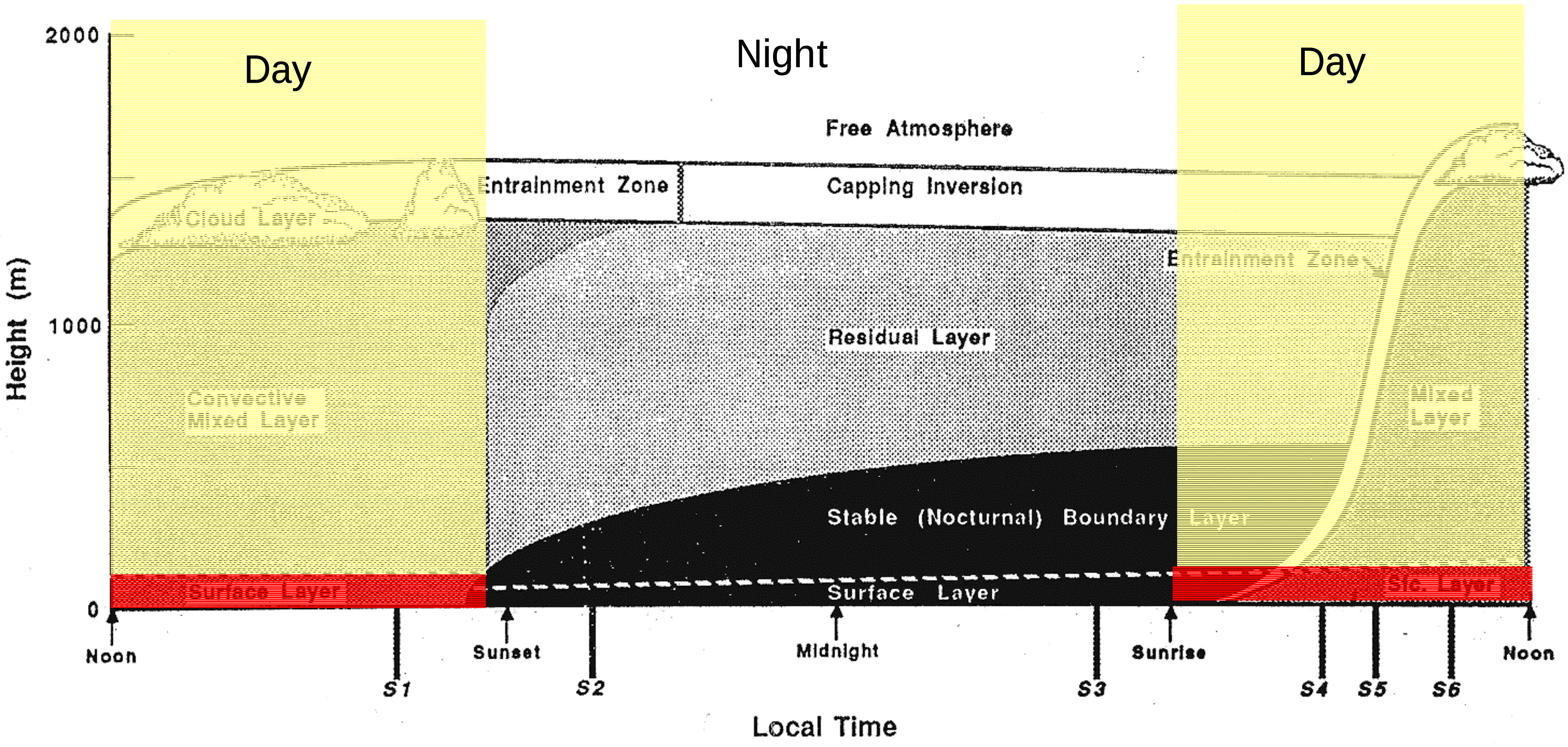
# Lecture 2:
# Atmospheric structure, stability and turbulence statistics

- Atmospheric boundary layer
- Surface layer
- Atmospheric stability
- Monin-Obukhov similarity
- Statistics
  - Time averaging
  - Variance
  - Covariance
  - Spectra and cospectra
  - Data sampling rates
  - Averaging periods

