Meteorology of the plant canopy layer

From perspective of NWP/GCM, wish minimum level of detail that gives adeqiuate model of surface radiative, energy and water balances. Assume horiz. homogeneity.

Wind above canopy might be formulated as

$$\bar{u}(z) = \frac{u_*}{k_v} \ln \frac{z-d}{z_0}$$

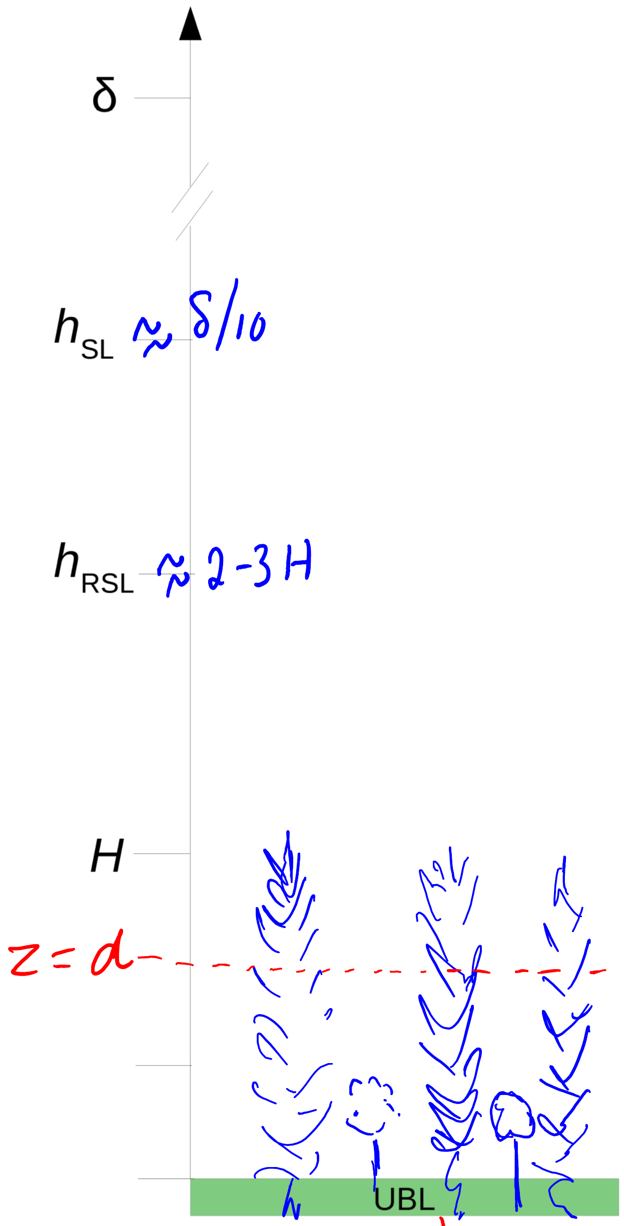
If interested (eg.) in crop spraying, one will be interested in $\bar{u}(z)$, $\sigma_w(z)$, $\tau(z)$, $\underbrace{\overline{T}(z), \bar{q}(z)}_{\text{e.g. leaf drying in rel}^n \text{ to fungus}}$

How to describe canopy?

H, LAI

$$LAI = \int_0^{\infty \text{ or } H} a(z)\, dz$$

a = leaf area denity $m^2\, m^{-3}$



for some purposes whole ASL might be unresolved

displacement height $\approx 2/3\, H$

} shrub layer

One treats the Unresolved Basal Layer superficially

Qualitative aspects of canopy flow (from observations)

① Very high turbulence intensity

$\sigma_u / \bar{u}$ ($\bar{u}$ mean horiz speed)

∴ need omnidirectional anemometers

② Turbulence is strongly non-Gaussian

③ Transport dominated by sweeps and ejections

⑥ Mean fluxes may run counter to mean gradients.

