Introduction to measuring fluxes over land using eddy covariance

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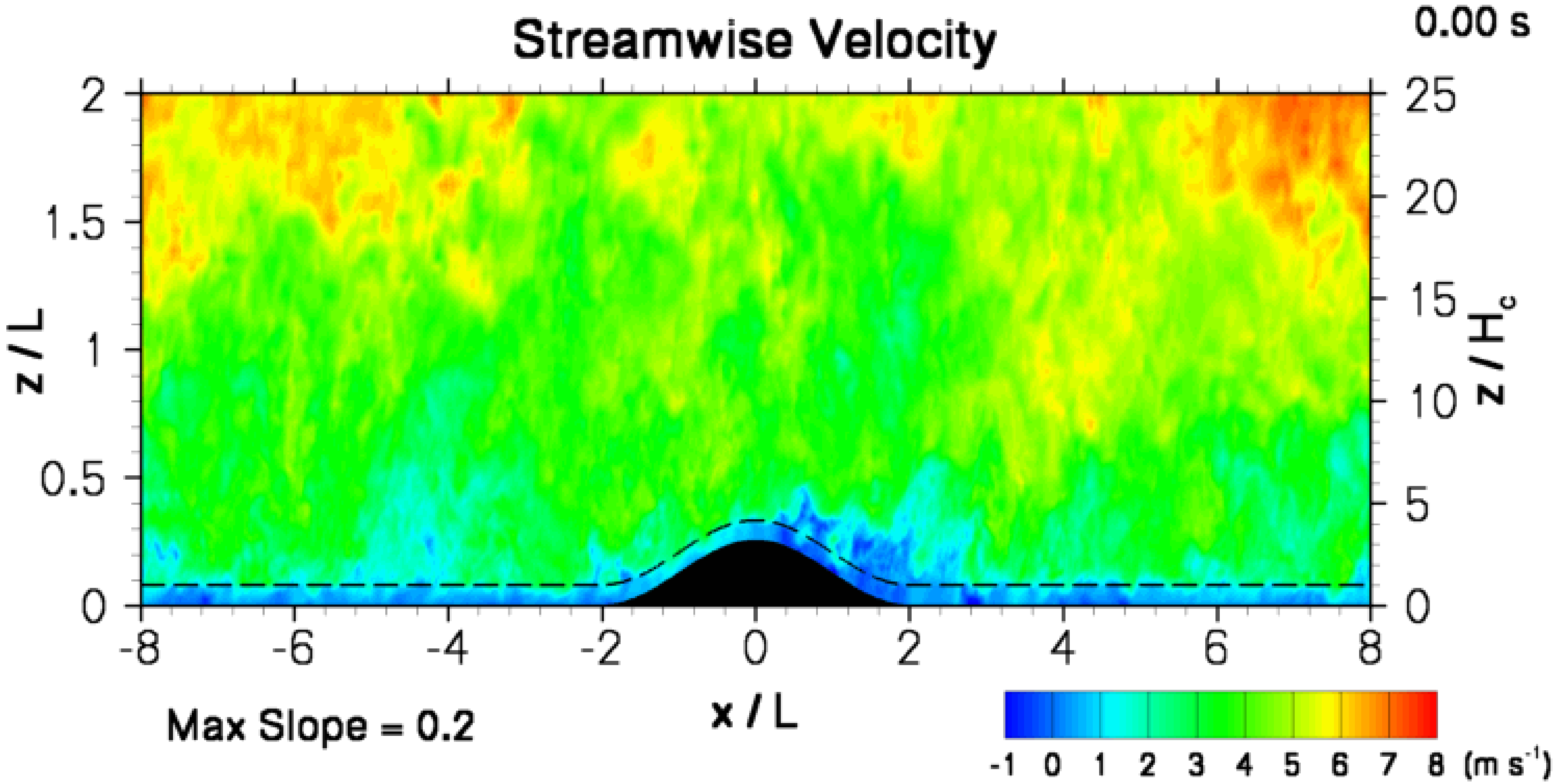
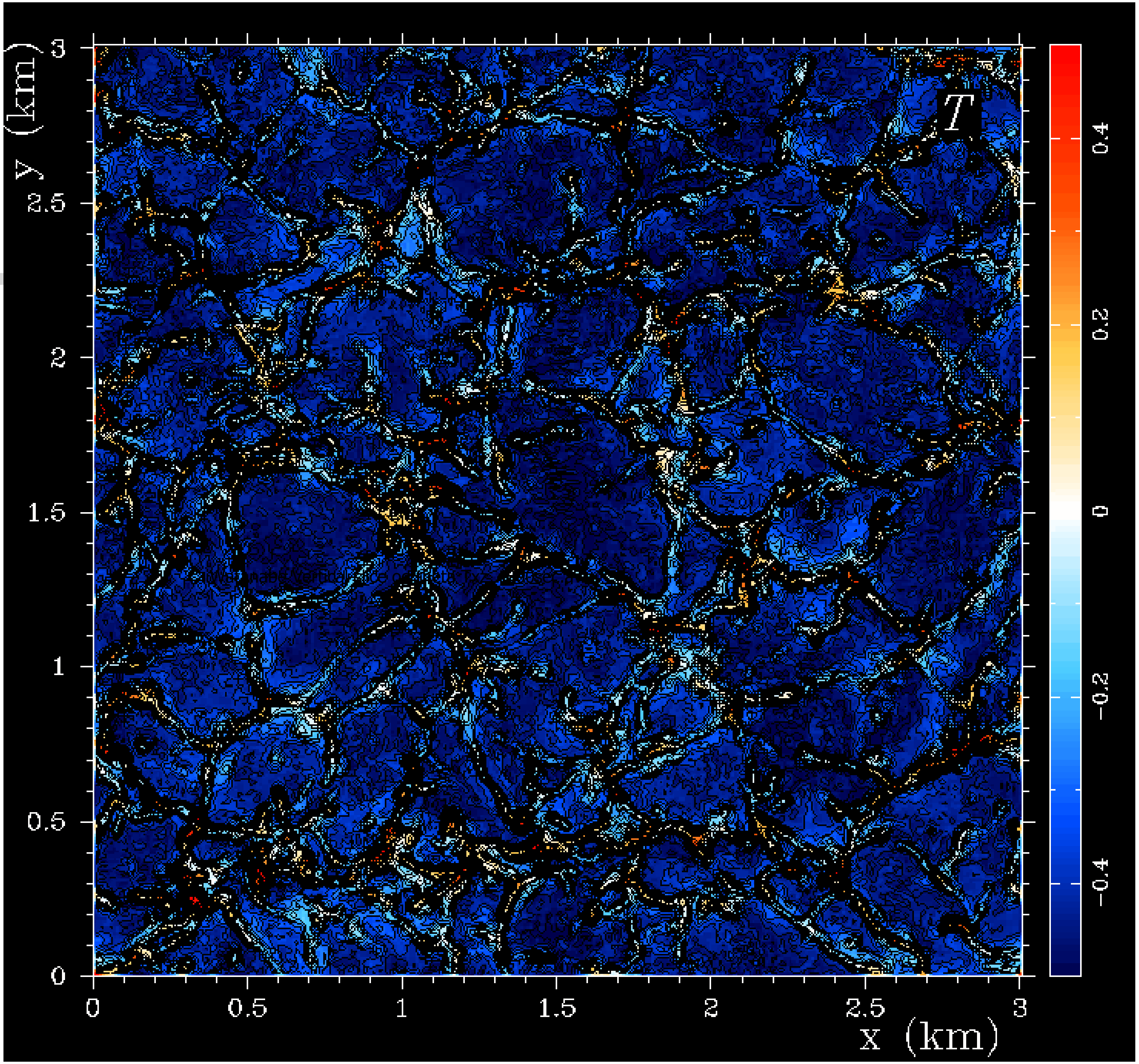
Atmospheric turbulence and air flow



