Essential concepts in atmospheric structure, stability & turbulence statistics

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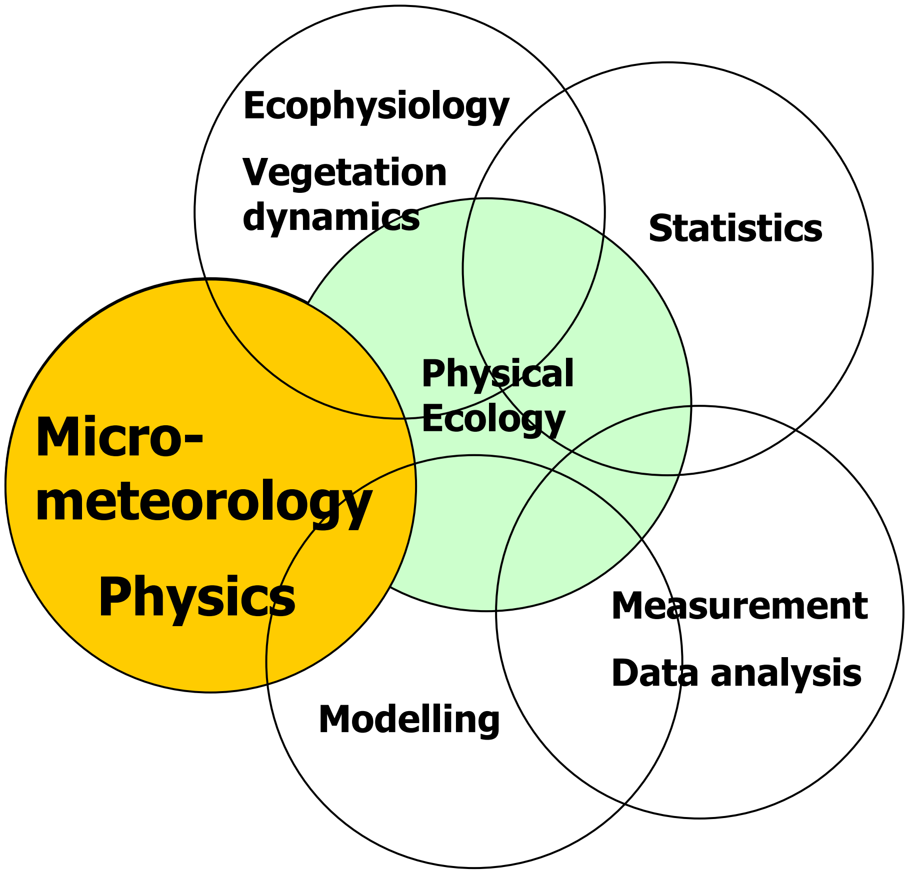
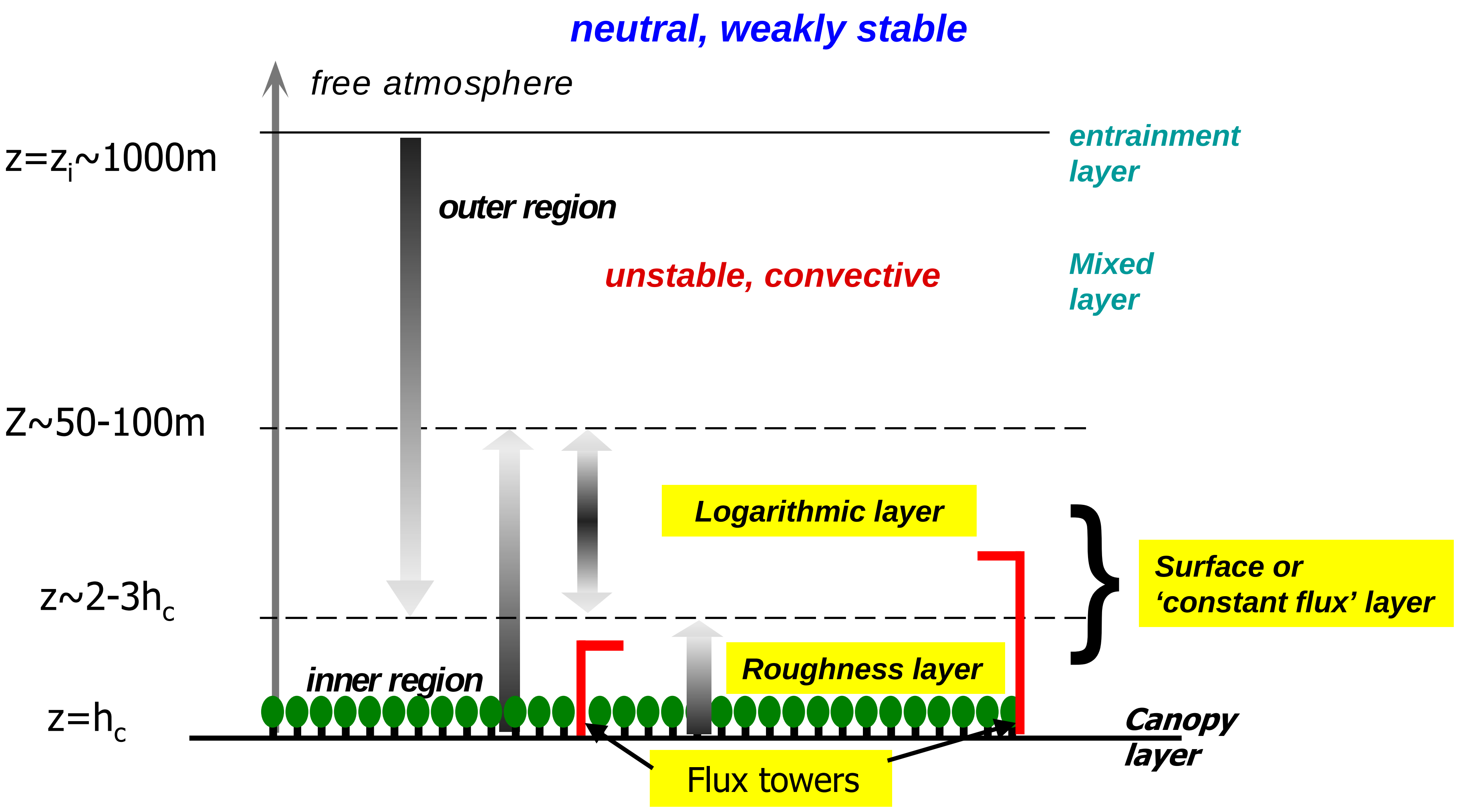
Motivation



- At flux towers, we use measurements of the turbulent wind and concentration fields to infer surface exchange.
- A basic understanding of boundary layer structure is essential to understand and interpret the measurements.
- In this lecture we cover:
  - Basic states of the atmospheric boundary layer
  - Basis of eddy-covariance method for flux measurements
  - Atmospheric stability in the surface layer
  - Some essential turbulence statistics

Sublayers in the Atmospheric Boundary Layer (ABL)

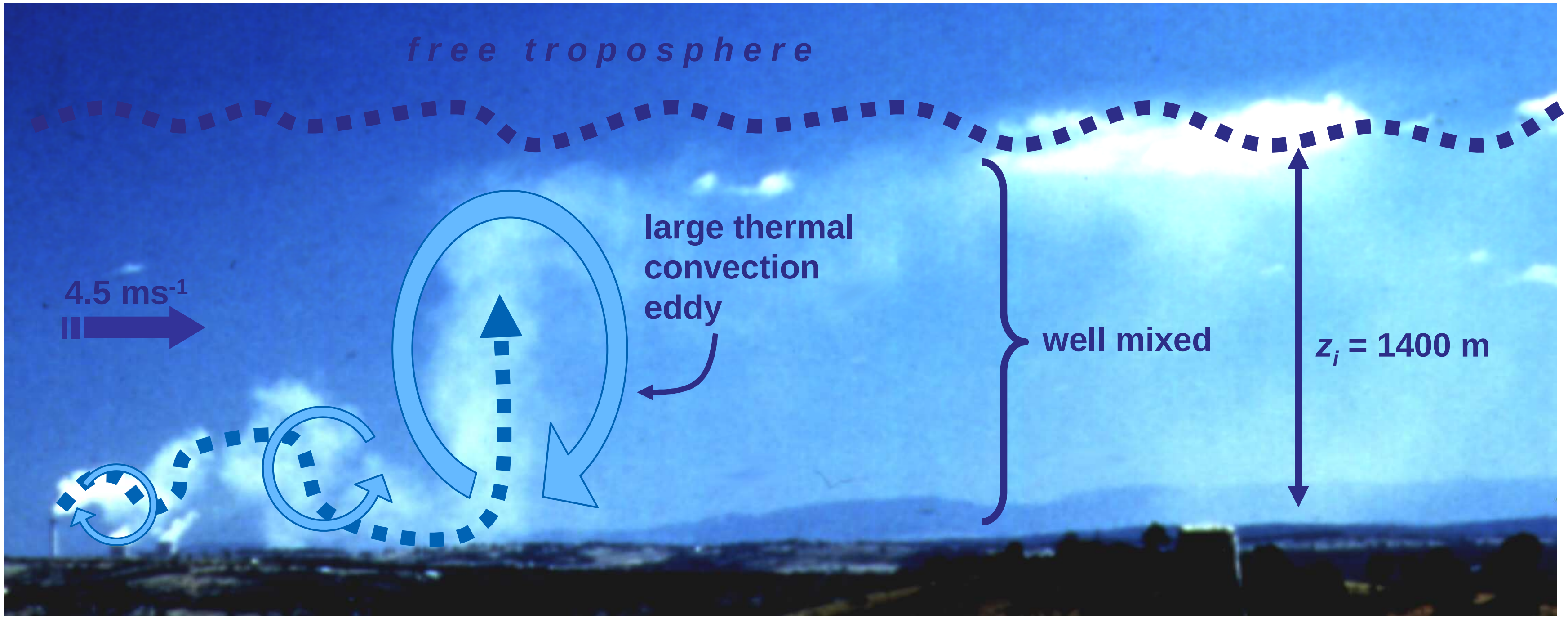


Courtesy Prof HP Schmid
Indiana University

Daytime Convective Boundary Layer (CBL)

Courtesy Prof HP Schmid
Indiana University

- Looping plume, in the presence of large convective thermal eddies
- Lifting limited by capping inversion; free troposphere above
- Well mixed conditions downwind, in mixed layer of ~1400 m depth