④ Intermittency

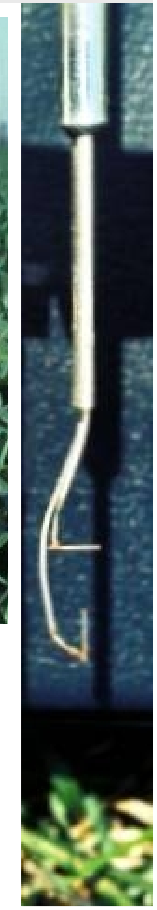
⑤ Turb. transport terms important in the turbulence budget eqns, e.g.

$$\frac{\partial \overline{w'^2}}{\partial t} + \bar{u} \cancel{\frac{\partial \overline{w'^2}}{\partial x}} + \ldots = 2 \frac{g}{\theta_0} \overline{w'\theta'} + \text{Redistr.} + \text{Dissip}^n - \frac{\partial \overline{w'^3}}{\partial z}$$

0 by hh

④ Very strong mean wind shear near $Z = H$

⑤ Rapid absorption of mtm flux $\overline{u'w'}$ by upper canopy



STATISTICS OF ATMOSPHERIC TURBULENCE WITHIN AND ABOVE A CORN CANOPY

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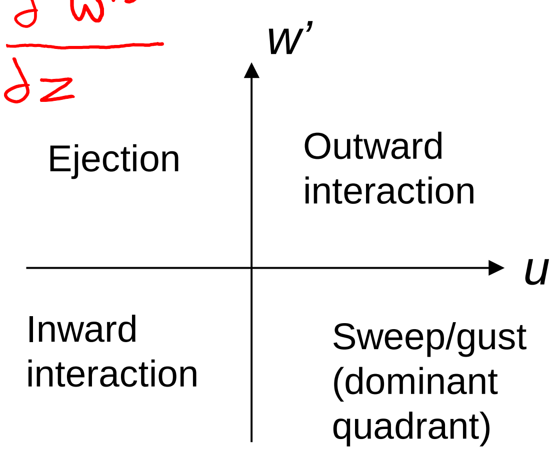
Boundary-Layer Meteorology **24** (1982) 495–519.



Momentum budget & the exponential wind profile

$$\cancel{\frac{\partial \bar u}{\partial t}} + \bar u \cancel{\frac{\partial \bar u}{\partial x}} + \cancel{\bar w} \frac{\partial \bar u}{\partial z} = 0 = \cancel{f\bar v} \; \frac{-1}{\rho}\cancel{\frac{\partial \bar p}{\partial x}} - \frac{\partial \overline{u'w'}}{\partial z} - \cancel{\frac{\partial \overline{u'^2}}{\partial x}} - S_u$$

stat. hh hh hh

ignore $f\bar v$

these three dominate above the RSL

parameterize viscous friction and form drag on leaves, which are controlled by details of the flow we shan't resolve