Courtesy Dr Ned Patton, NCAR

Free convection

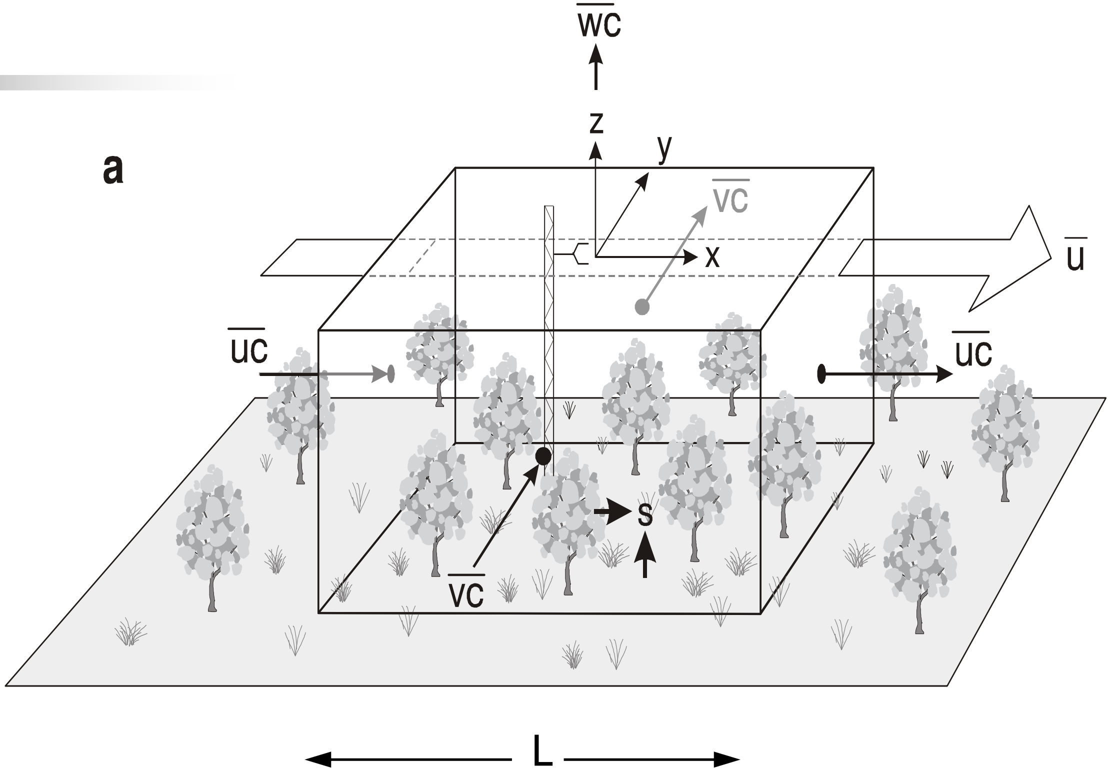
Courtesy of Dr Watenabe



Eddy flux measurement theory

- Mass balance of a control volume
- Time vs spatial averaging concepts
- Time domain
  - Reynolds decomposition & averaging
  - Covariance
  - Coordinate system
  - Flux calculation
- Frequency domain
  - Variance, covariance
  - High-cut filtering
  - High-pass filtering & averaging

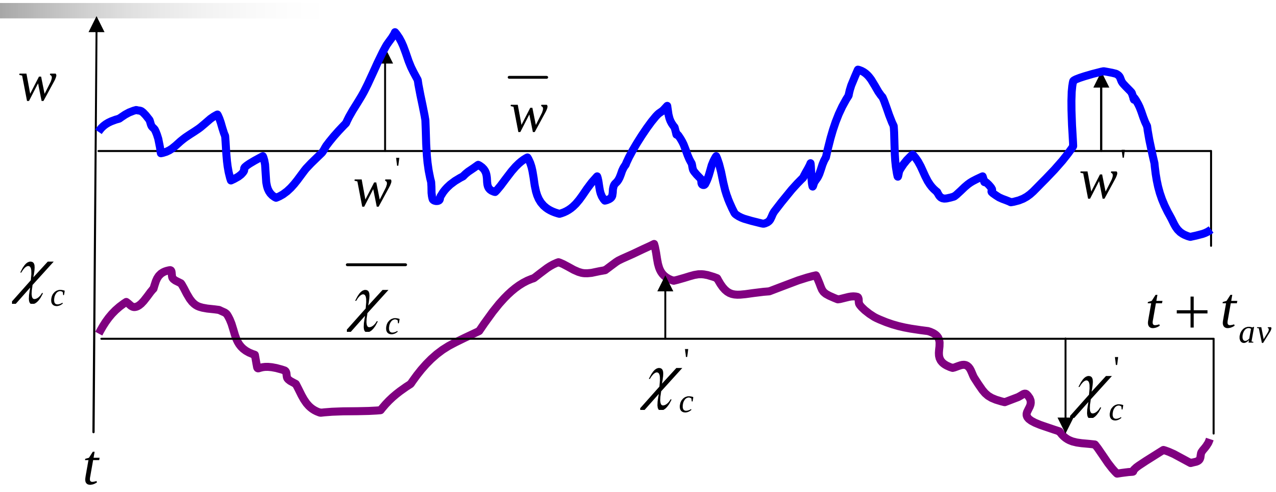
Mass conservation in Control Volume



change in χ = Σ(Flux in) – Σ(Flux out)