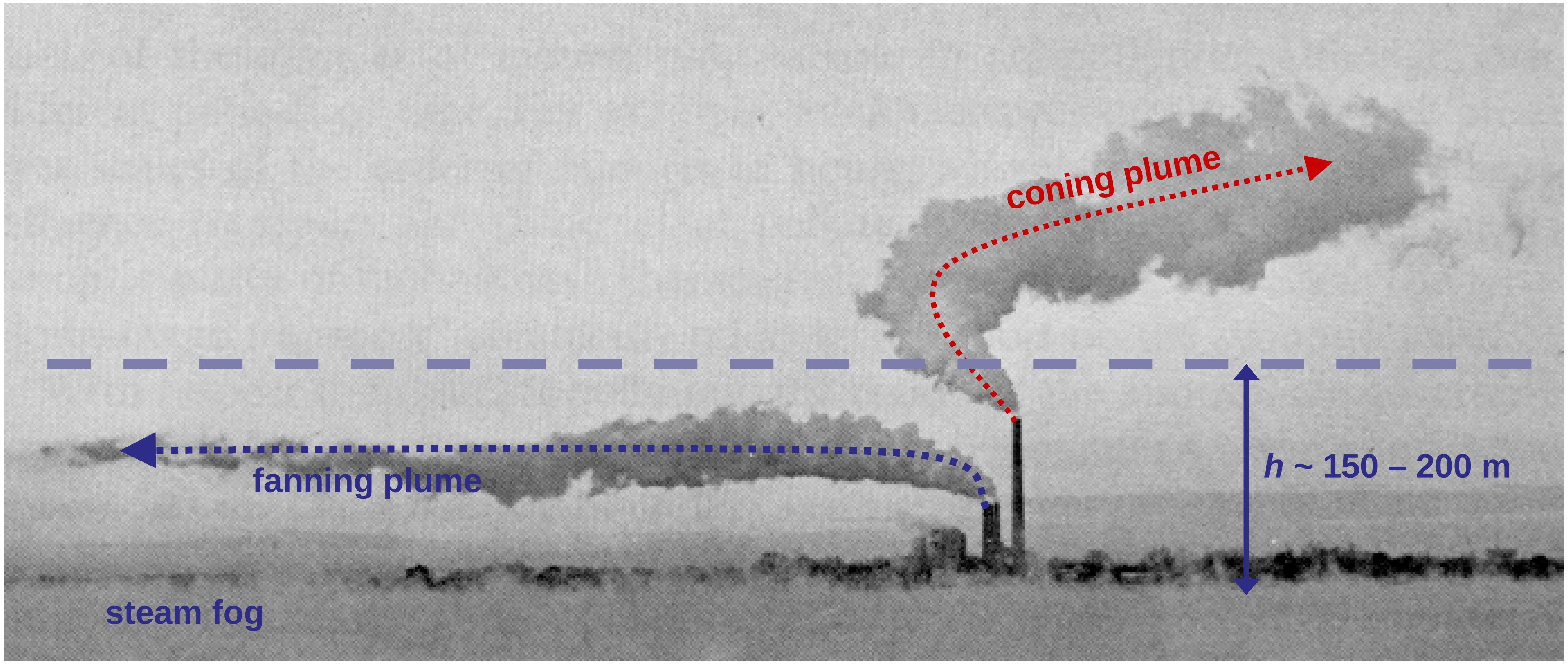
Tarong, Queensland (AUS), stack height: 210 m, z_i = 1400 m, w* = 2.5 ms^{-1}. Photo: Geoff Lane, CSIRO (AUS)

Nocturnal Boundary Layer (NBL)

Nighttime Stable Boundary Layer

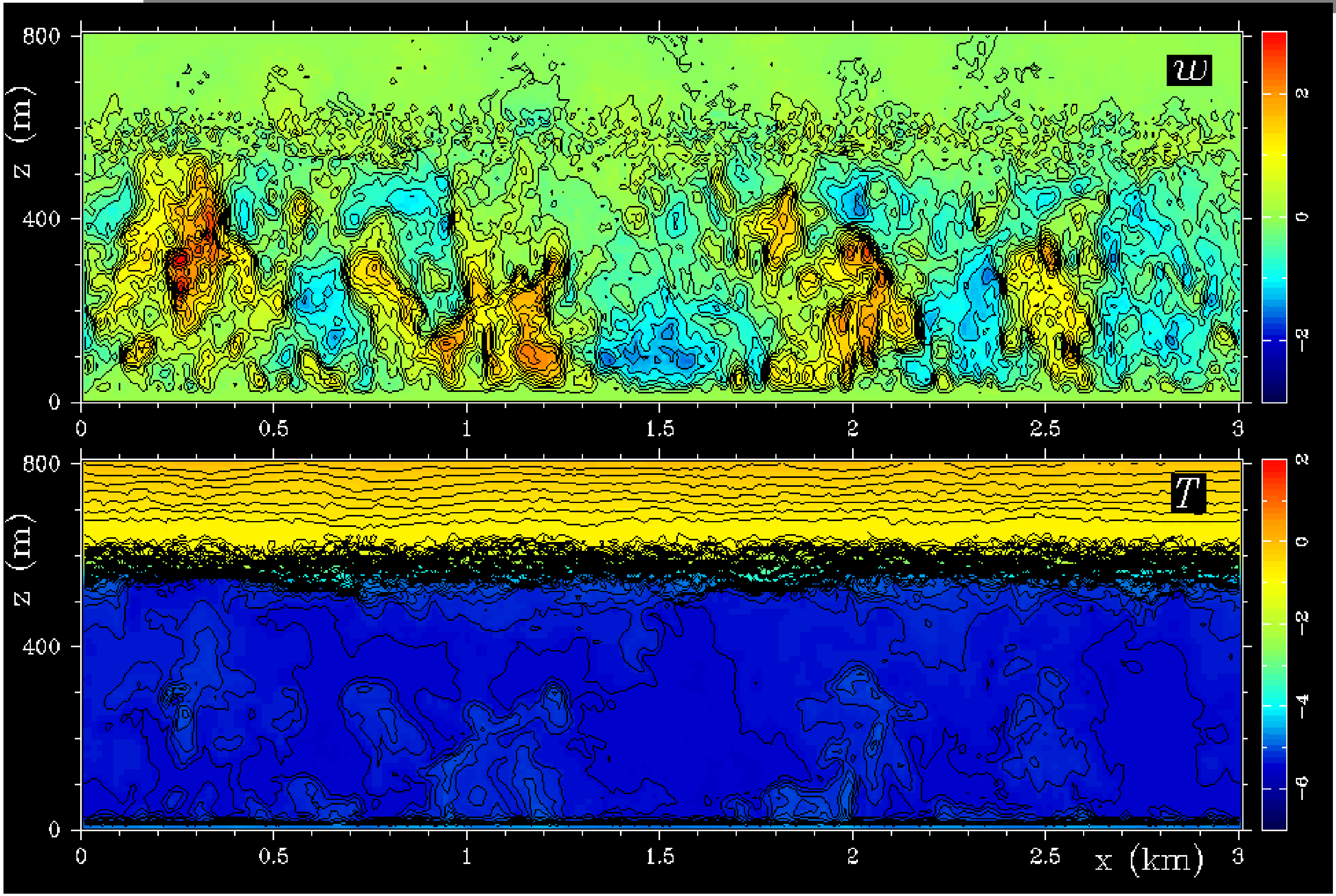
Courtesy Prof HP Schmid
Indiana University

- Early morning, steam fog indicates surface inversion
- "fanning" plume from 75 m stack indicates strong stability, flow from right
- "coning" plume from 150 m stack indicates neutral stability, flow from left
- In between, strong wind direction shear, $h \approx 150$ - 200 m



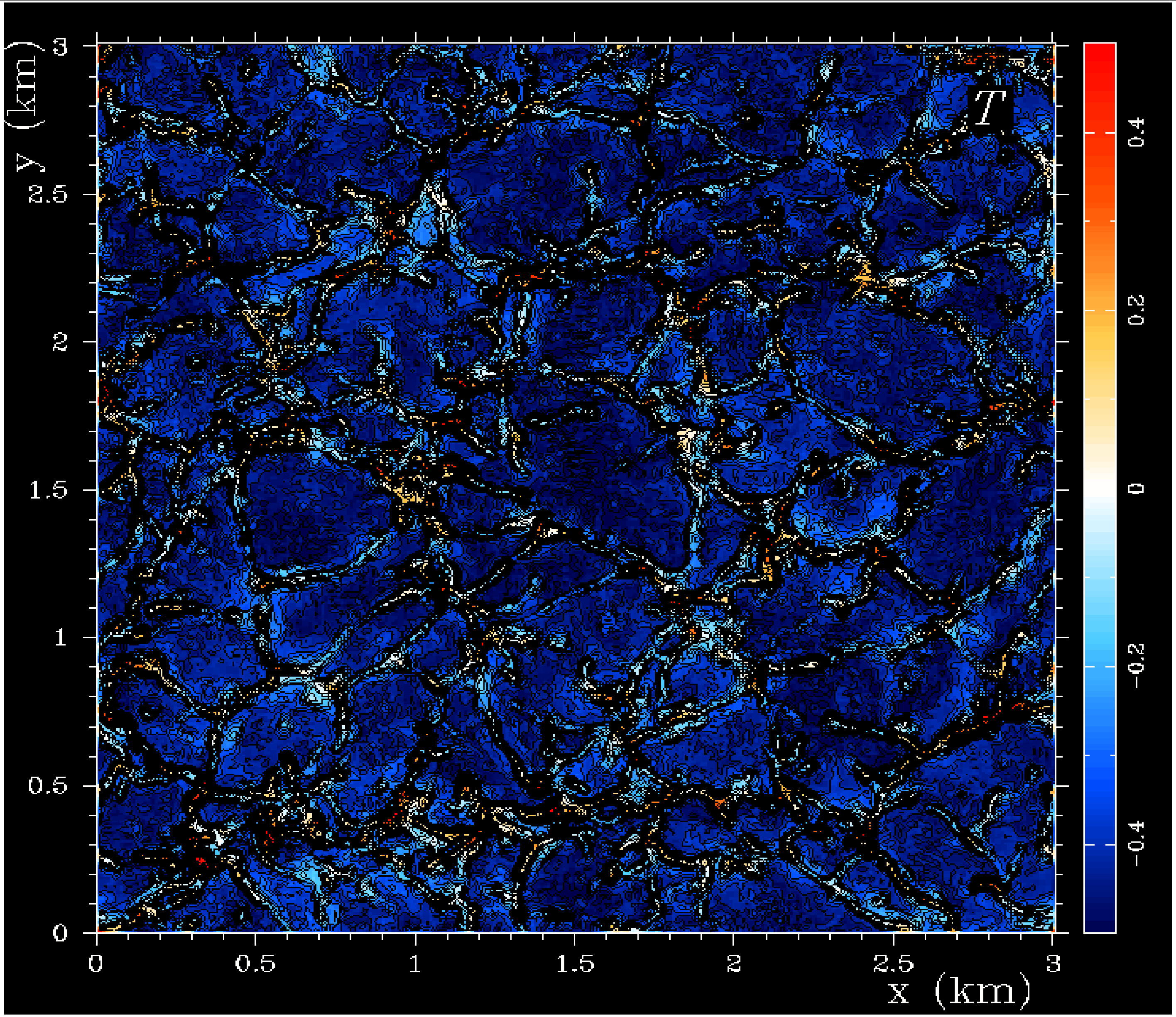
Salem (Mass.) on a very cold February morning. Photo: Ralph Turcotte, *Beverly Times*