# Atmospheric Boundary Layer (ABL)

## *Schematic Fair-Weather Structure and Daily Evolution*

Courtesy Prof HP Schmid
Indiana University

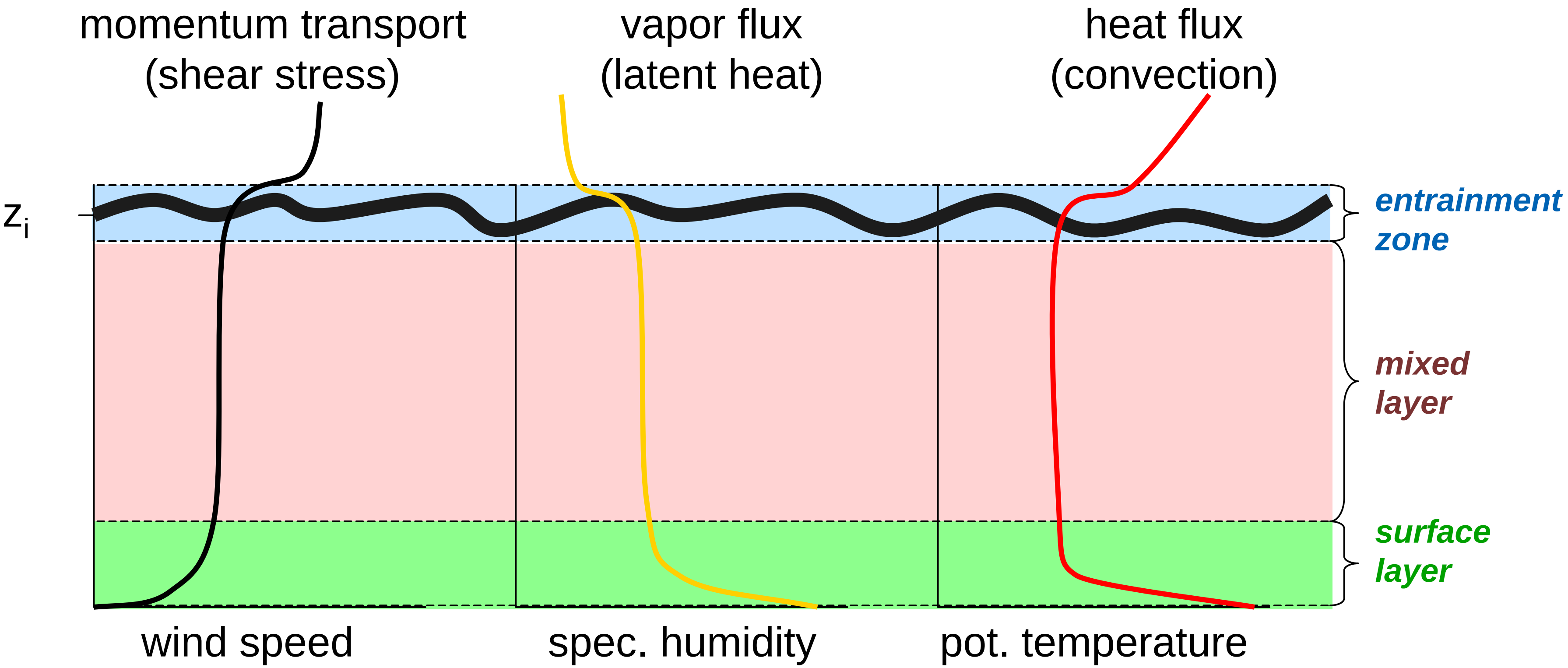


from Stull, 1988

# Atmospheric Boundary Layer (ABL)

## *Schematic Daytime Profiles*

Courtesy Prof HP Schmid
Indiana University

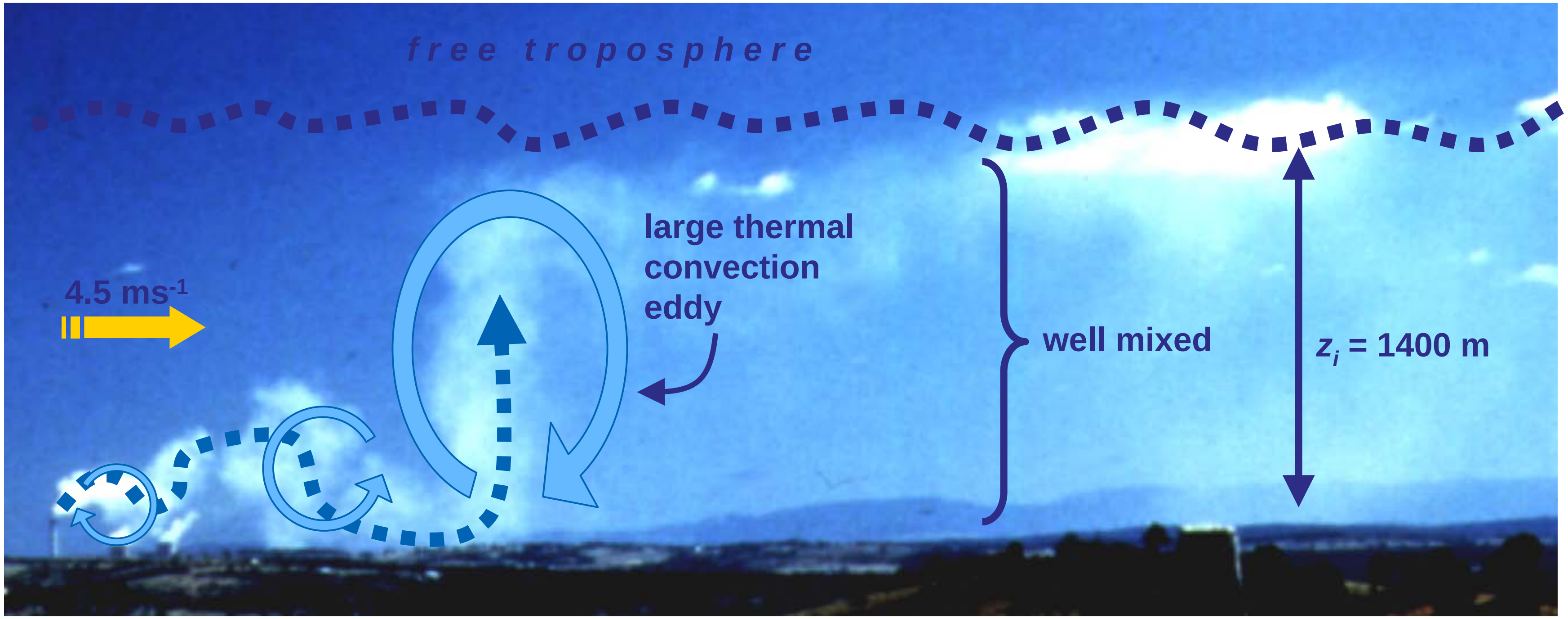


# Atmospheric Boundary Layer (ABL)

## *Daytime Convective Boundary Layer*

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

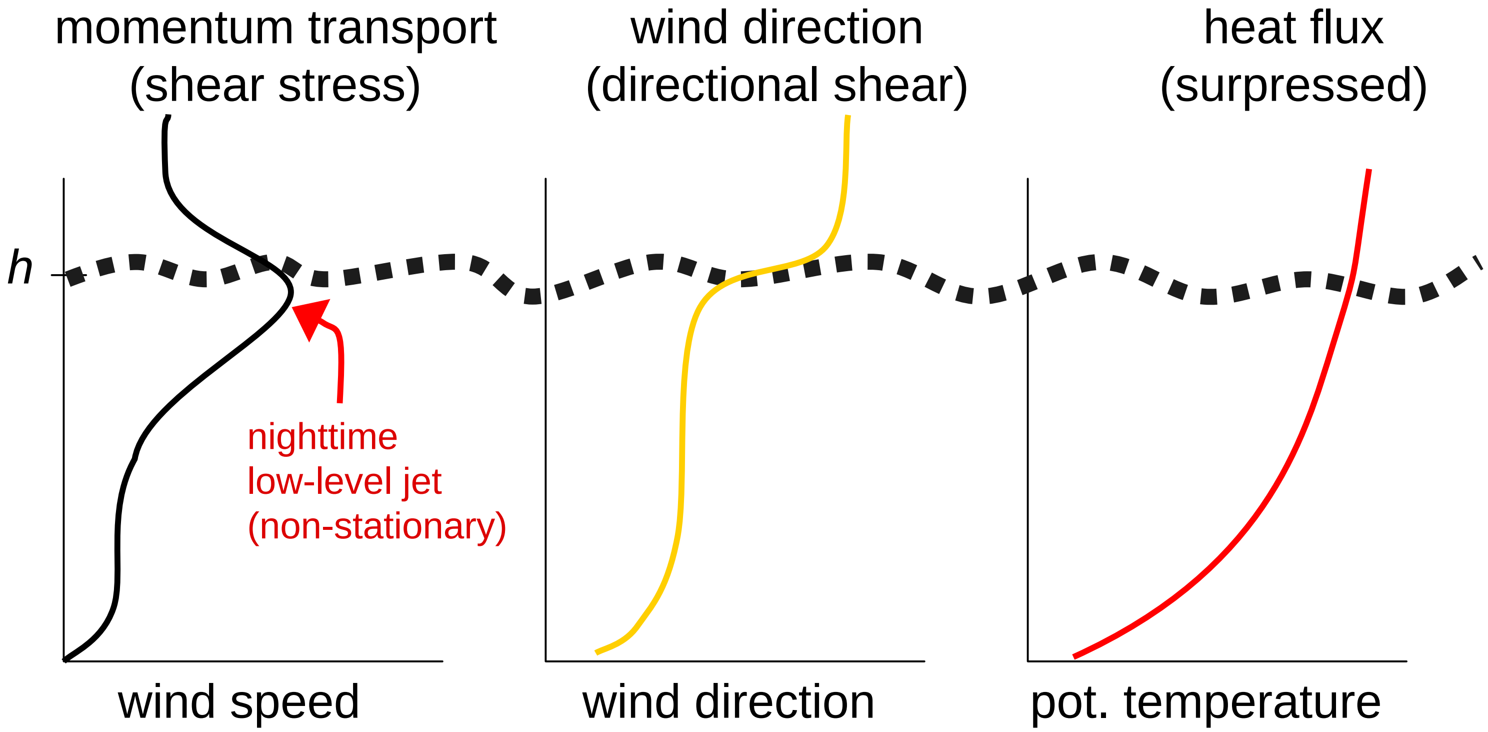


Tarong, Queensland (AUS), stack height: 210 m, $z_i$ = 1400 m, w* = 2.5 $ms^{-1}$. Photo: Geoff Lane, CSIRO (AUS)