Some notation

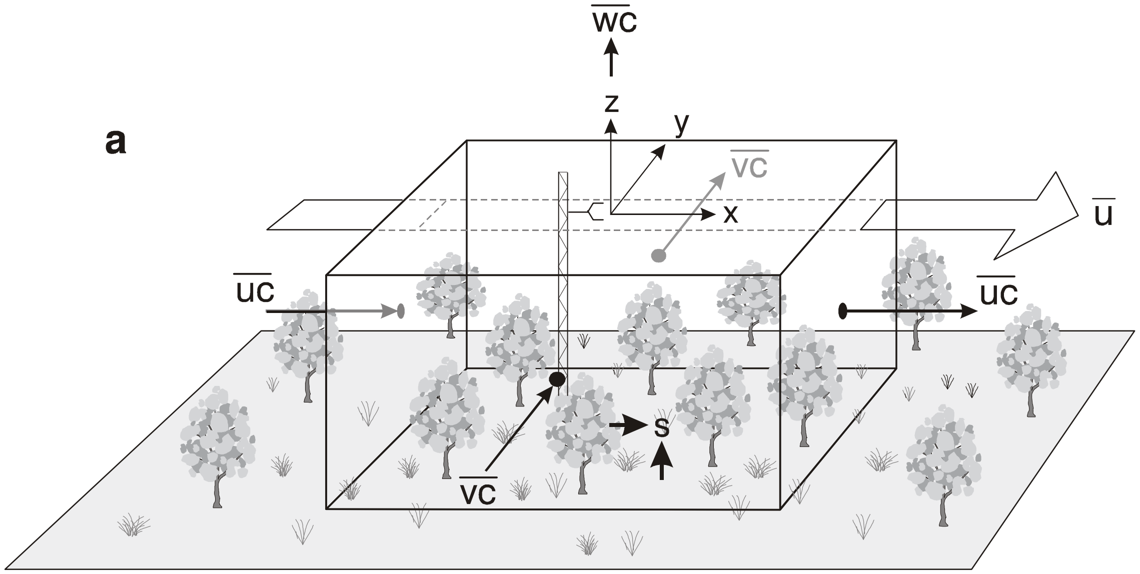
Averaging, Reynolds decomposition & covariance



$$\overline{w} = (1/\Delta t)\int_t^{t+\Delta t} w\,dt \qquad w = \overline{w} + w'$$

$$\overline{w\chi_c} = \overline{(w' - \overline{w})(\chi_c' - \overline{\chi_c})} = \overline{w}\,\overline{\chi_c} + \overline{w'\chi_c'}$$

Mass balance on a control volume



$$\overline{F_0} = \frac{1}{L^2}\int_0^L\int_0^L\int_0^h \overline{c_d}\,\frac{\partial\overline{\chi_c}}{\partial t}\,dxdydz$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\overline{uc_d}\,\frac{\partial\overline{\chi_c}}{\partial x}+\overline{vc_d}\,\frac{\partial\overline{\chi_c}}{\partial y}+\overline{wc_d}\,\frac{\partial\overline{\chi_c}}{\partial z}\right]dxdydz$$

$$+\frac{1}{L^2}\int_0^L\int_0^L\int_0^h \left[\cancel{\frac{\partial\overline{c_d}\,\overline{u'\chi_c'}}{\partial x}}+\cancel{\frac{\partial\overline{c_d}\,\overline{v'\chi_c'}}{\partial y}}+\frac{\partial\overline{c_d}\,\overline{w'\chi_c'}}{\partial z}\right]dxdydz$$

Coordinate system

- Have used rectangular Cartesian coordinates
- Can rarely measure all components of mass balance. To maximize information at tower choose site and coordinate system to ensure:

$$\int_{S_1} \overline{u\chi_c}\, dS_1 = \int_{S_1} \overline{u\chi_c}\, dS_2$$

Horizontal homogeneity – no advection

$$\overline{v} = \overline{w} = 0$$

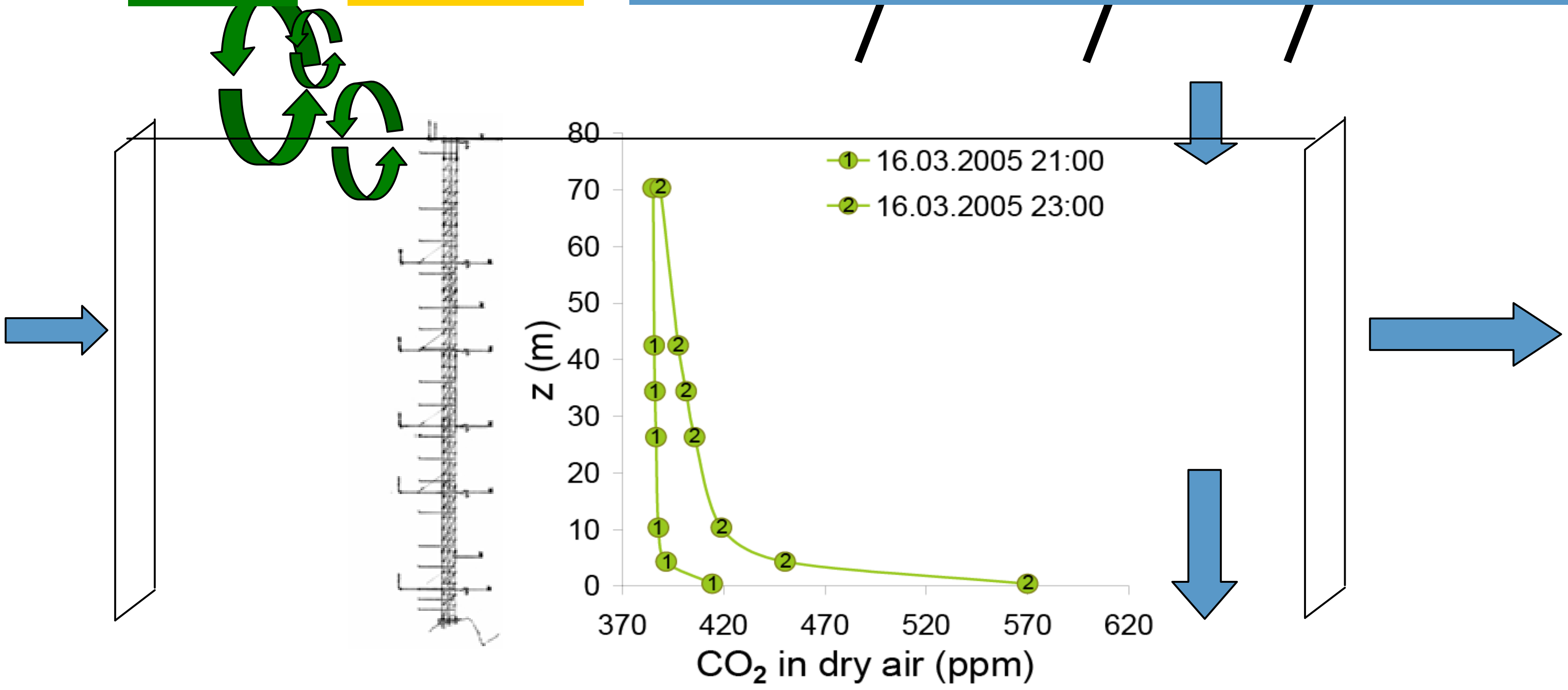
Coordinate rotation
(a topic in itself)