$$S_u = C_d\, a\, \bar u\, |\bar u|$$

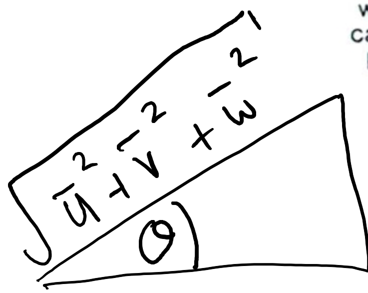
Mean drag force has magnitude

$$|\vec F| = \rho\, a\, C_d \left(\bar u^2 + \bar v^2 + \bar w^2\right)$$

$$\frac{N}{m^3} = \frac{kg}{m^3}\;\frac{m^2}{m^3}\qquad m^2\, s^{-2}$$

$$\frac{kg\; m\; s^{-2}}{m^3} = kg\; m^{4-6}\; s^{-2}$$

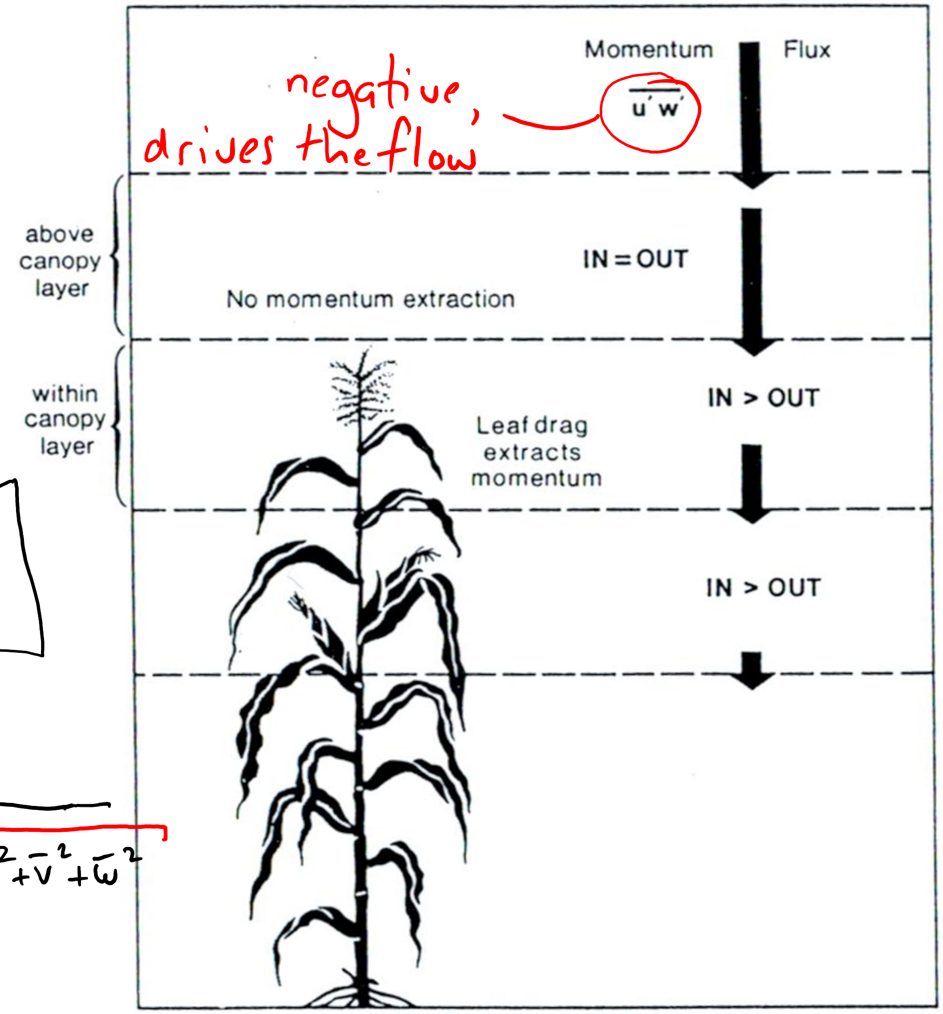
$$kg\; m^{-2}\; s^{-2}$$



$$\cos\theta = \frac{\bar u}{\sqrt{\bar u^2 + \bar v^2 + \bar w^2}}$$

$$|F_x| = |\vec F| \cos\theta$$

$$= \rho\, a\, C_d\, \bar u \sqrt{} \simeq \rho\, C_d\, a\, \bar u\, |\bar u|$$



Derivation of a canopy wind profile

$$0 = -\frac{\partial \overline{u'w'}}{\partial z} - C_d a \bar{u}^2 \quad \text{and write} \quad \overline{u'w'} = -K \frac{\partial \bar{u}}{\partial z}$$

Prandtl approach: $K = \ell^2 \frac{\partial \bar{u}}{\partial z}$

Prove this works for the ideal neutral ASL (in which $\bar{u} = \frac{u_*}{k_v} \ln \frac{z}{z_0}$ and $\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{k_v z}$)

Proof: by def^n $\overline{u'w'} = -K \frac{\partial \bar{u}}{\partial z}$

But $\overline{u'w'} = -u_*^2$ and $\partial \bar{u}/\partial z = u_*/k_v z$

$\therefore \quad -u_*^2 = -K \, u_*/k_v z$

$\therefore \quad K = k_v u_* z = (k_v z)^2 \frac{u_*}{k_v z} \equiv (k_v z)^2 \frac{\partial \bar{u}}{\partial z}$, $\ell = k_v z$