# Nocturnal Boundary Layer (NBL)

## *Schematic Nighttime Profiles*

Courtesy Prof HP Schmid
Indiana University



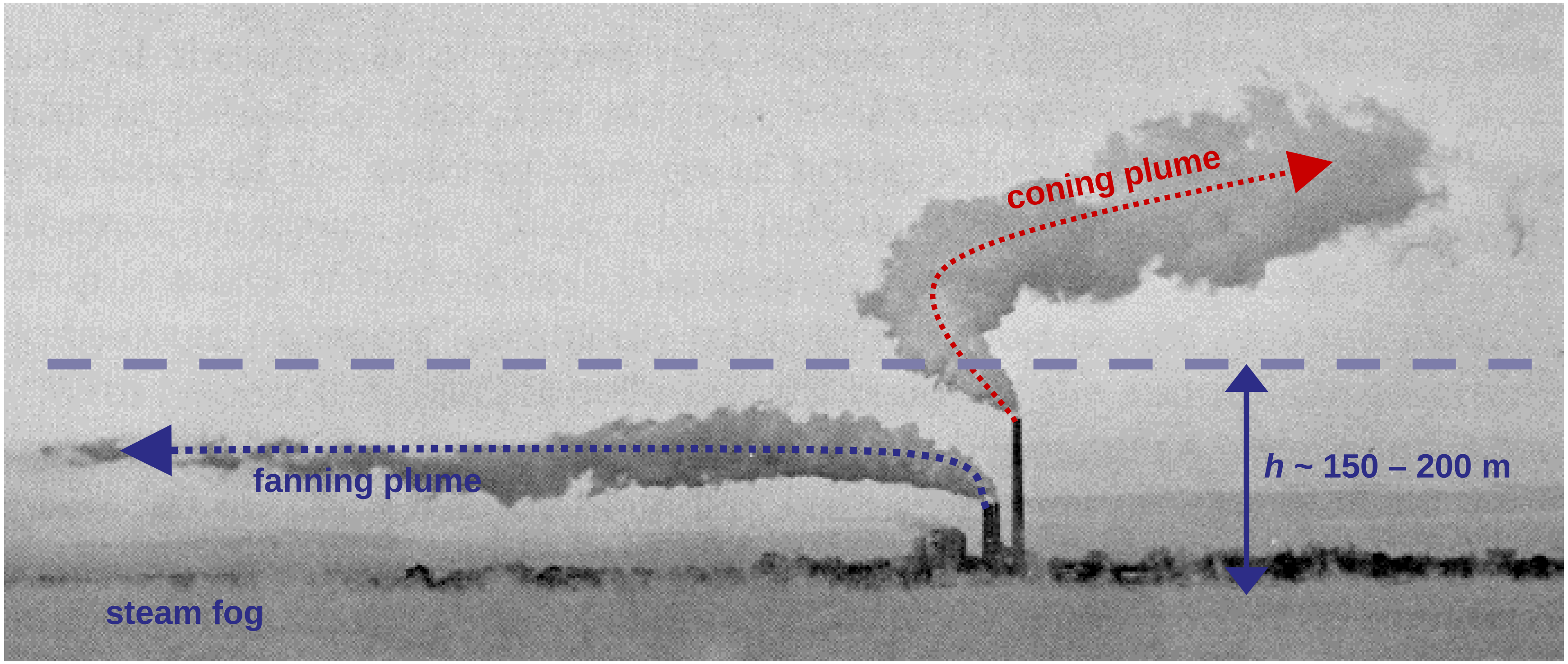
- strong vertical gradients
- mixing and vertical fluxes supressed
- stable ABL growth slow, driven by radiation and forced convection

# 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*

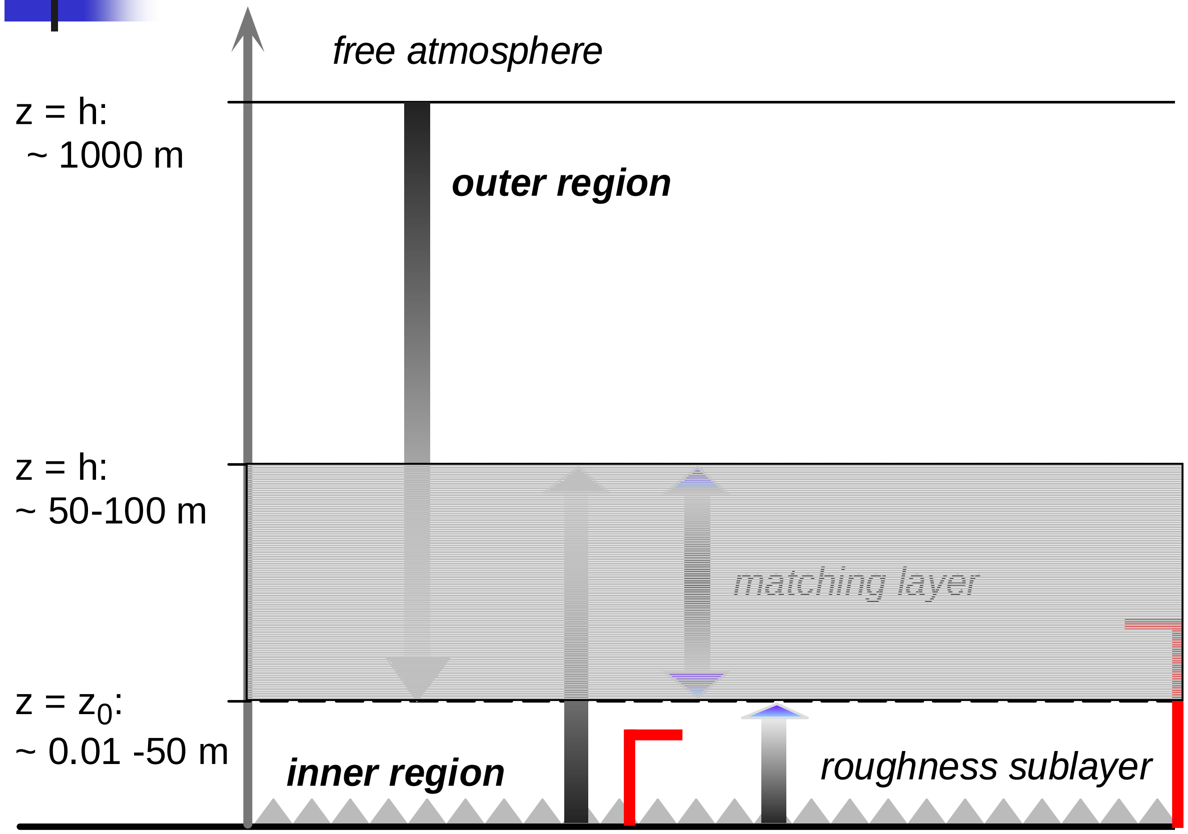
# Atmospheric Boundary Layer (ABL)

Courtesy Prof HP Schmid
Indiana University

## *Sublayers*

***neutral, weakly stable***

***unstable, convective***



*free atmosphere*

z = h:
~ 1000 m

***outer region***

z = h:
~ 50-100 m

*matching layer*

z = $z_0$:
~ 0.01 -50 m

***inner region***

*roughness sublayer*

Flux towers

***entrainment layer***

***mixed layer***

***surface layer***
***("constant flux layer")***

***roughness sublayer***

# The neutrally stratified surface layer

- Occupies ~ 10% of the PBL
- Strong gradients in:
  - wind speed
  - temperature
  - other scalars.
- Controlling length scale
  - distance to the surface, $z$
  - not depth of whole PBL depth, $z_i$

# The logarithmic velocity profile

Friction velocity

$$\frac{dU}{dz} = \frac{u_*}{\kappa z} \qquad u_* = \sqrt{\frac{\tau_0}{\rho}}$$

Shear stress = momentum flux

Density of air

$$\tau_0 = -\rho \overline{u' w'}$$

Integrate from $z_0$ to $z$

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \qquad U = 0 \text{ at } z_0$$

