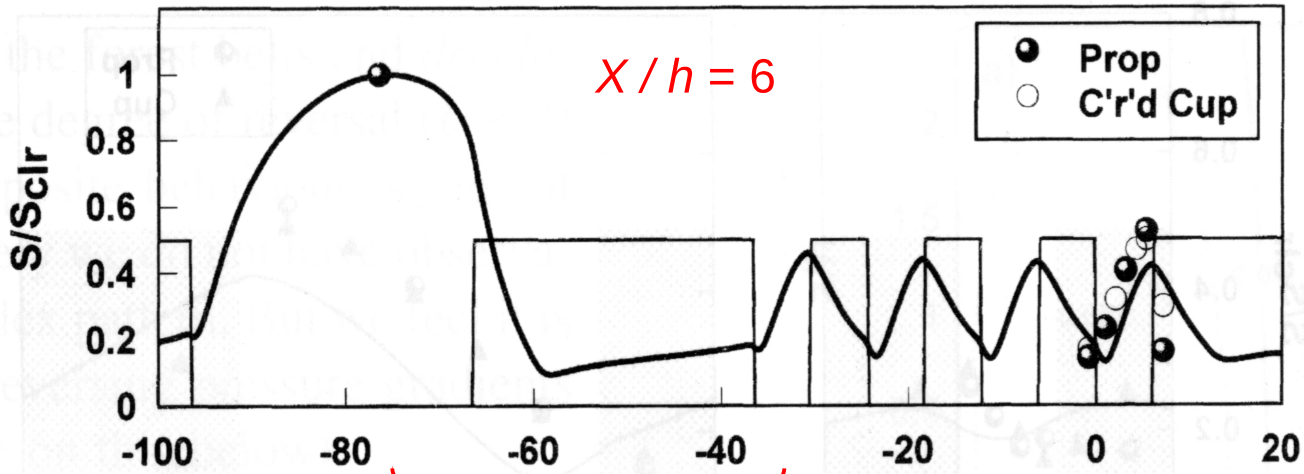
Rao-Wyngaard-Coté closure on a refined grid, with $k_r = 1.8$ tuned away from experimental value (2.4) so that model's "potential shelter" curve (black) matches observation...



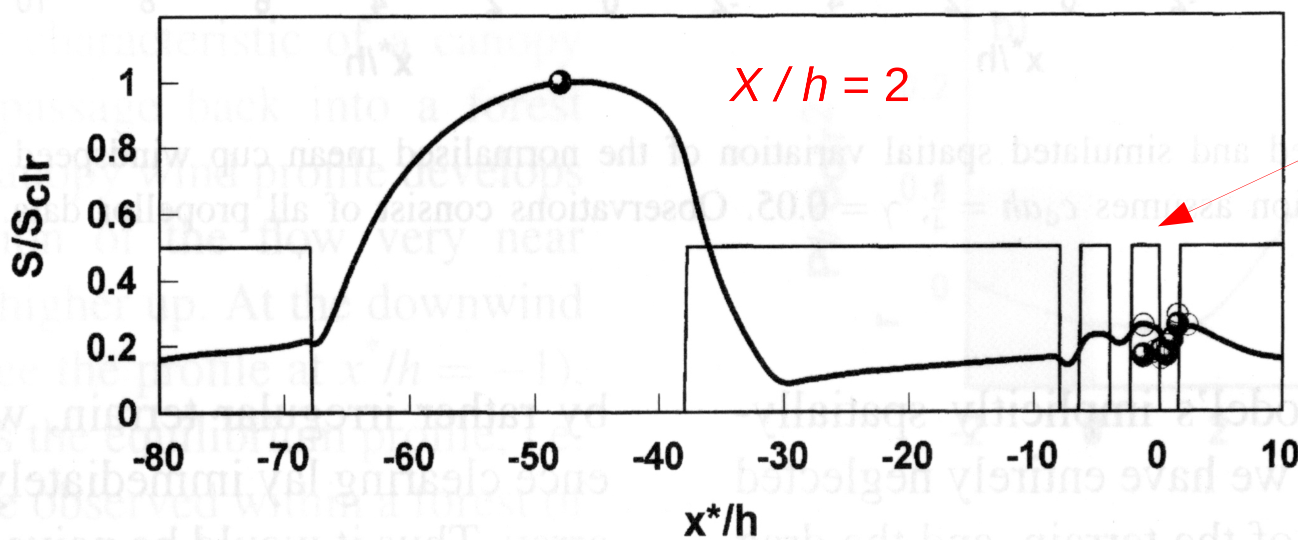
Measured and modelled mean winds S/S_{clr} in forest cutblocks (width X)

Simpler closure $K = \lambda(x, z)\sqrt{k(x, z)}$ with prescribed λ and one free parameter ($c_d\, a\, h$)

Reference speed S_{clr} is in a far-off (5 km distant) large clearing



In real world, separated by 5 km of irregular terrain



Manning, Alberta

Measured and modelled TKE in forest cutblocks