Apply this to canopy (approach pioneered by Inoue and Uchijima)

$\ell = \text{const.} = \alpha H$ and take $C_d a = \text{const}$

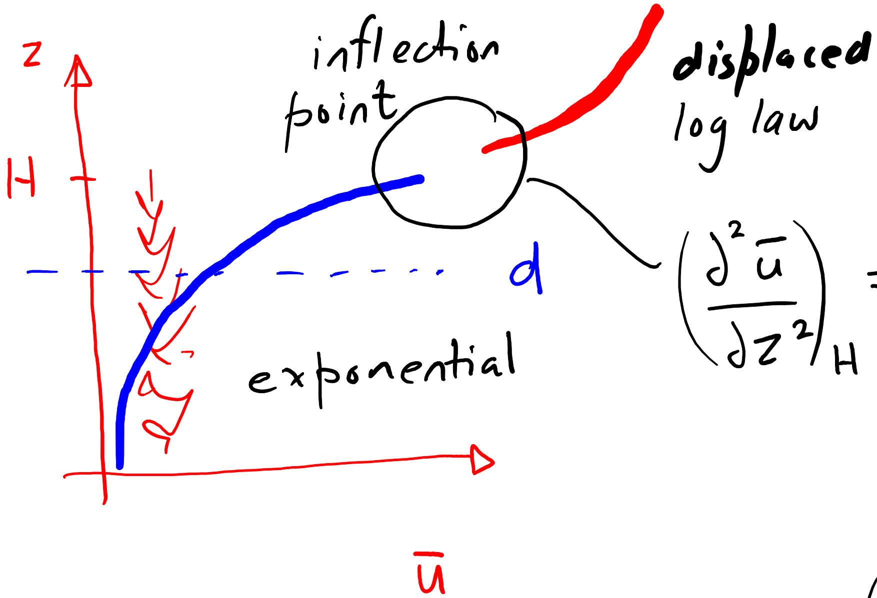
$$\therefore \frac{\partial}{\partial z}\Big[\underbrace{\ell^2 \frac{\partial \bar{u}}{\partial z}}_{K} \frac{\partial \bar{u}}{\partial z}\Big] = C_d a \bar{u}^2$$

Assume $\bar{u} = c_1 e^{mz}$ and substitute $\longrightarrow$ $\bar{u}(z) = \bar{u}_H \, e^{\beta(z/H - 1)}$

where extinction coefft.

$$\beta^3 = \frac{C_d a H^3}{2\ell^2}$$

Works quite well, treat β as empirical



$$\left(\frac{\partial^2 \bar{u}}{\partial z^2}\right)_H = 0$$ causing generation of large eddies

How to get the drag coeff't? (We can measure $a(z)$ directly)