Von Karman
constant = 0.4

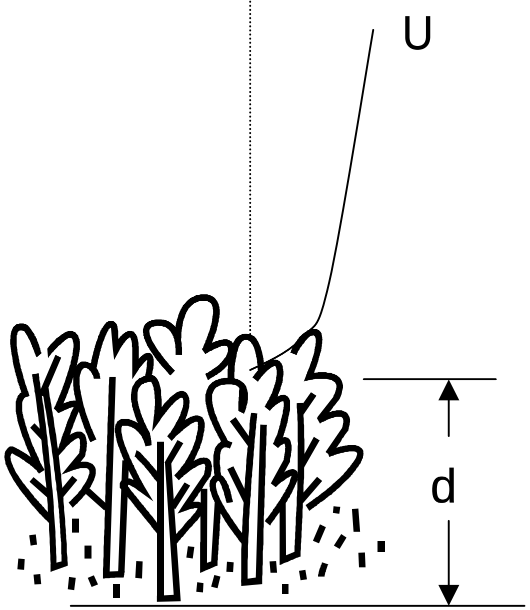
Roughness length

# Modifications to the neutral log law

- Tall roughness: displacement height *d*

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

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



# Monin-Obukhov similarity

## Thermal stability adds the Obukhov length scale, *L*

Gradients

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

$$\frac{\kappa z}{\theta_*}\frac{d\theta}{dz} = \phi_H\left(\frac{z}{L}\right)$$

Potential temperature – similar for other scalars

Mechanical production

$$\frac{z}{L} = -\kappa z \frac{1}{u_*^3}\frac{gH}{\rho c_c T_0}$$

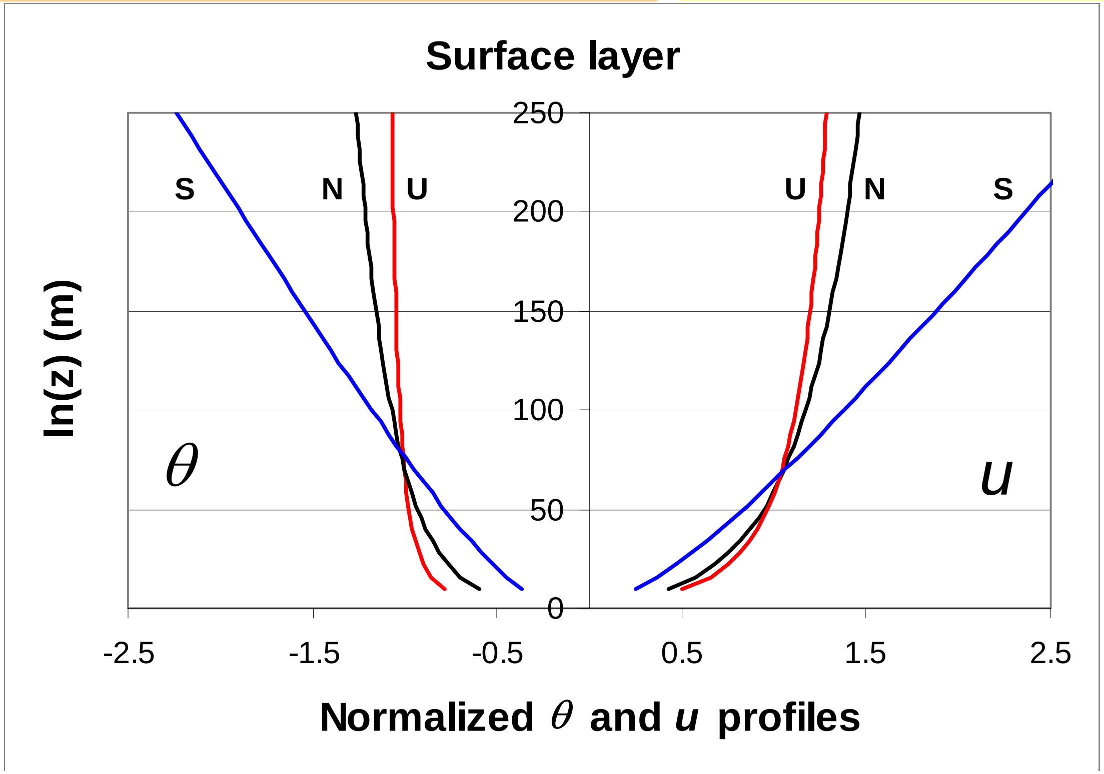
Buoyancy

$$H = -u_*\theta_* = \rho c_p \overline{w^{'}T^{'}}$$

# M-O similarity – $\theta$ & $u$ profiles

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

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



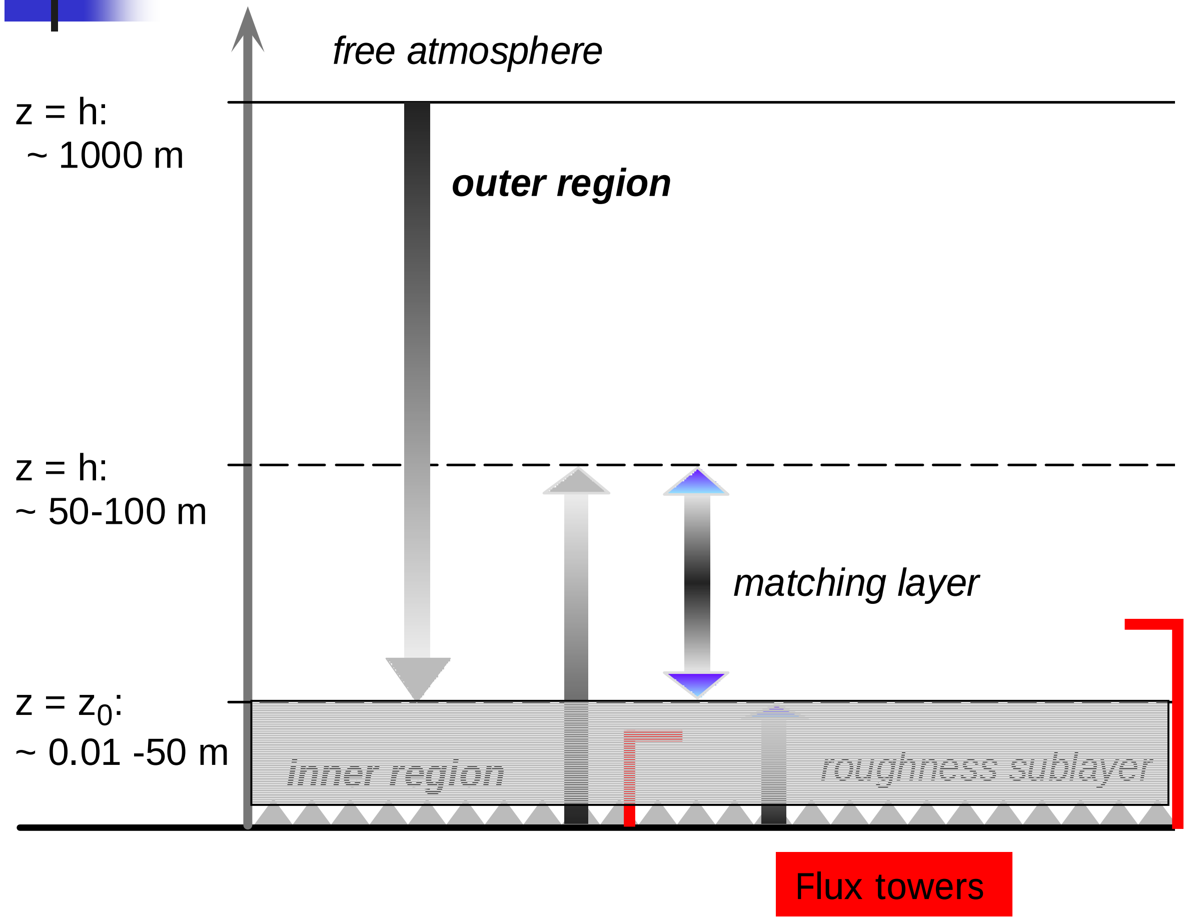
# Atmospheric Boundary Layer (ABL)