$$\overline{w\chi_c} = \overline{w}\,\overline{\chi_c} + \overline{w'\chi_c'} = \overline{w'\chi_c'}$$

Leaves only vertical eddy flux

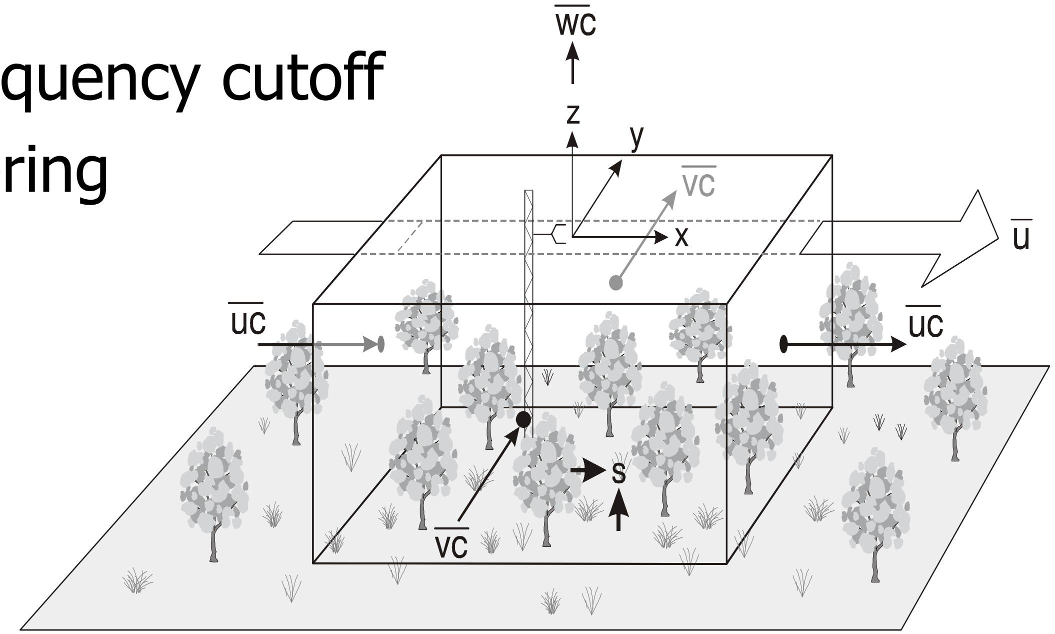
Horizontally homogeneous flow

$$F_c = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^h \overline{c_d}\frac{\partial\overline{\chi_c}}{\partial t}dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^h\left[\cancel{\overline{uc_d}\frac{\partial\overline{\chi_c}}{\partial x}}+\cancel{\overline{vc_d}\frac{\partial\overline{\chi_c}}{\partial y}}+\cancel{\overline{wc_d}\frac{\partial\overline{\chi_c}}{\partial z}}\right]dx\,dy\,dz$$



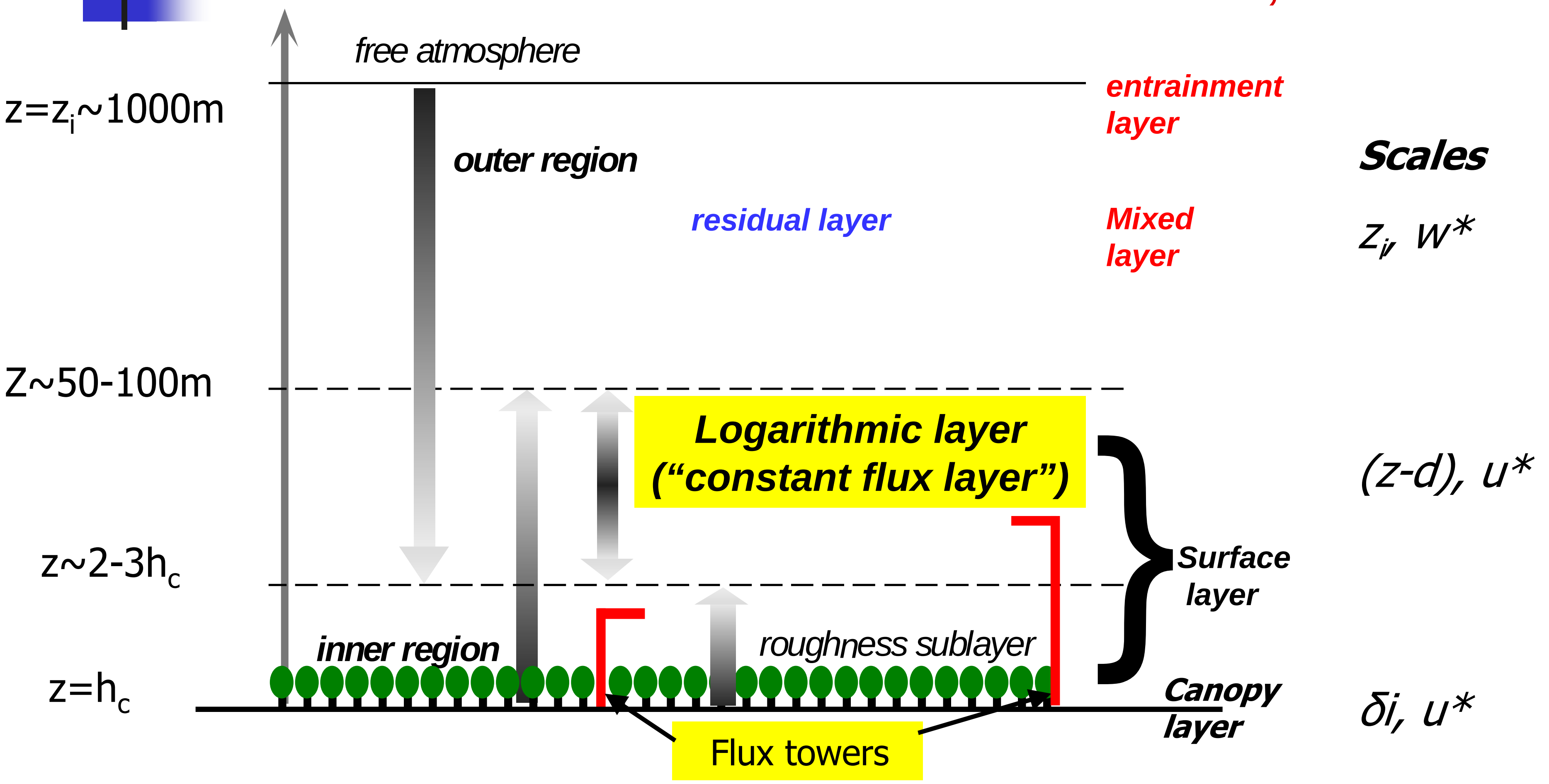
Design considerations for eddy flux measurements