Atmospheric turbulence has structure at multiple spatial scales



Tsutomu WATANABE

Atmospheric turbulence has structure at multiple scales



Tsutomu WATANABE

Mechanisms of turbulence generation

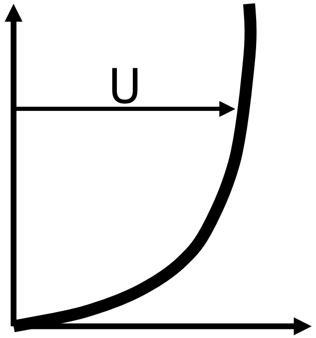
- Mechanical mixing
  - as the air flows over a rough surface due to dynamic instability of the large wind shear that develops in the lowest layer

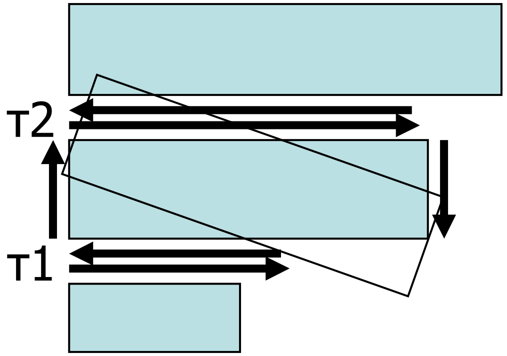
- Buoyant or convective mixing
  - Air flow over a warmer underlying surface - unstable
  - Air flow over colder surface - stable

- Water vapour is lighter than dry air
  - surface evaporation also contributes to buoyancy of the air.

Mechanisms of turbulence generation

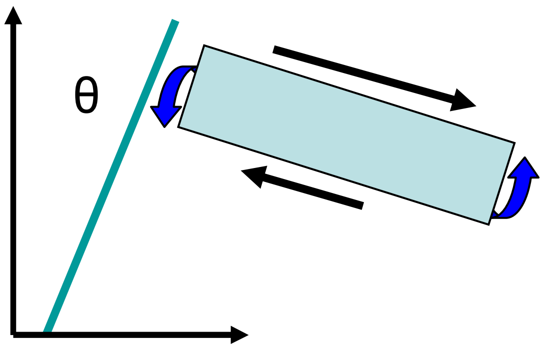
Mechanical production



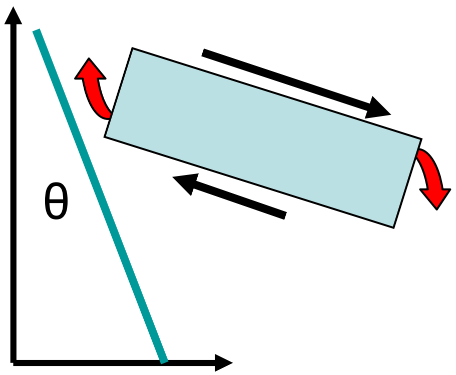


Buoyant production/destruction

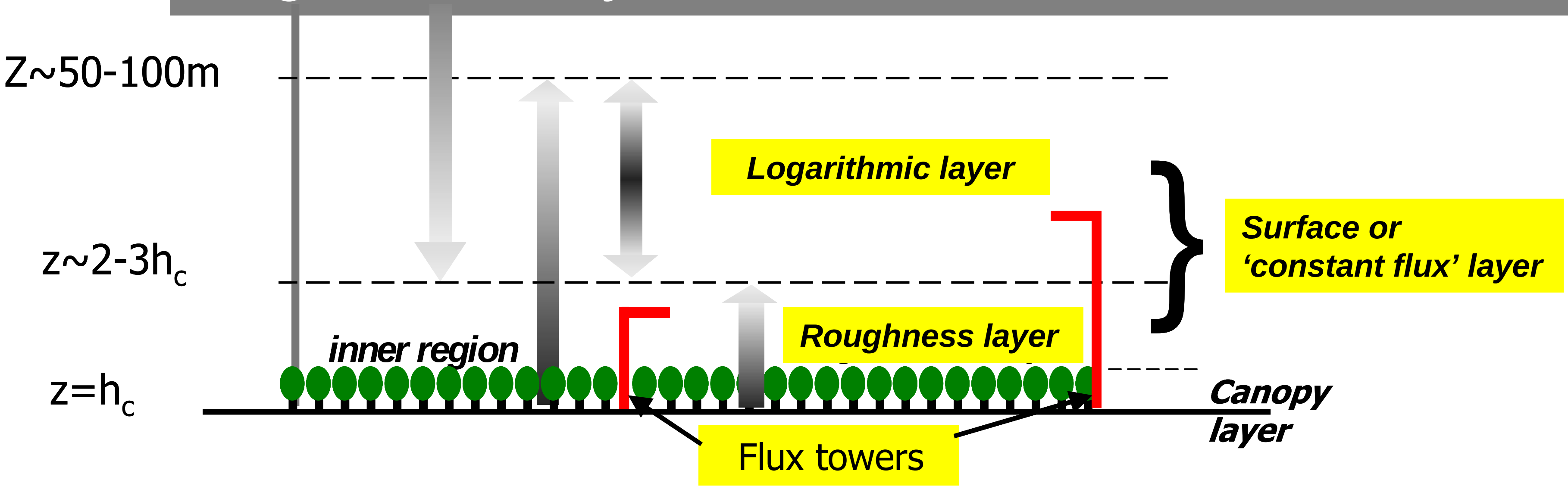
Stable: buoyancy ***suppresses*** mechanical production



Unstable: buoyancy ***augments*** mechanical production



Logarithmic layer



Lowest ~ 10% of ABL

Constant fluxes

Strong gradients in:

- wind speed, temperature, other scalars

Controlling length scale

- distance to the surface, *z* (or *z* - *d*)

Controlling velocity scale

- Friction velocity, *u**

The neutral logarithmic velocity profile

Gradient

$$\frac{dU}{dz} = \frac{u_*}{\kappa z}$$

Friction velocity (constant)

$$u_*^2 = -\overline{u'w'}$$

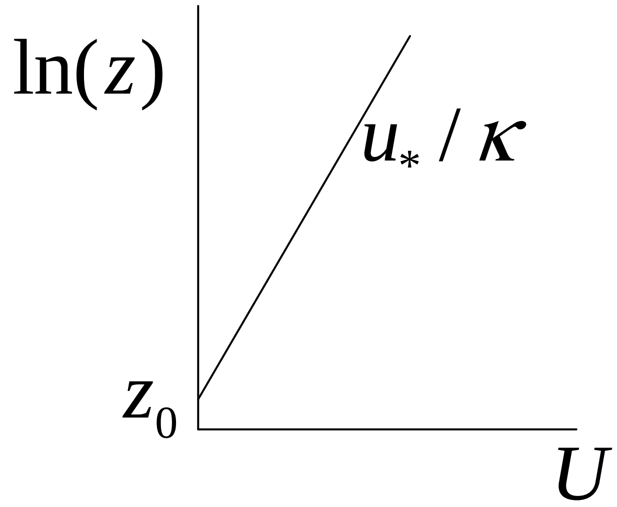
Eddy flux – see later

Integrate from z_0 to z, $U = 0$ at z_0

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

Von Karman constant = 0.4

Roughness length

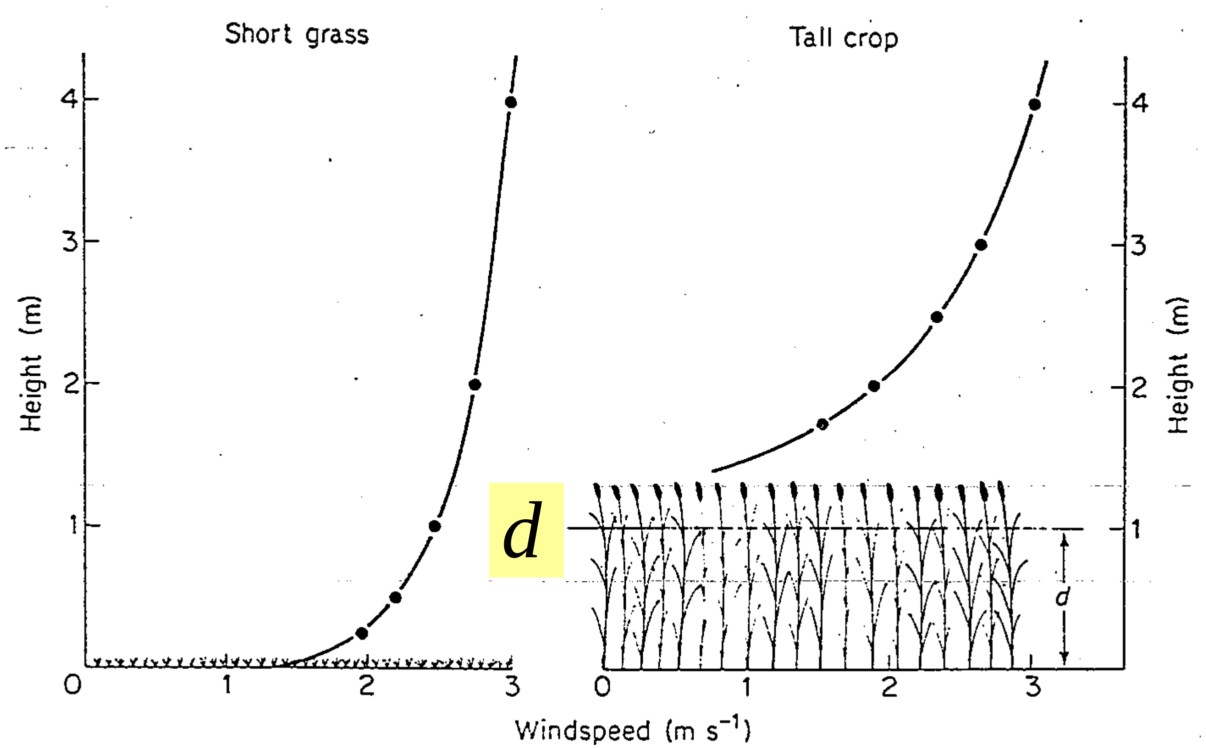


Modifications to the neutral log law (1)