## *Subdivision into Sublayers*

Courtesy Prof HP Schmid
Indiana University

***neutral, weakly stable***

***unstable, convective***



*free atmosphere*

z = h:
~ 1000 m

***outer region***

z = h:
~ 50-100 m

*matching layer*

z = $z_0$:
~ 0.01 -50 m

*inner region*

*roughness sublayer*

Flux towers

***entrainment layer***

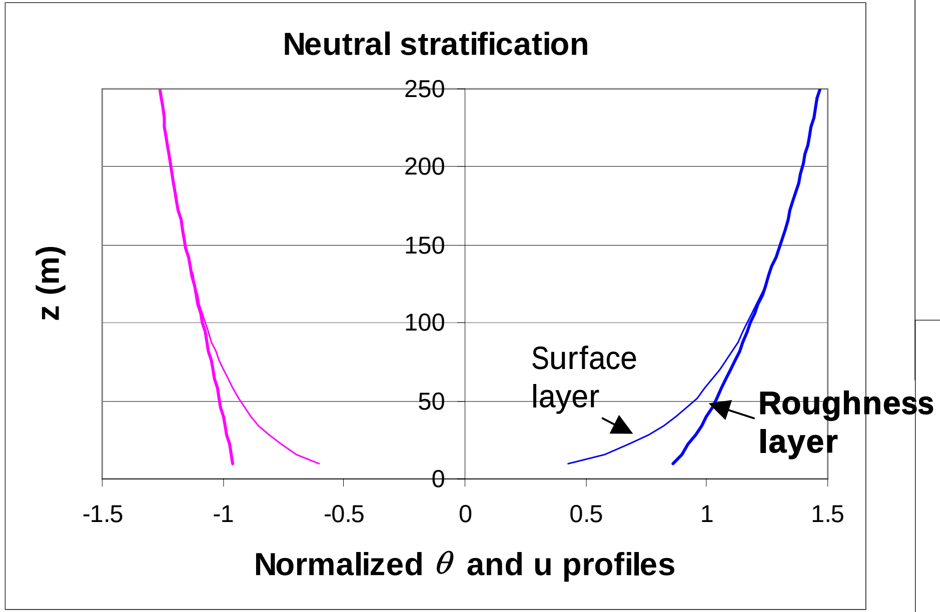
***mixed layer***

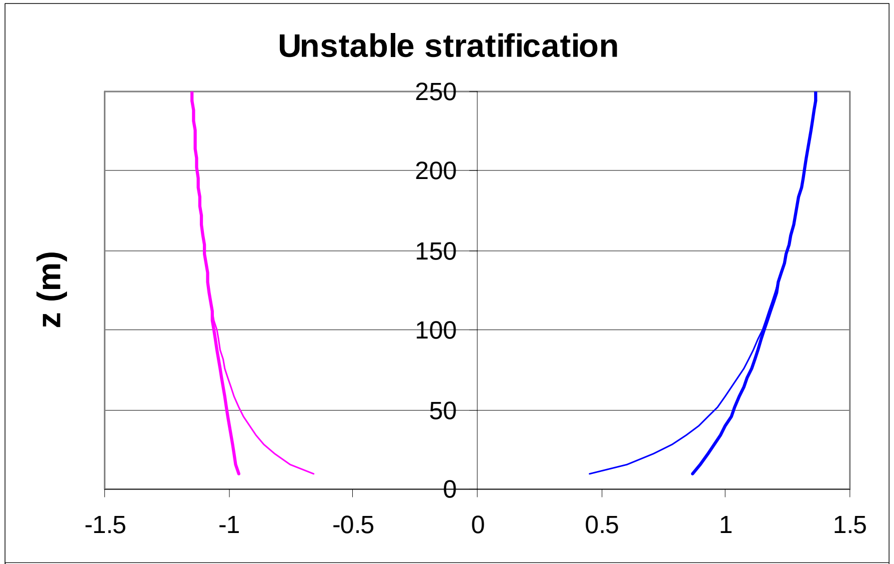
***surface layer***
***("constant flux layer")***

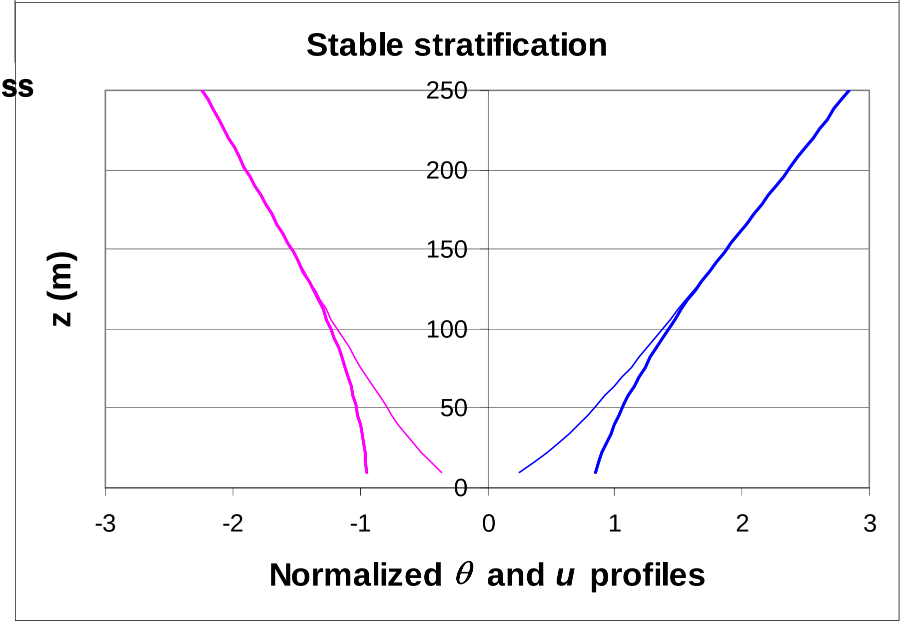
***roughness sublayer***

# Normalized $\theta$ and $u$ profiles

## Roughness sublayer







$z_0$ =2.7 m

$d$ =30 m

$z^*$ = 145 m

# Atmospheric surface layer - summary

- Monin-Obukhov scaling links mean fields and scalar fluxes in the surface layer
- M-O scaling used in many micrometeorological methods and techniques

# Statistics

- Variance and covariance
- Spectra & cospectra
- Data sampling rates
- Averaging periods

# Eddy fluxes

1) $\overline{H} = \overline{\rho} c_p \overline{w' T'}$ Heat

2) $\overline{E} = \overline{c_d} \, \overline{w' \chi_v'}$ Water vapor

3) $\overline{F_c} = \overline{c_d} \, \overline{w' \chi_c'}$ $CO_2$

4) $\overline{\tau} = \overline{\rho} \, \overline{w' u'}$ Momentum

Covariances

# Variance and covariance

$$\mathrm{var}(\theta) = \overline{\theta'^2} = \frac{1}{\Delta t}\int_t^{t+\Delta t} (\theta - \overline{\theta})^2\, dt \approx \int_0^\infty S_\theta(n)\, dn$$

$$\mathrm{cov}(w\theta) = \overline{w'\theta'} = \frac{1}{\Delta t}\int_t^{t+\Delta t} (w - \overline{w})(\theta - \overline{\theta})\, dt \approx \int_0^\infty C_{w\theta}(n)\, dn$$