- Measurement height
- Fetch/footprint - rule of thumb $z_m = x/100$
- Horizontal homogeneity of surface and topography
- Averaging – low frequency cutoff
- High frequency filtering



Layers and controlling scales of the ABL

Sublayers



neutral, weakly stable

unstable, convective

free atmosphere

$z=z_i$~1000m

outer region

entrainment layer

Scales

residual layer

Mixed layer

z_i, $w*$

Z~50-100m

Logarithmic layer (“constant flux layer”)

$(z\text{-}d)$, $u*$

z~2-3h_c

Surface layer

inner region

roughness sublayer

$z=h_c$

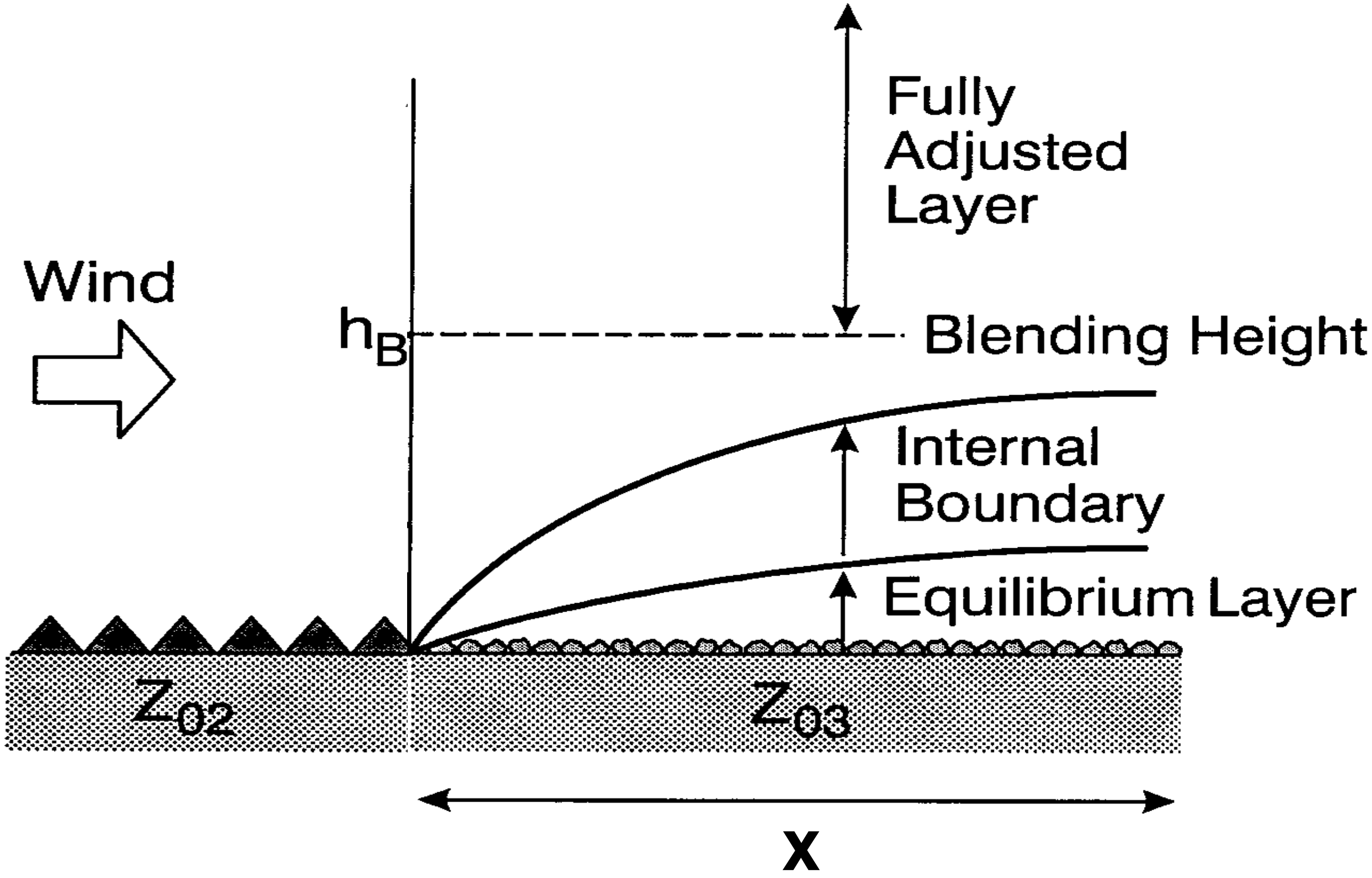
Canopy layer

δi, $u*$

Flux towers

Courtesy Prof HP Schmid
Indiana University

Internal boundary & equilibrium layers



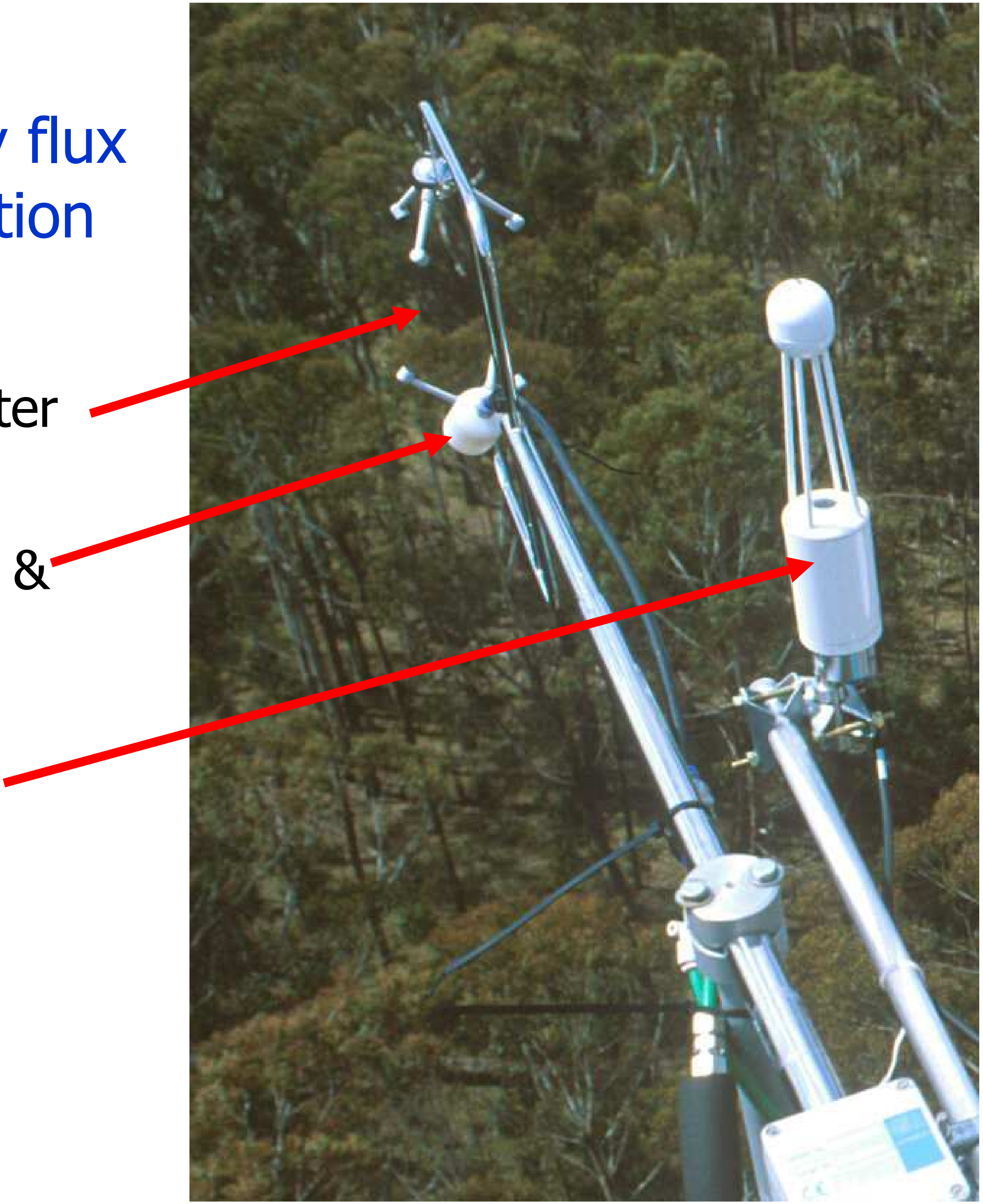
Height-to-fetch ratio

- **100:1 fetch rule of thumb**
  - Neutral conditions
  - > for stable conditions
  - < for unstable conditions

$$z_m \leq X/100$$

- **Instrument placement**
  - Often a compromise between a representative footprint and avoiding advective effects