Tall roughness: displacement height *d*

$$U = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right)$$

$$U = 0 \text{ at } z = d + z_0$$



Modifications to the neutral log law (2)

Buoyancy Controlling scales are now: $u_*,\ z,\ \theta_*,\ L$

Generalized gradients

$$\frac{\kappa z}{u_*}\frac{dU}{dz} = \phi_M\left(\frac{z}{L}\right)$$

$$\frac{\kappa z}{T_*}\frac{dT}{dz} = \phi_H\left(\frac{z}{L}\right)$$

Potential temperature

similar for other scalars

Mechanical production

$$L = \kappa u_*^2 \frac{T_0}{g\,T_*}$$

Buoyancy

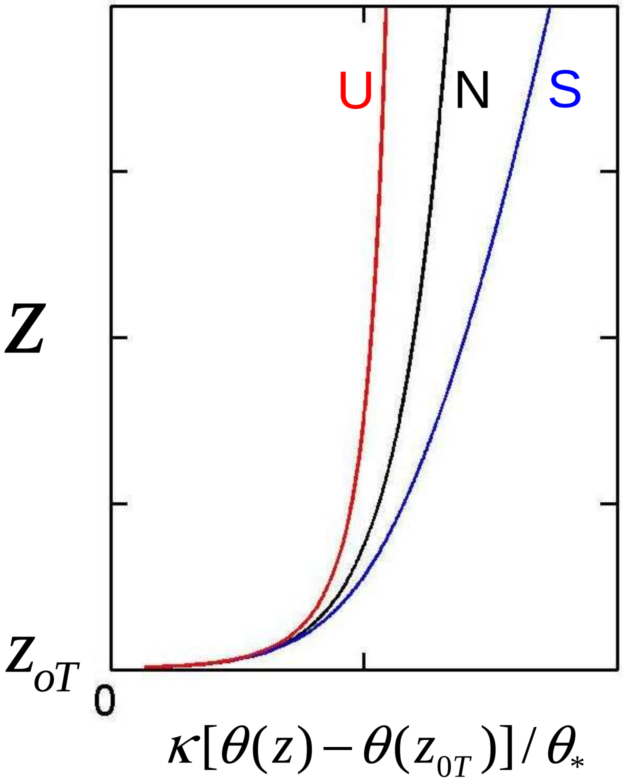
MO length

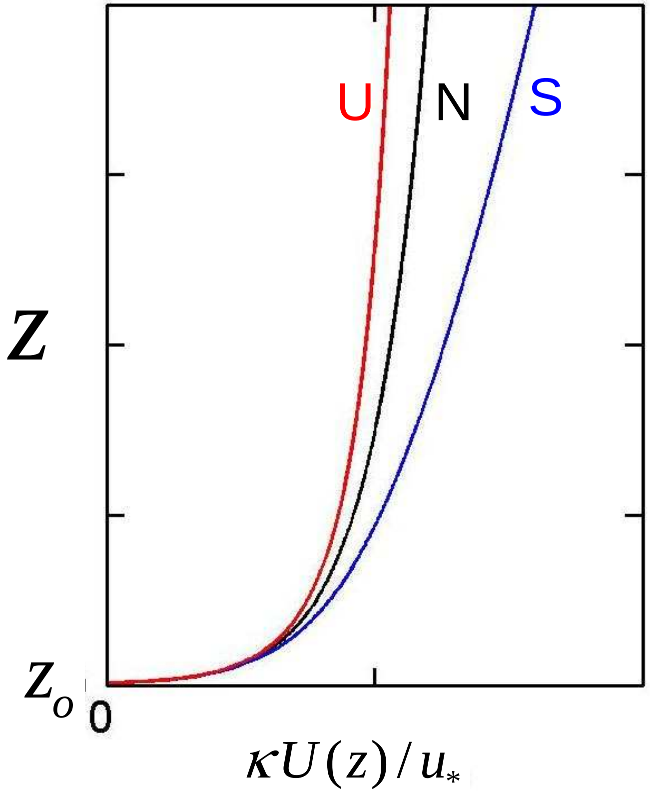
$$u_* T_* = -\overline{w' T'}$$

M-O similarity – θ & u profiles

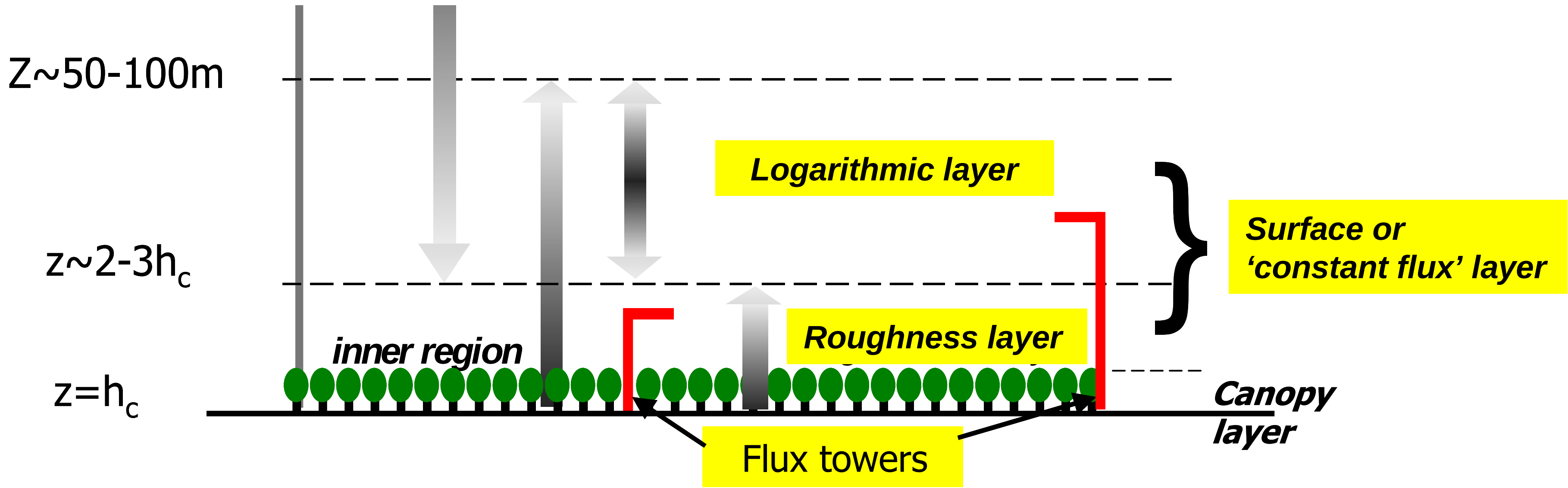
$$\frac{\kappa}{\theta_*}[\theta(z)-\theta(z_{0T})] = \ln\left(\frac{z}{z_{0T}}\right) - \psi_H\left(\frac{z}{L}\right)$$

$$\frac{\kappa}{u_*}U(z) = \ln\left(\frac{z}{z_0}\right) - \psi_M\left(\frac{z}{L}\right)$$





Roughness sublayer (RSL)

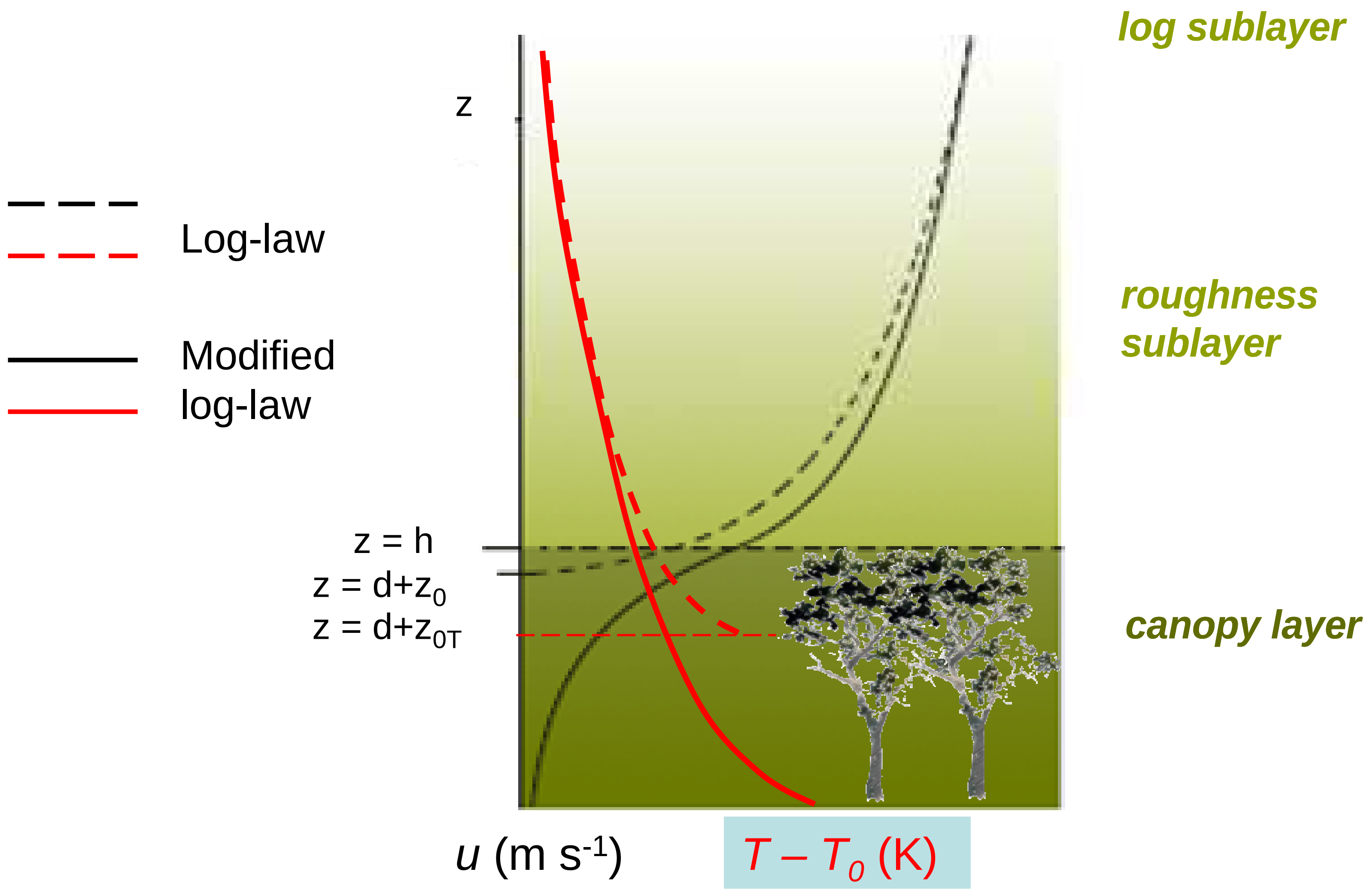


RSL influenced by the underlying surface through:

- windspeed inflection instability
- source/sink distribution

RSL extends from the canopy top to 2–3 x h_c

Coupled log, roughness & canopy layers



Eddy fluxes

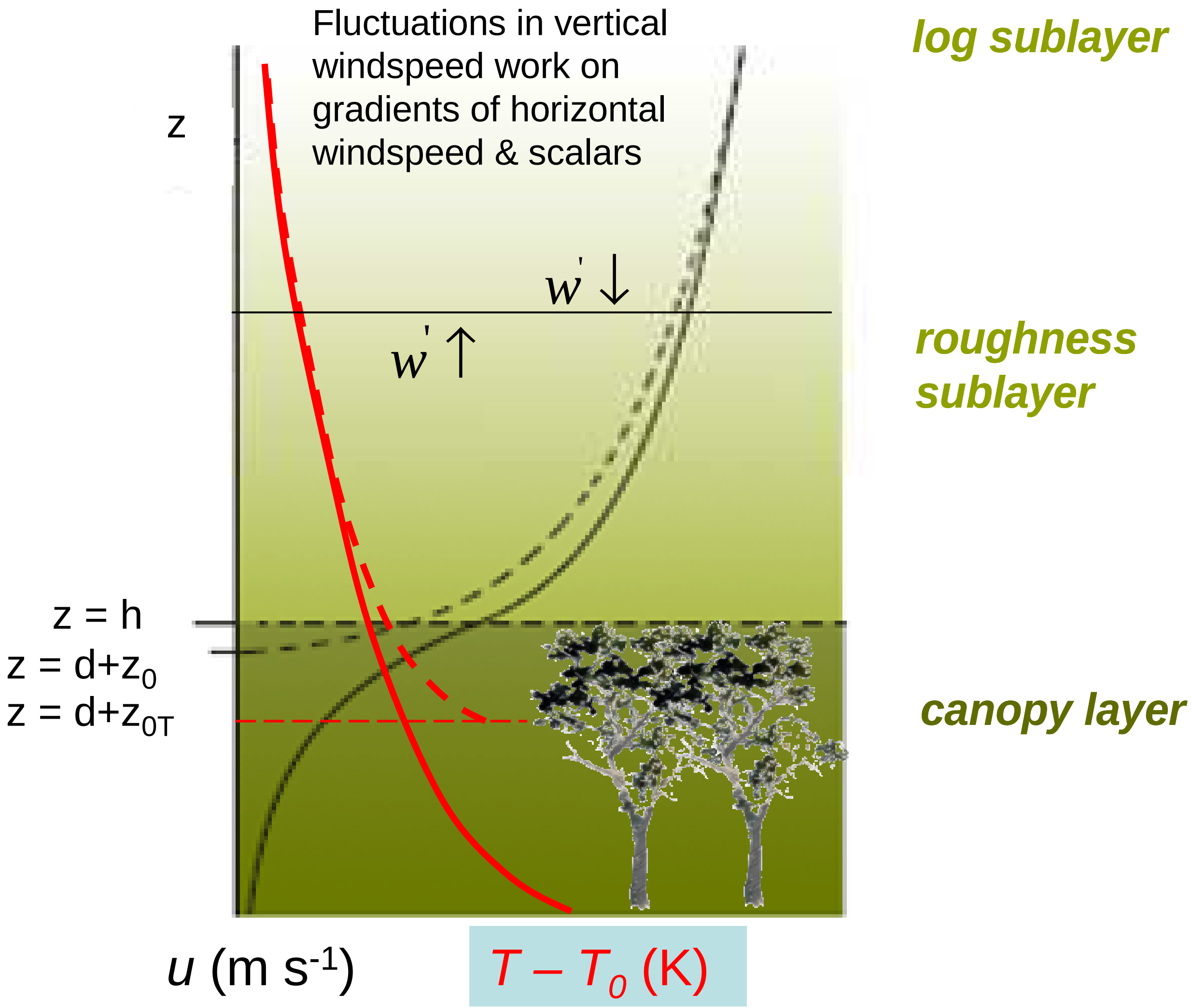
$$\overline{\tau} = -\overline{\rho}\,\overline{w'u'}$$

$$\overline{H} = \overline{\rho}c_p\,\overline{w'T'}$$

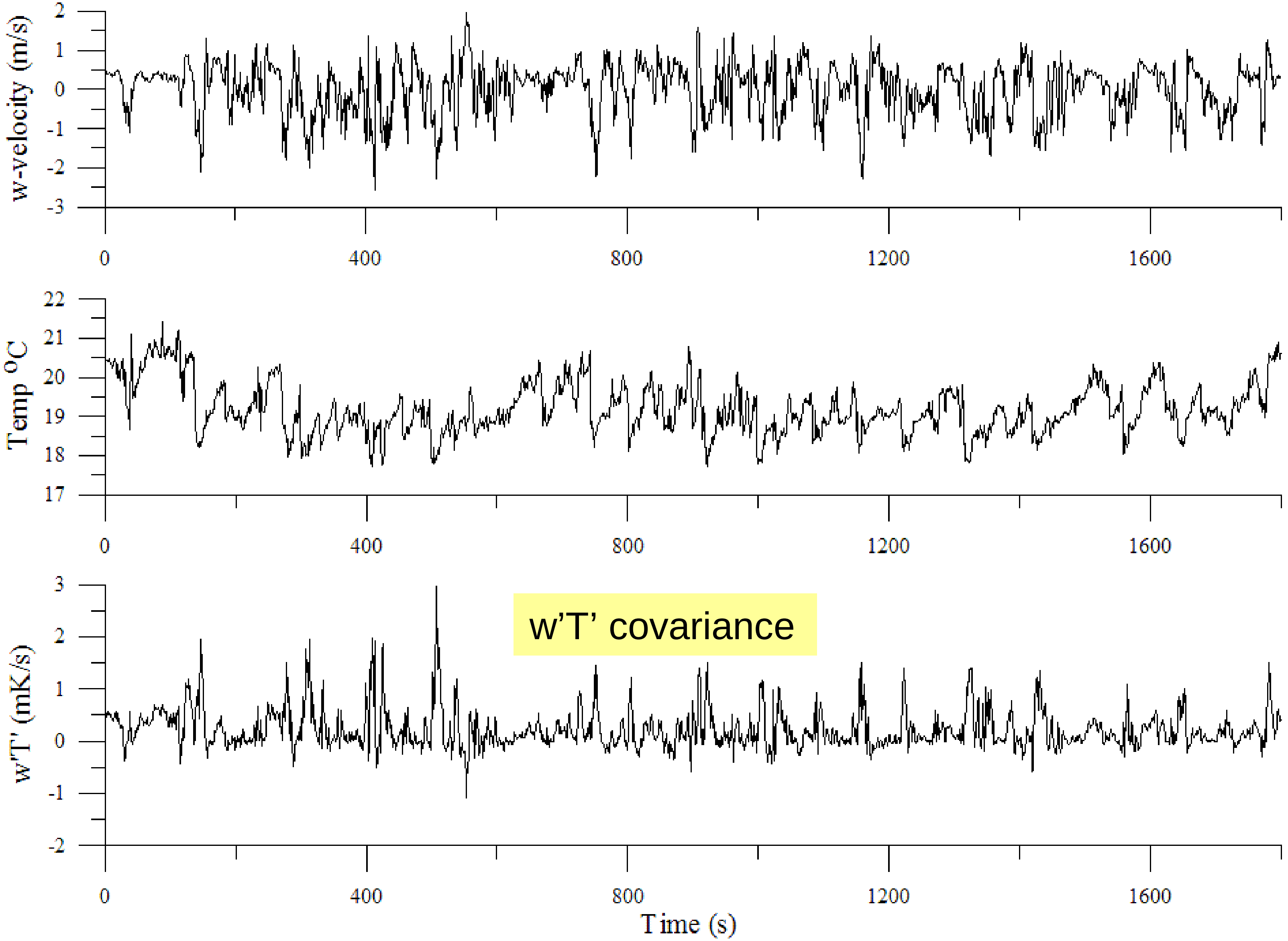
$$\overline{E} = \overline{\rho_a}\,\overline{w'\chi_v'}$$

$$\overline{F_c} = \overline{\rho_a}\,\overline{w'\chi_c'}$$

Covariances

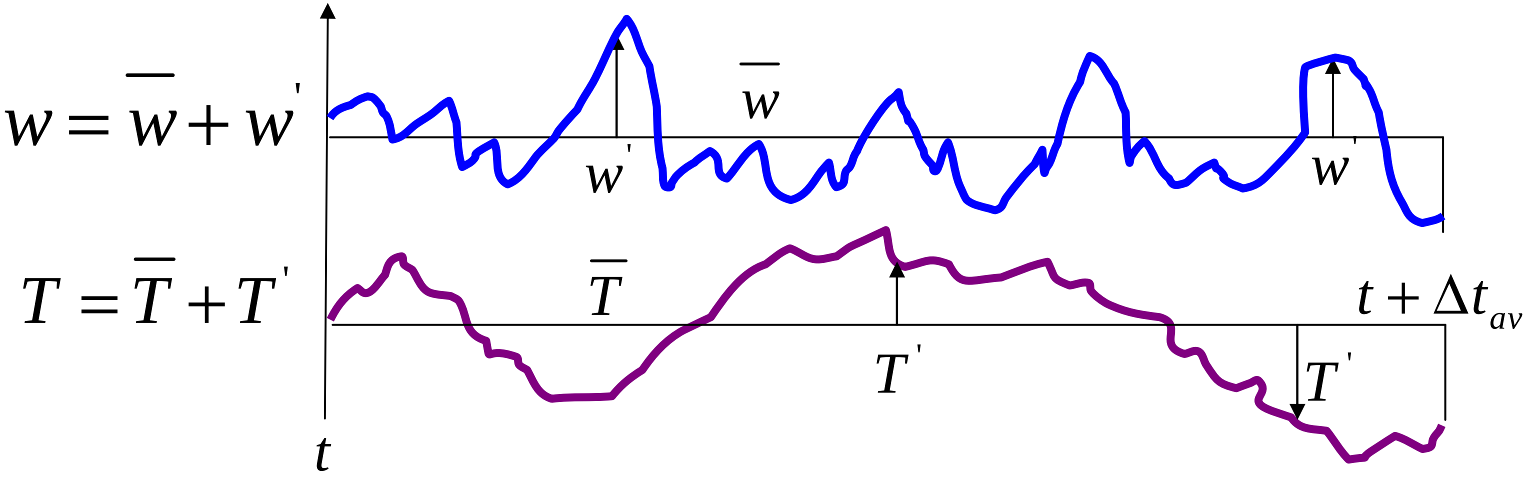


Eddy covariance is about analysing signals generated by atmospheric turbulence



Some notation

Reynolds decomposition & time averages



Averages $\overline{w} = \frac{1}{\Delta t_{av}} \int_t^{t+\Delta t_{av}} w dt$ $\overline{T} = \frac{1}{\Delta t_{av}} \int_t^{t+\Delta t_{av}} T dt$