$$0 = -\frac{d\overline{u'w'}}{dz} - C_d a \bar{u}^2$$

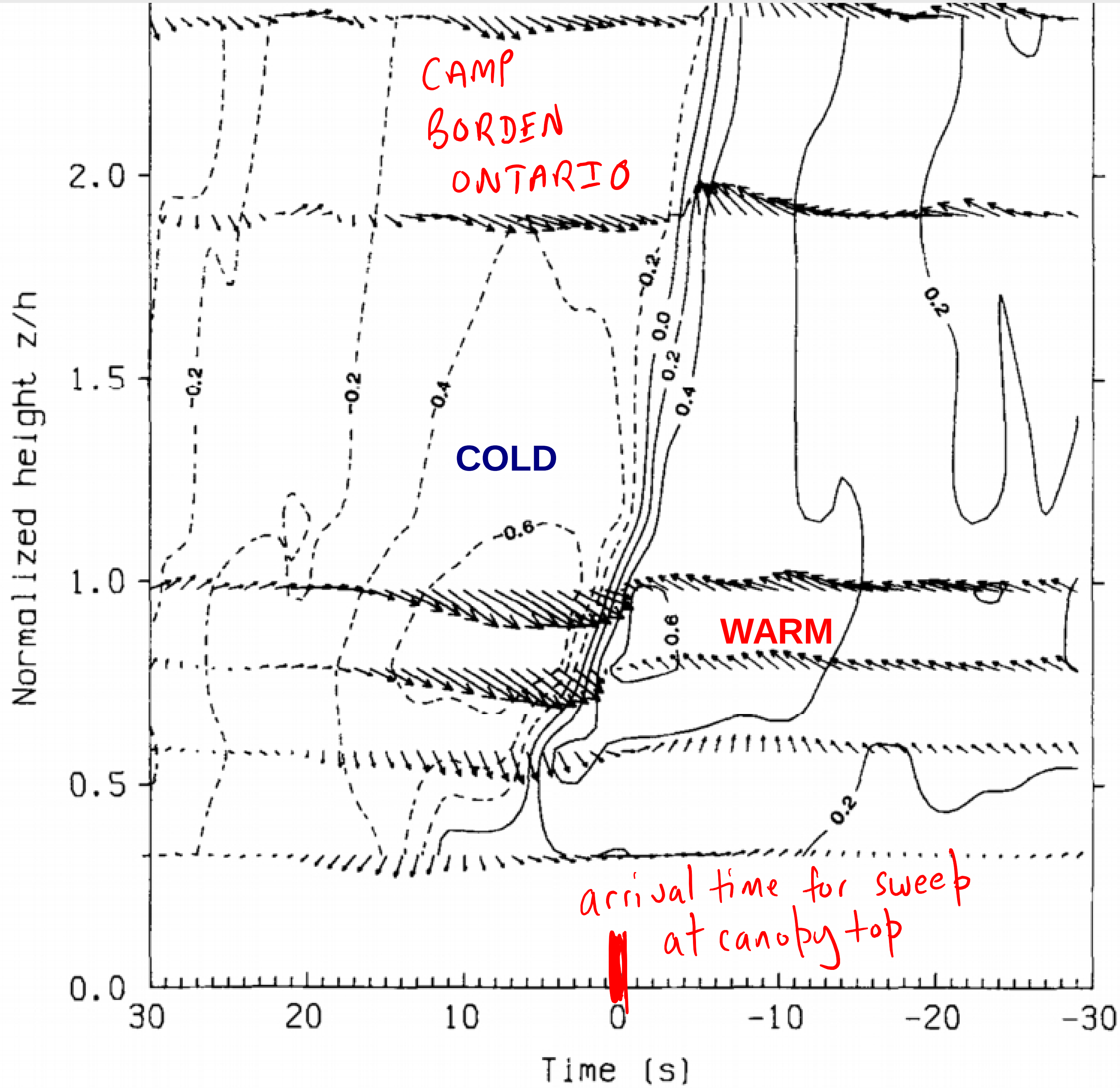
$$-\int_0^H \frac{d\overline{u'w'}}{dz}\,dz - \overline{C_d a}\int_0^H \bar{u}^2\,dz = 0 = \underbrace{-\overline{u'w'}(H)}_{u_{*H}^2} + \underbrace{\overline{u'w'}(0)}_{\text{negligible for dense canopy}} - \overline{C_d a}\int_0^H \bar{u}^2 dz$$

$$\overline{C_d a} = u_{*H}^2 \Big/ \int_0^H \bar{u}^2\,dz$$

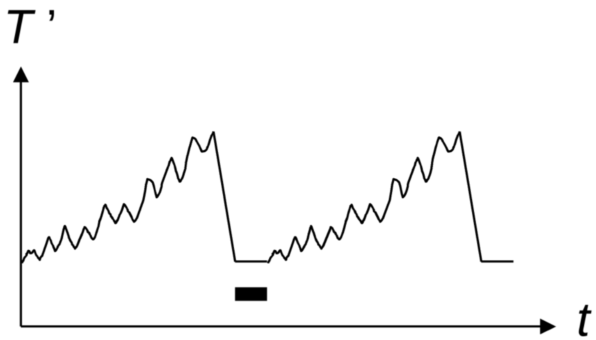
Occurrence of micro-fronts separating ejections and gusts

A composite of many events, from Gao et al. (1989, Boundary-Layer Meteorol.)