Typical eddy flux instrumentation



Sonic anemometer

Air intake for closed-path CO_2 & H_2O analyser

Open-path CO_2 & H_2O analyser

High frequency attenuation

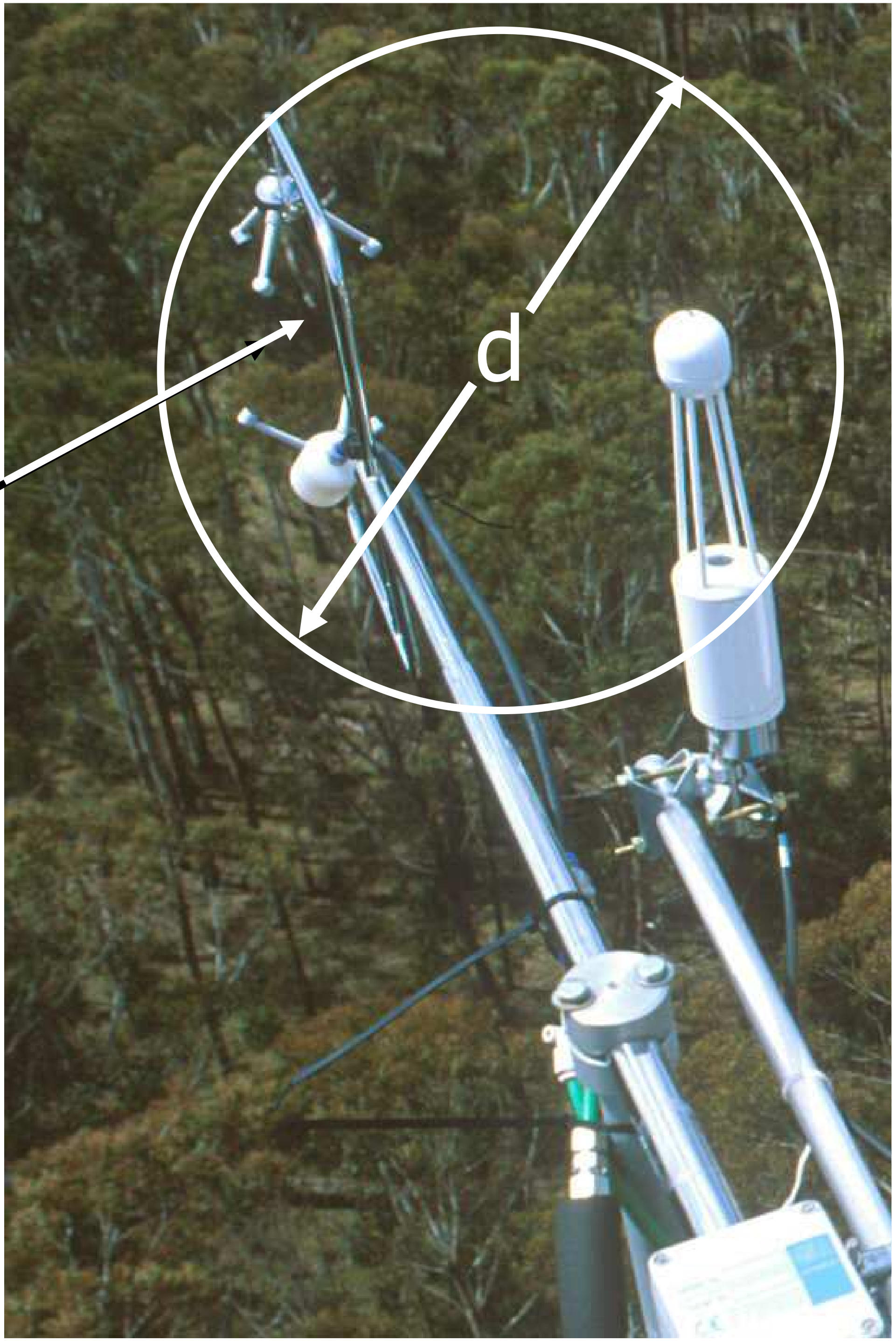
Line-averaging along instrument path

  – loss of variance

Spatial separation between instruments

  – loss of covariance

  - Samples eddies > ~2d