$\overline{w'} = 0$ $\overline{T'} = 0$

Statistics – time domain

Variance – a measure of how a signal varies about its mean

$$\mathrm{var}(T) = \overline{T'^2} = \frac{1}{\Delta t_{av}} \int_{t}^{t+\Delta t_{av}} (T - \overline{T})^2 \, dt$$

Covariance – a measure of how the product of two signals vary about their respective means

$$\mathrm{cov}(wT) = \overline{w'T'} = \frac{1}{\Delta t_{av}} \int_{t}^{t+\Delta t_{av}} (w - \overline{w})(T - \overline{T}) \, dt$$

Statistics – frequency domain

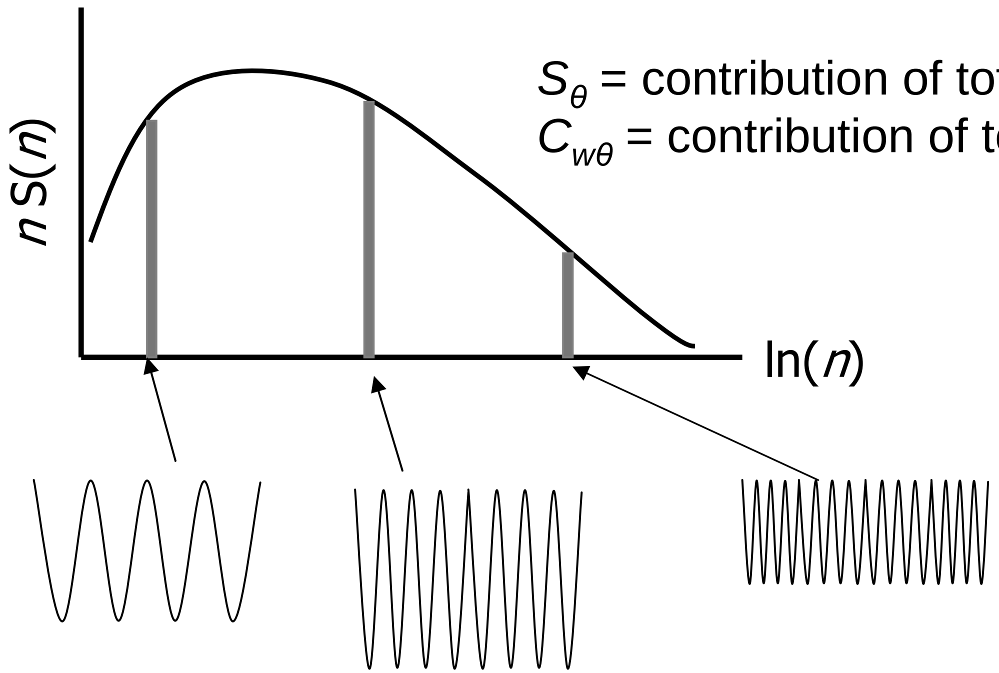
$$\mathrm{var}(T) = \overline{T'^2} = \int_0^\infty n S_T(n)\,\mathrm{d}\ln(n)$$

$$\mathrm{cov}(wT) = \overline{w'T'} = \int_0^\infty n C_{wT}(n)\,\mathrm{d}\ln(n)$$

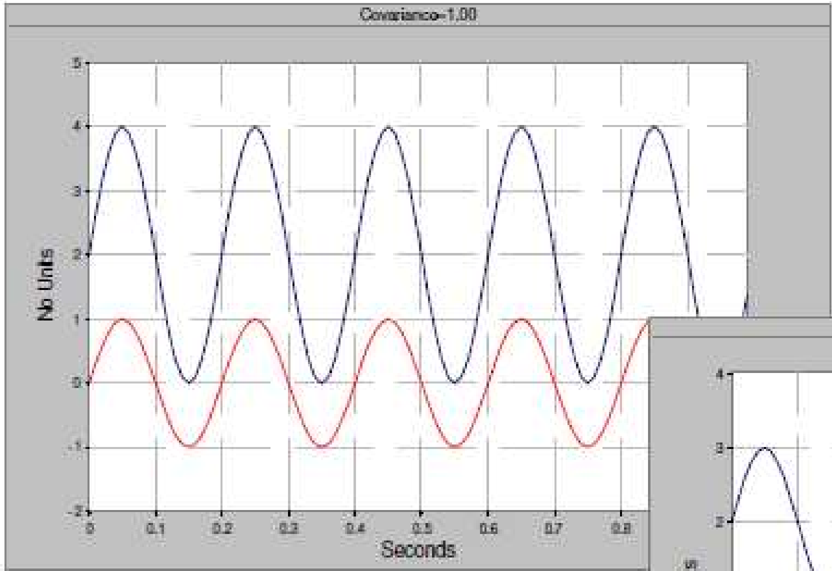
(Co)variance is area under the (co)spectral density curve

S_θ = contribution of total variance per unit dn

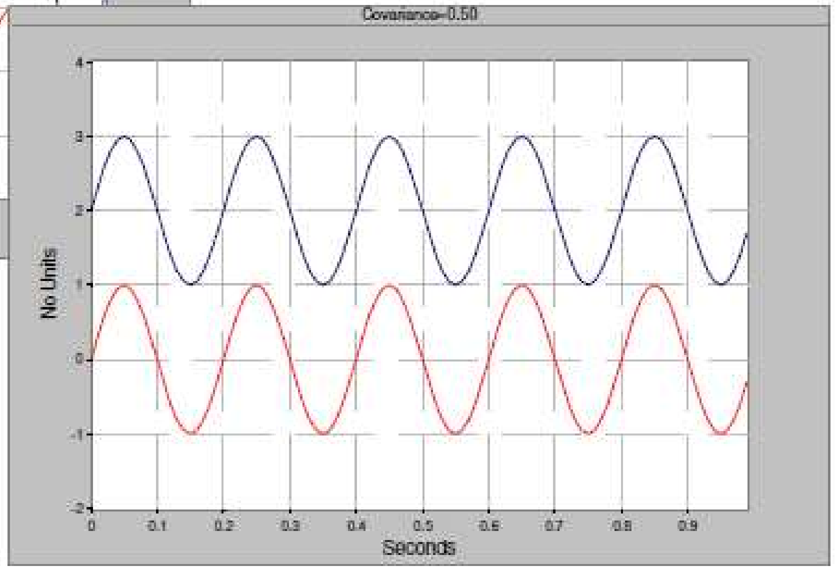
$C_{w\theta}$ = contribution of total covariance per unit dn