Time domain

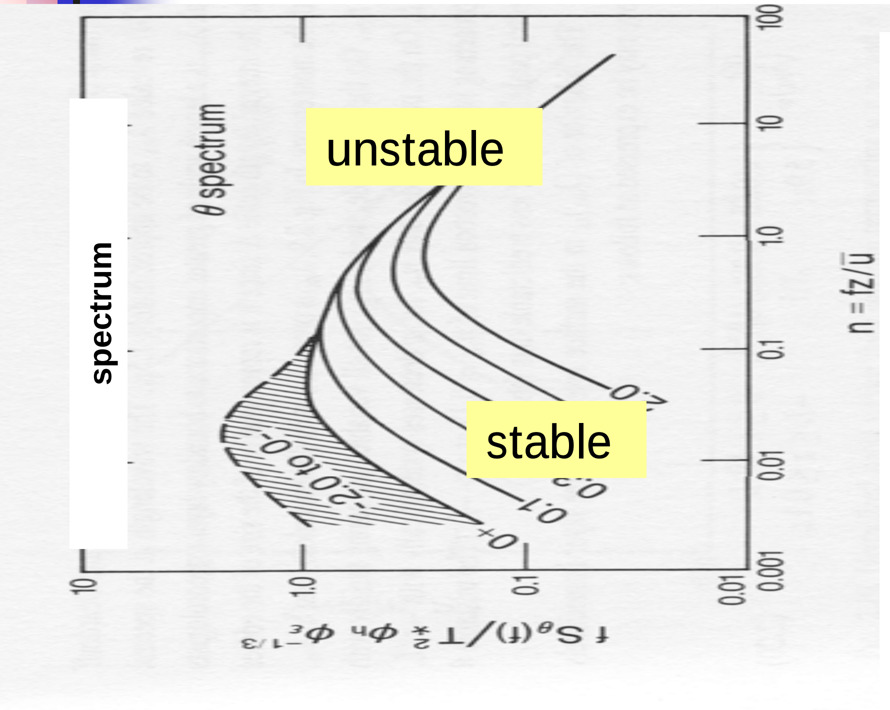
Frequency domain

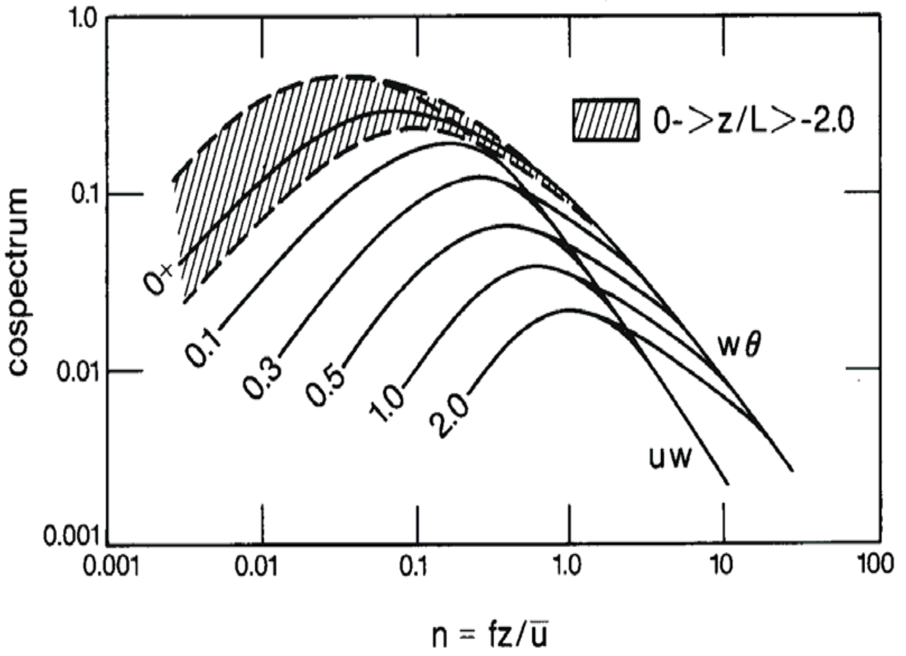
$S_n$ = contribution of the total variance of $\theta$ per unit $dn$

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

Approximation b/c calculations are over a finite time interval $\Delta t$

# Spectra & cospectra at Kansas grassland





normalized frequency: $n = fz / u$

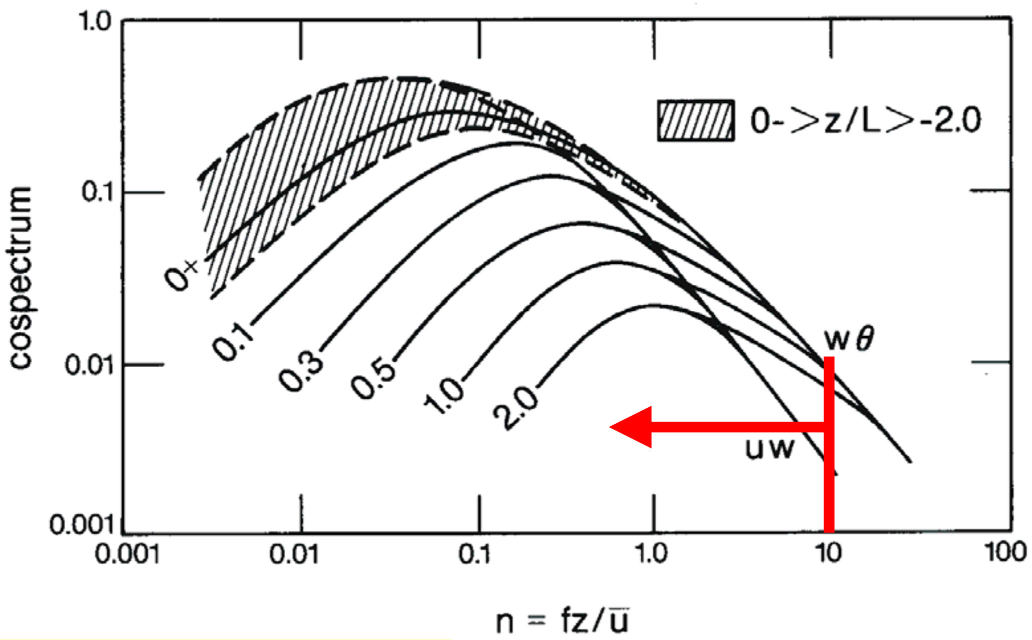
Spectra & cospectra depend on stability parameter *z*/*L*

# The covariance term:
# Horizontally homogeneous, 1D conditions

Must ensure that we:

- Measure all significant contributions to $\overline{w'c'}$
  - at high frequency
  - at low frequency