Frequency domain
- variance and covariance

Variance

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

Covariance

= eddy flux

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

⇧ Time domain

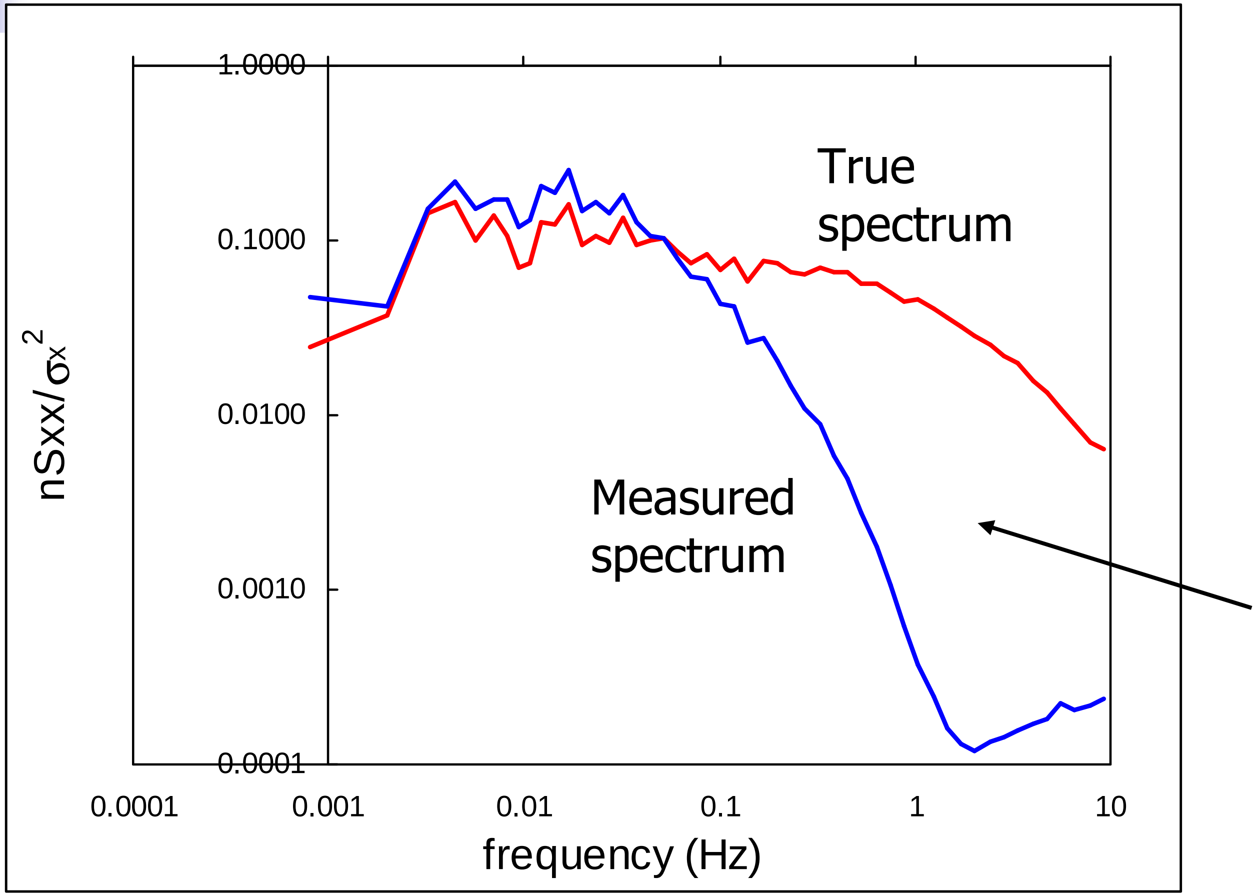
⇧ Frequency domain

$S_{\chi c}$ = contribution of the total variance of χ_c per unit *dn*