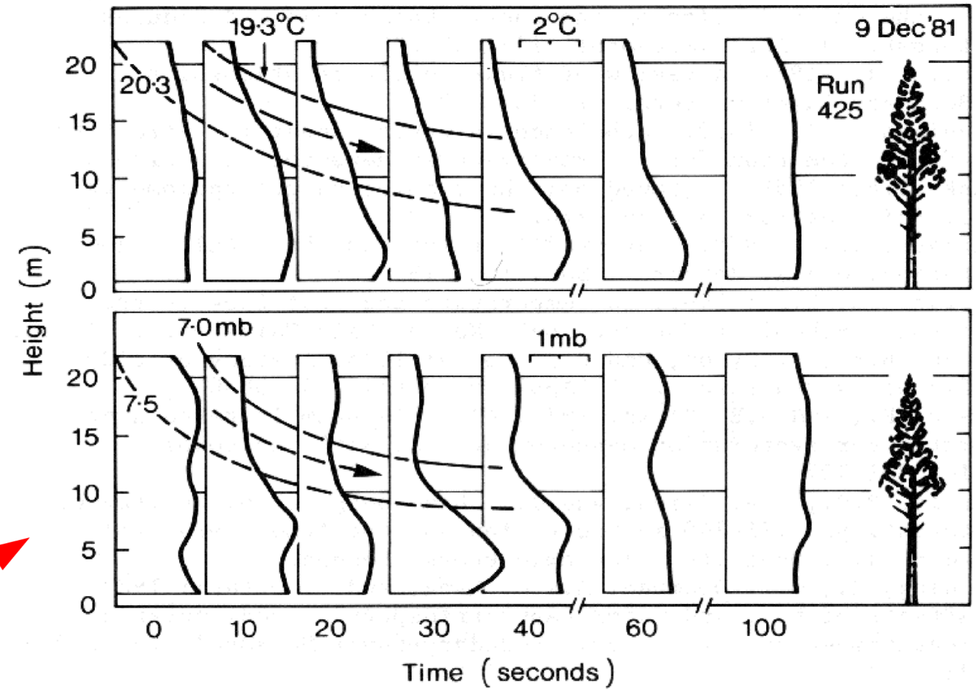
The "clean sweep" model of canopy layer/ABL interaction exploits this viewpoint.



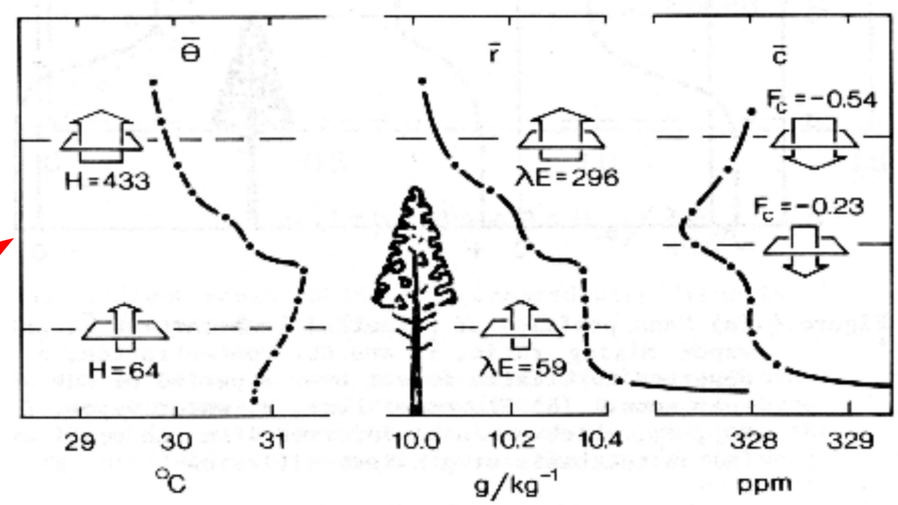
Intermittency; flushing of the canopy; occurrence of counter-gradient transport



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



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)



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 description using Generalized Langevin model correctly handles the problem

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.

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