# High frequency covariance
# - how fast is fast enough?



Kansas
cospectrum
over
grassland

Measure @ > 2 canopy heights

$$h > 2h_C \ : \ n = fz/\bar{u}(z)$$

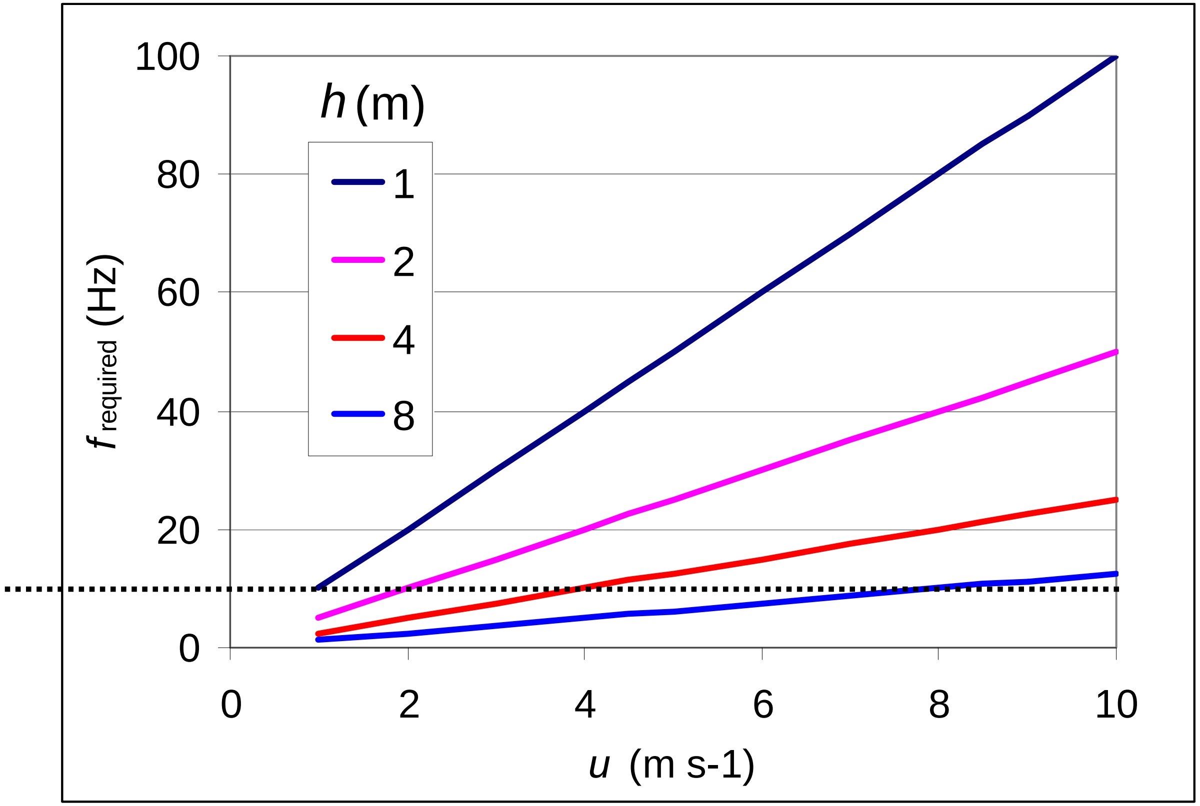
$$f_{required} = \frac{10\bar{u}}{h}$$

Measure @ < 2 canopy heights

$$h < 2h_C \ : \ n = f\, h_C/\bar{u}(h_C)$$

$$f_{required} = \frac{10\bar{u}(h_C)}{h_C}$$

# Maximum sampling frequency vs windspeed & measuring height

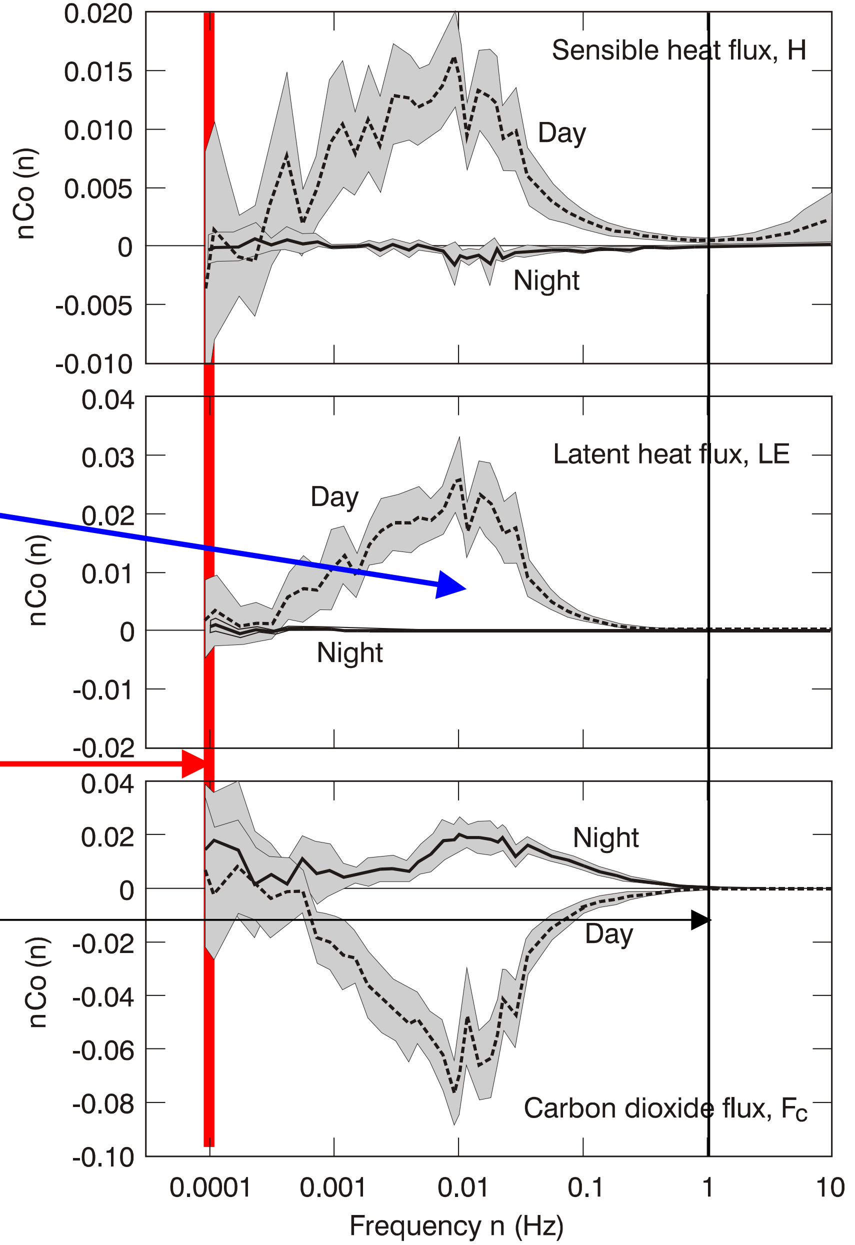


10 Hz typical sampling frequency

# Low Frequency covariance
# - how long should averaging period be?

- Average for long enough so that
  - $\overline{u}$ and $x$ axis are parallel to the ground
  - $z$ is normal to the ground
  - thus can ignore mean advection
- Include all significant low-frequency contributions to the covariance $\overline{w'c'}$
- In deep, convective, non-steady boundary layers, and in complex topography,
  - classic Kaimal Kansas spectra underestimate the low frequency contributions to $\overline{w'c'}$