Computing covariance – amplitude attenuation

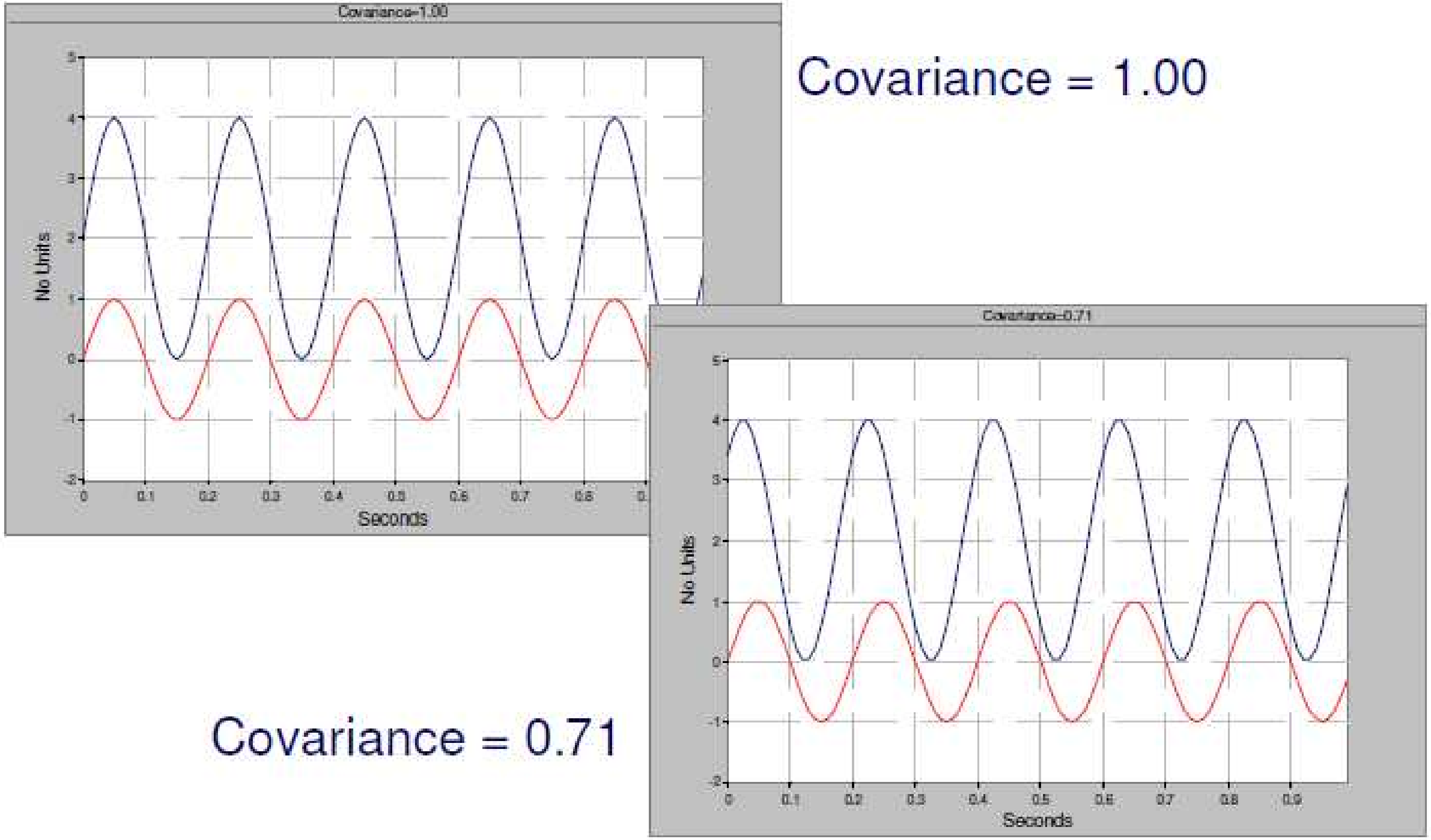


Covariance = 1.00



Covariance = 0.50

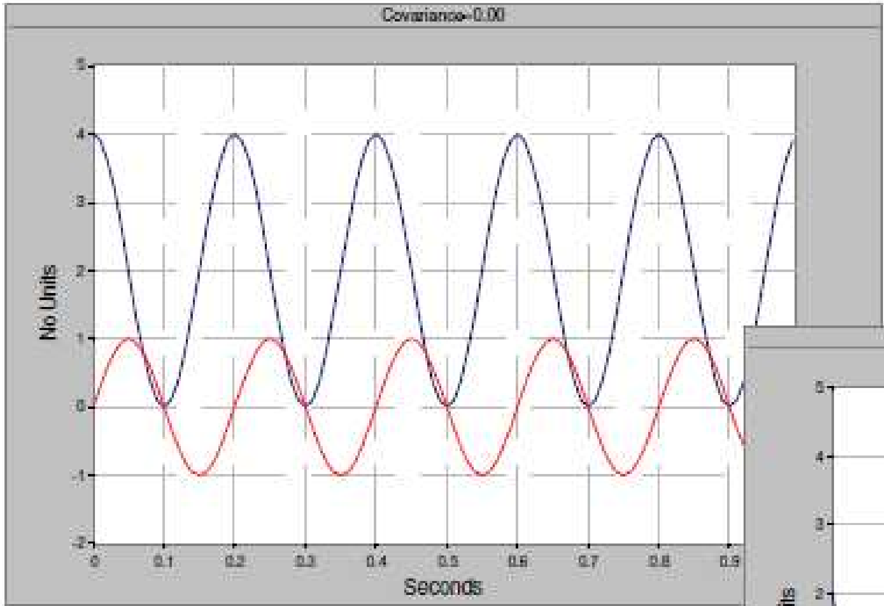
Computing covariance – signal time delay (1)



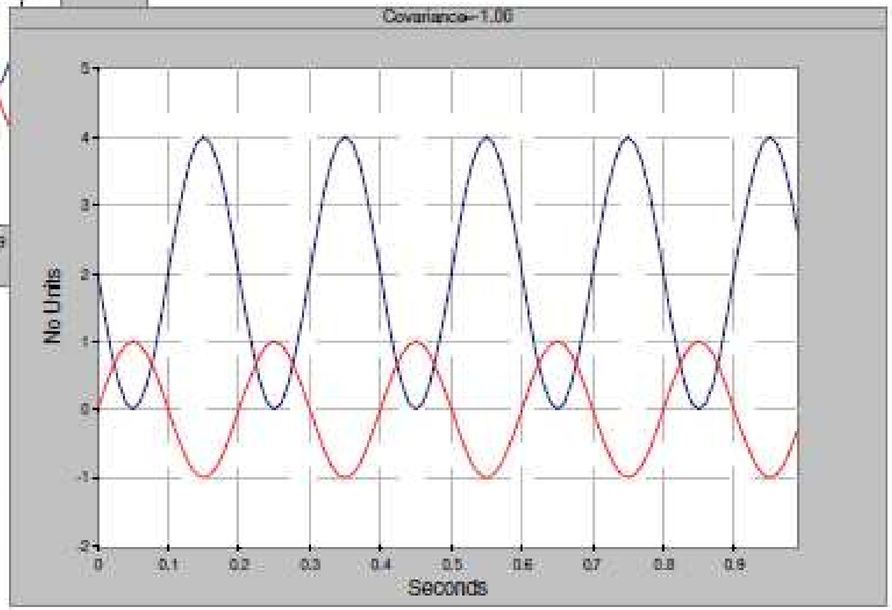
Covariance = 1.00

Covariance = 0.71

Computing covariance – signal time delay (2)



Covariance = 0.00

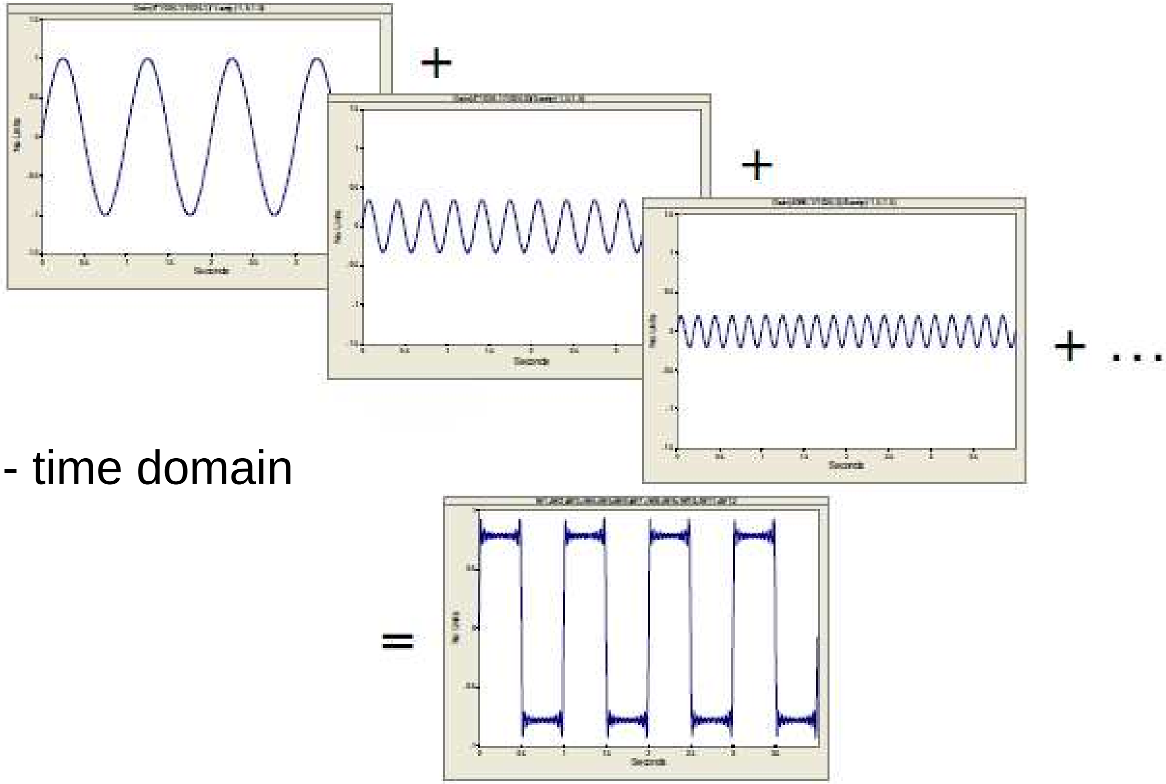


Covariance = -1.00

Spectral decomposition

- We can decompose any signal into a sum of cosines with varying amplitude, frequency and phase

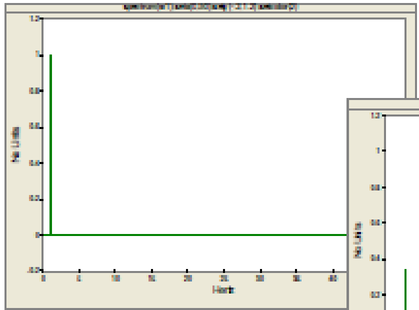
$$s_a(t) = A_{a0} + A_{a1}\cos(\omega_{a1}t + \phi_{a1}) + A_{a2}\cos(\omega_{a2}t + \phi_{a2}) + A_{a3}\cos(\omega_{a3}t + \phi_{a3}) + \ldots$$

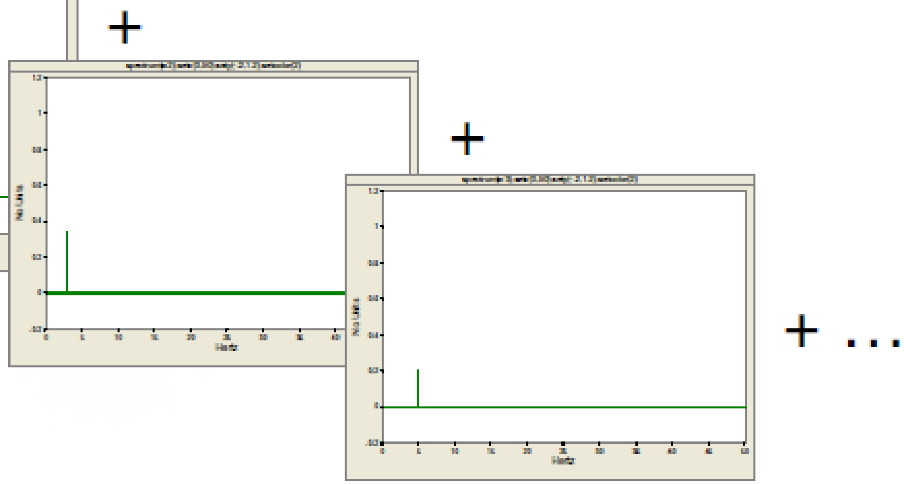


Square wave - time domain

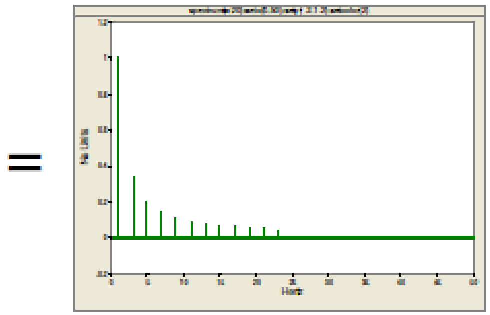
Variance in frequency domain

$$Var(s_a) = \frac{A_{a1}^2}{2} + \frac{A_{a2}^2}{2} + \frac{A_{a3}^2}{2} + \ldots$$