# Low frequency covariance on a flat site



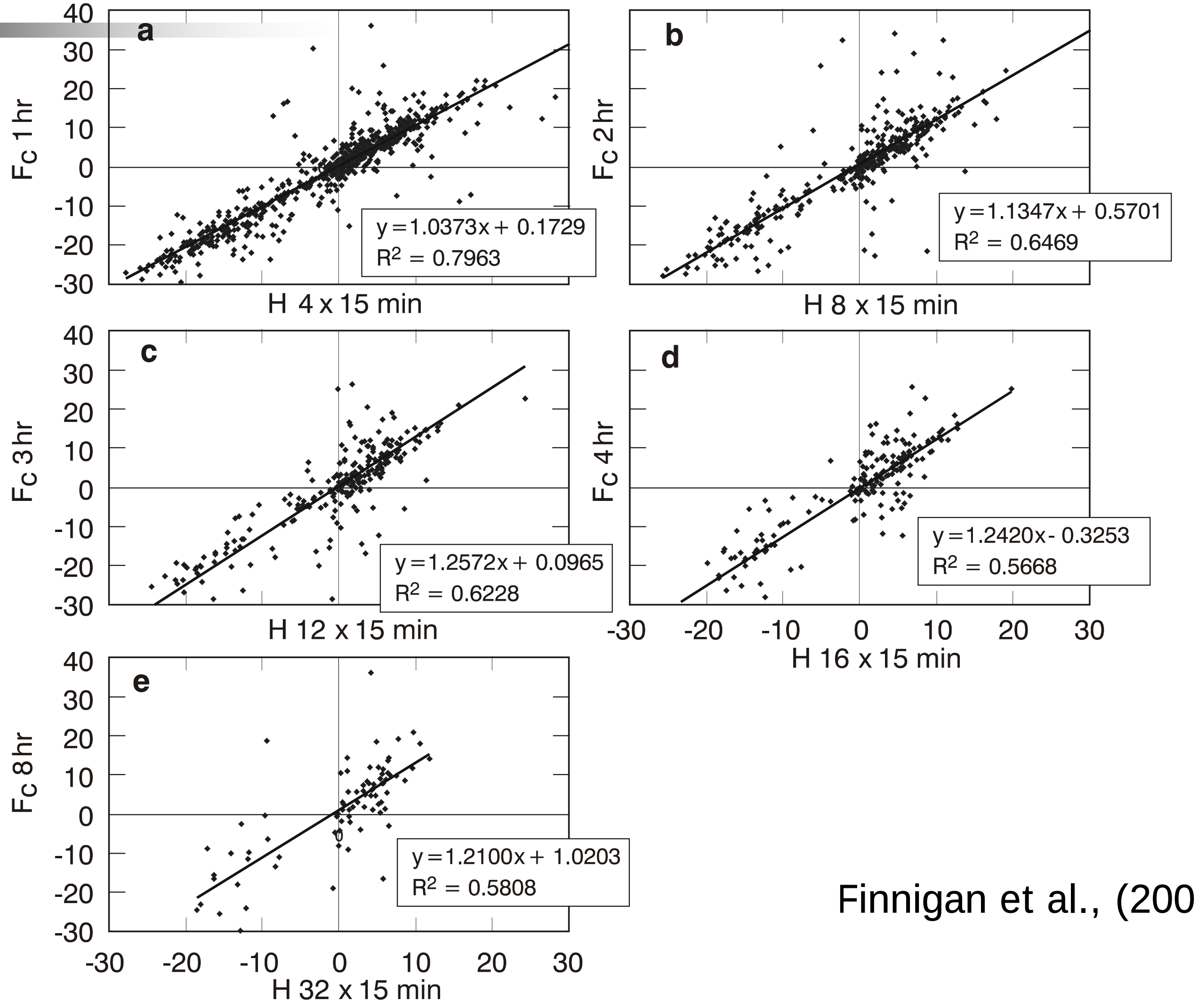
Area under curves is the flux

$$1/\,f_{\min} = 10000\,\mathrm{s} = 2.8\,\mathrm{h}$$

Sampling at 10 Hz is OK here

Finnigan, Clement, Malhi,
Leuning and Cleugh (2001)

# Effect of increasing averaging time on $F_c$

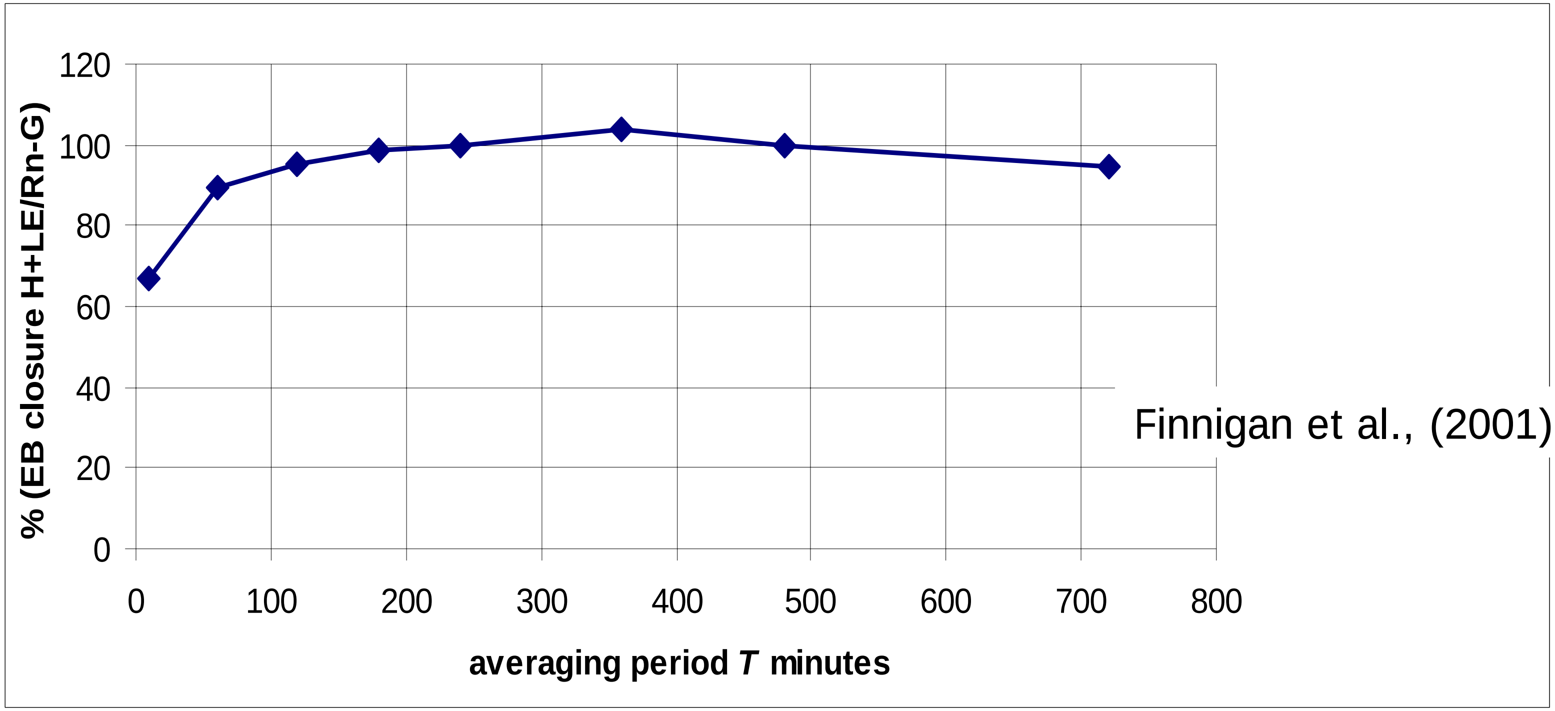


Finnigan et al., (2001)

# Typical averaging periods 30 mins

## May be too short to capture all the significant LF covariance.

- Convective conditions at Manaus tropical forest site ensure significant low frequency content in the covariance.
- This is lost if the averaging-coordinate rotation period is < ~4 hours



Finnigan et al., (2001)

# Summary:1

- The surface boundary layer occupies the lower 10% of the atmospheric boundary layer
- Strong gradients in wind speed, temperature & other scalars in surface boundary layer
- Controlling length scales in surface layer
    - distance to the surface, $z$
    - Obukhov stability parameter, $L$
- Similarity scaling principles apply – log law profiles under neutral conditions
- Stability modifies wind and scalar profiles
- Eddy flux measurements made in surface layer or
- in roughness sublayer (additional length scale needed)

# Summary:2

- Eddy fluxes calculated as covariances in the time domain

  $\overline{u'w'}$ momentum

  $\overline{w'T'}$ heat

  $\overline{w'\chi'}$ scalars

- Spectra and cospectra in the frequency domain

  High frequency sampling rate $f_{required} \geq 10\overline{u}/h$

- Averaging period must be long enough to capture low-frequency contributions to eddy fluxes
- Averaging periods may be >30 mins commonly used, especially over tall vegetation