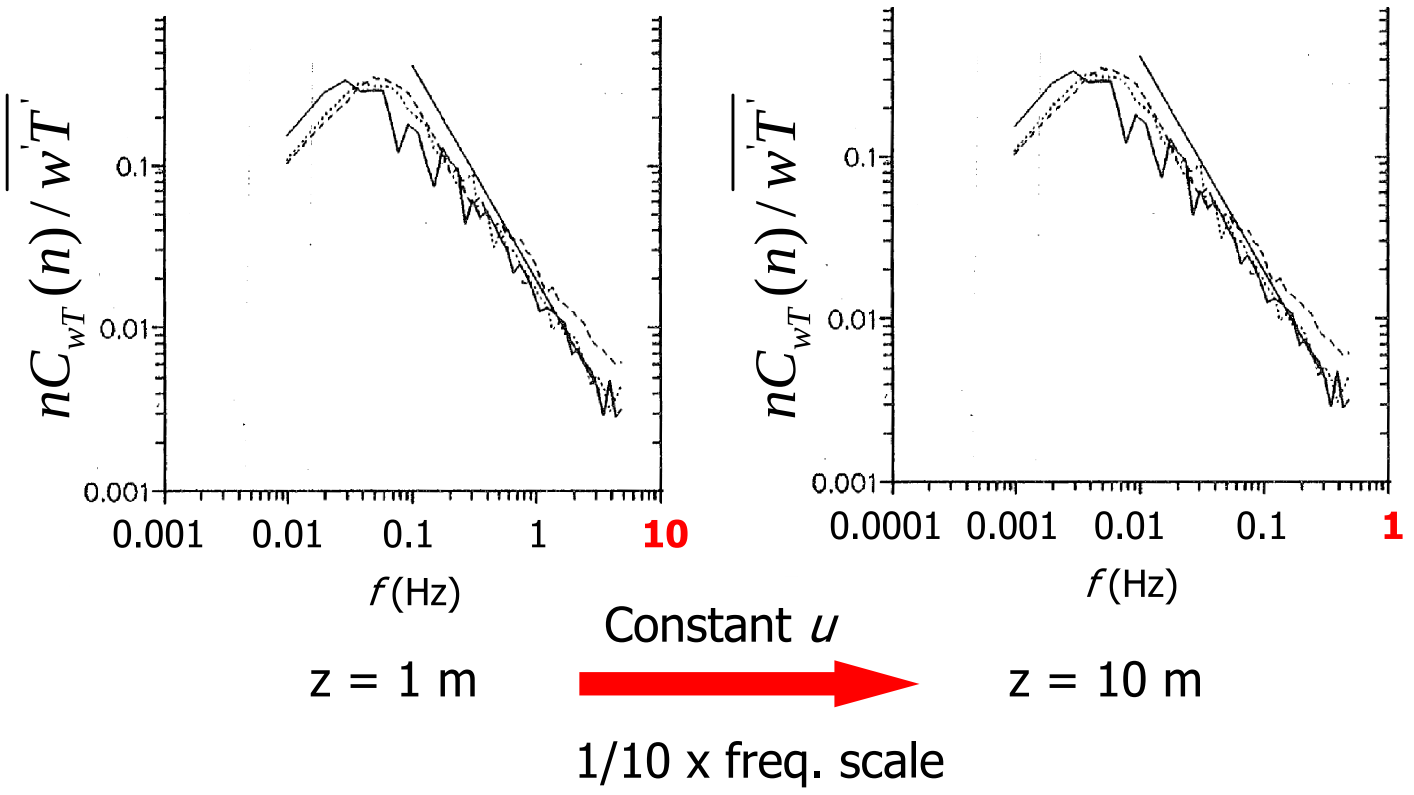


Square wave - frequency domain



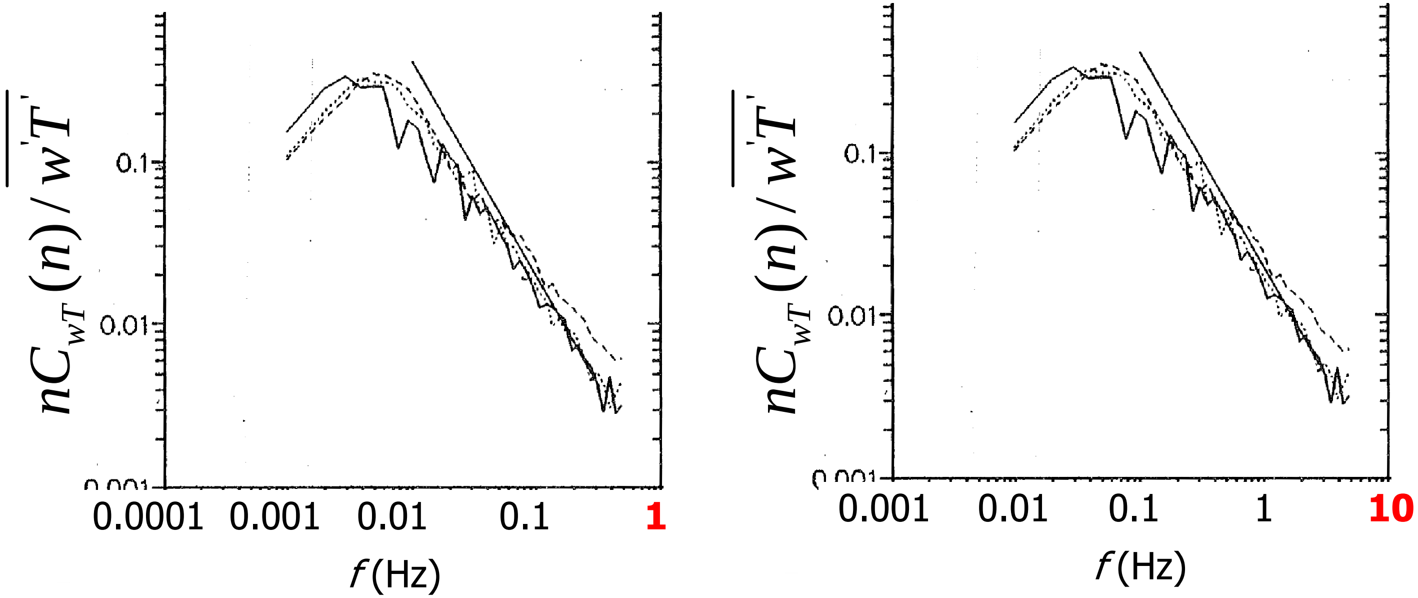
Frequency scaling

Spectral peak moves to lower frequencies as measurement height increases



Frequency scaling

Spectral peak moves to higher frequencies as windspeed increases



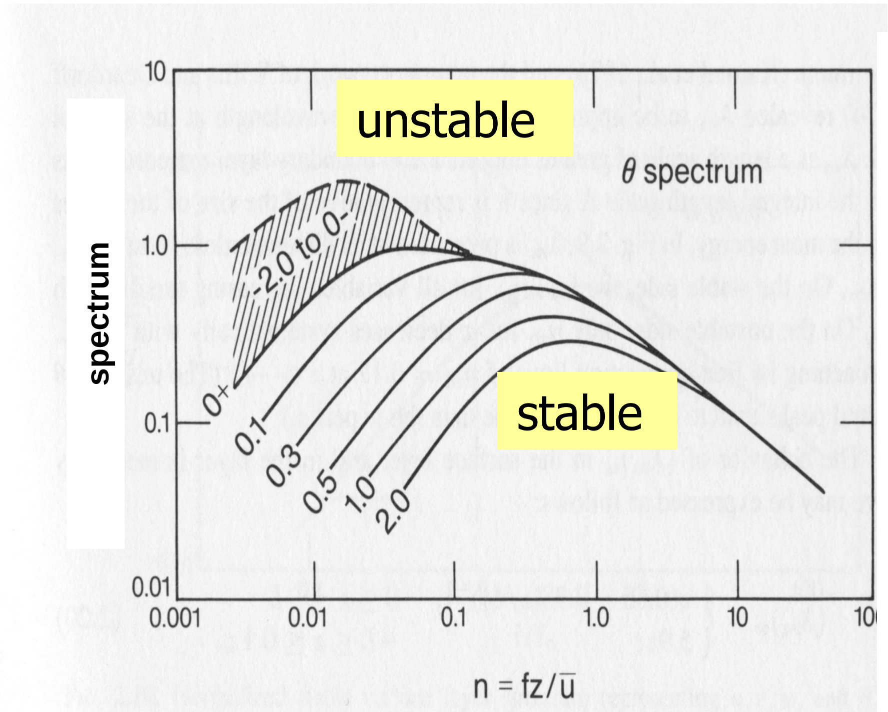
Constant z_m

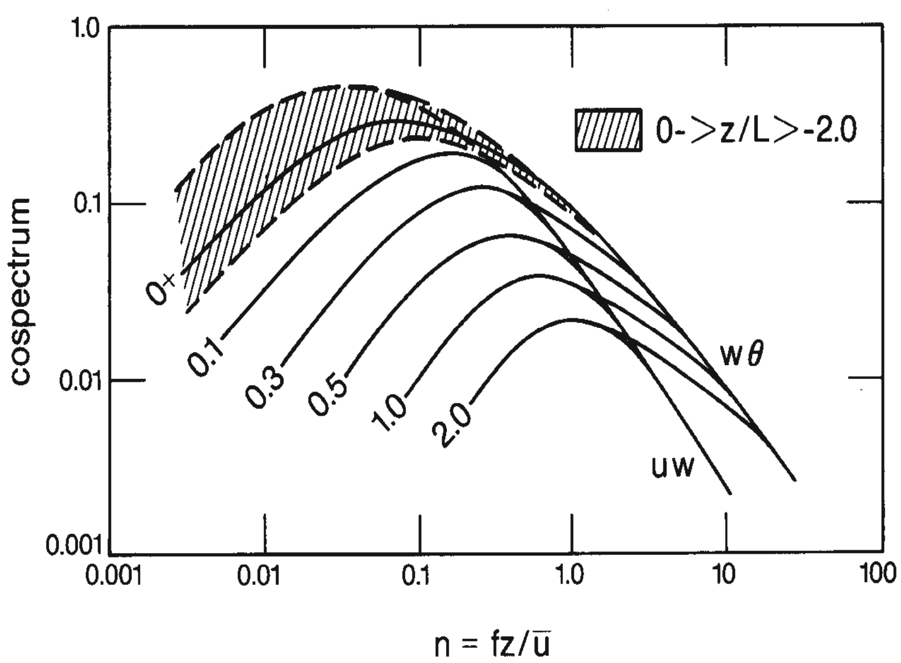
$u = 1\ m\ s^{-1}$ → $u = 10\ m\ s^{-1}$

10 x freq. scale

Spectra & cospectra depend on stability *z/L*

Normalize frequency: $n = fz / u$





Summary

- Atmospheric surface layer = log + roughness sublayers
  - Occupies lowest 10% of the ABL
  - Fluxes ~ constant
  - Strong gradients wind speed, temperature & other scalars
  - Controlling scales $u_*,\ z,\ \theta_*,\ L$
- Turbulence has structure, generated by mechanical and buoyancy forces
- Need to understand statistics of variances and covariances in both *time* and *frequency* domains
  - Important for EC system design and good measurements
- Atmospheric (co)spectra scale with $n = fz/u$
- (Co)spectra are stability dependent