$C_{w\chi c}$ = contribution of total covariance of $w\chi_c$ per unit *dn*

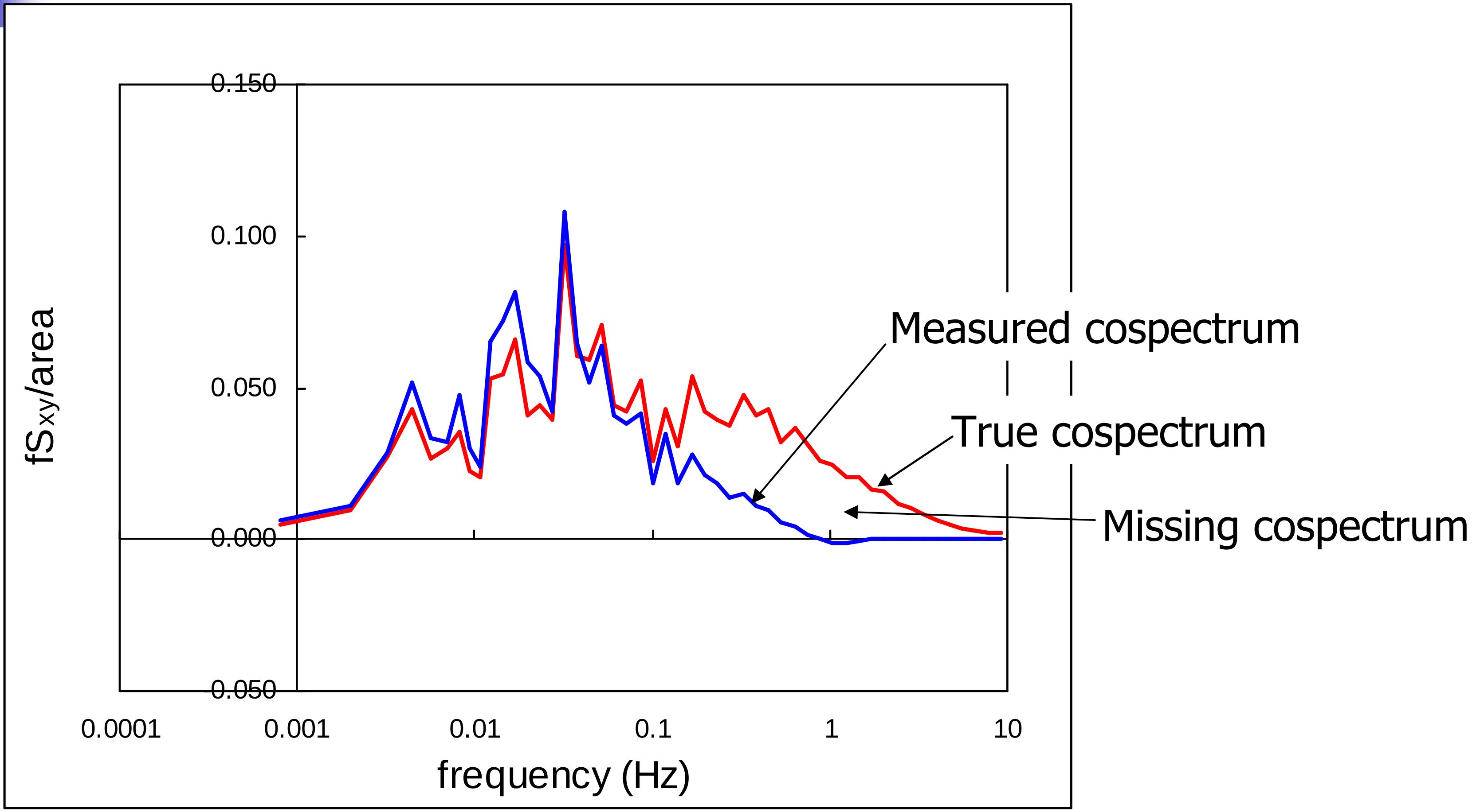
Approximation because calculations are over a finite time interval *dt*

Variance spectrum - high-cut filter

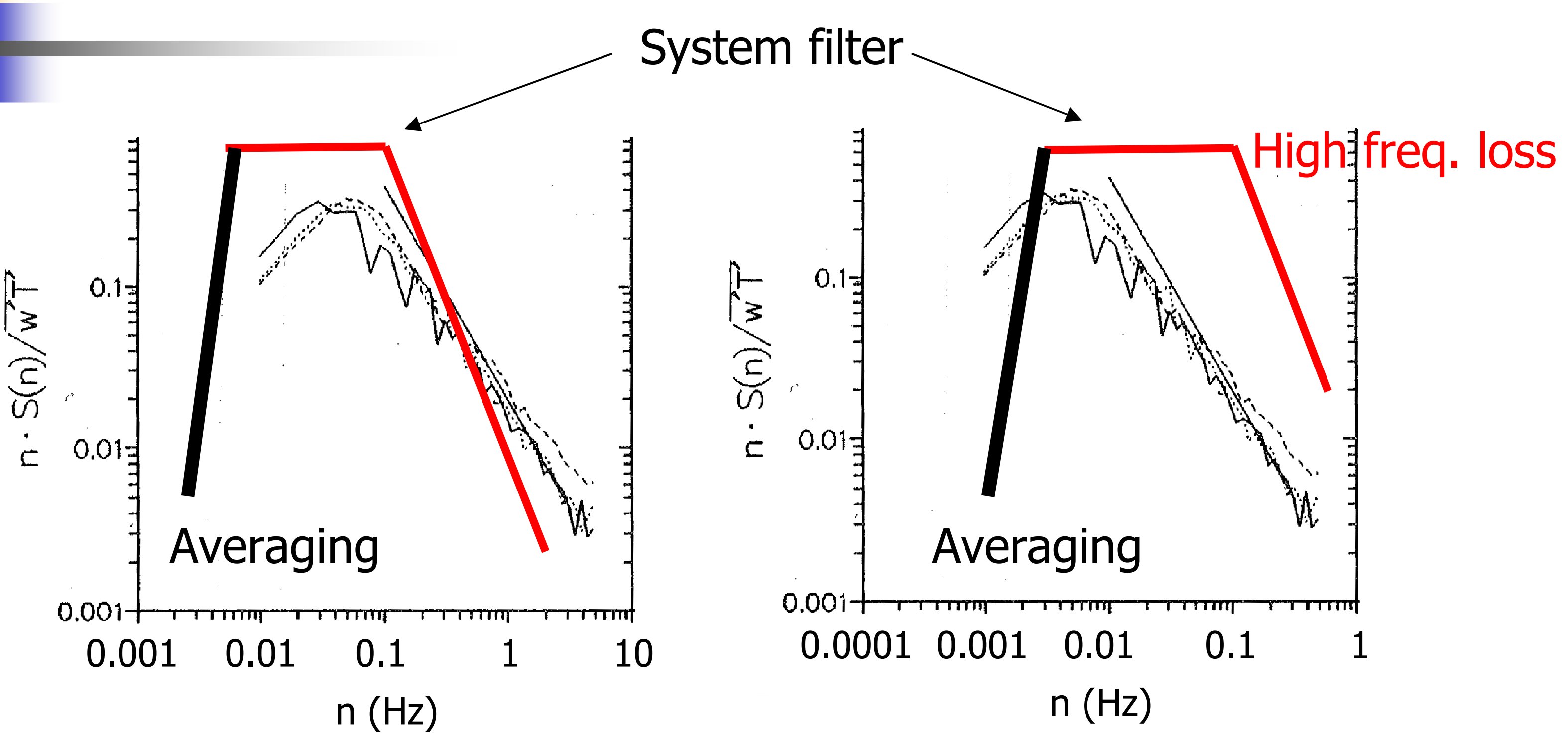


Missing spectral response

Covariance spectrum – high cut filter



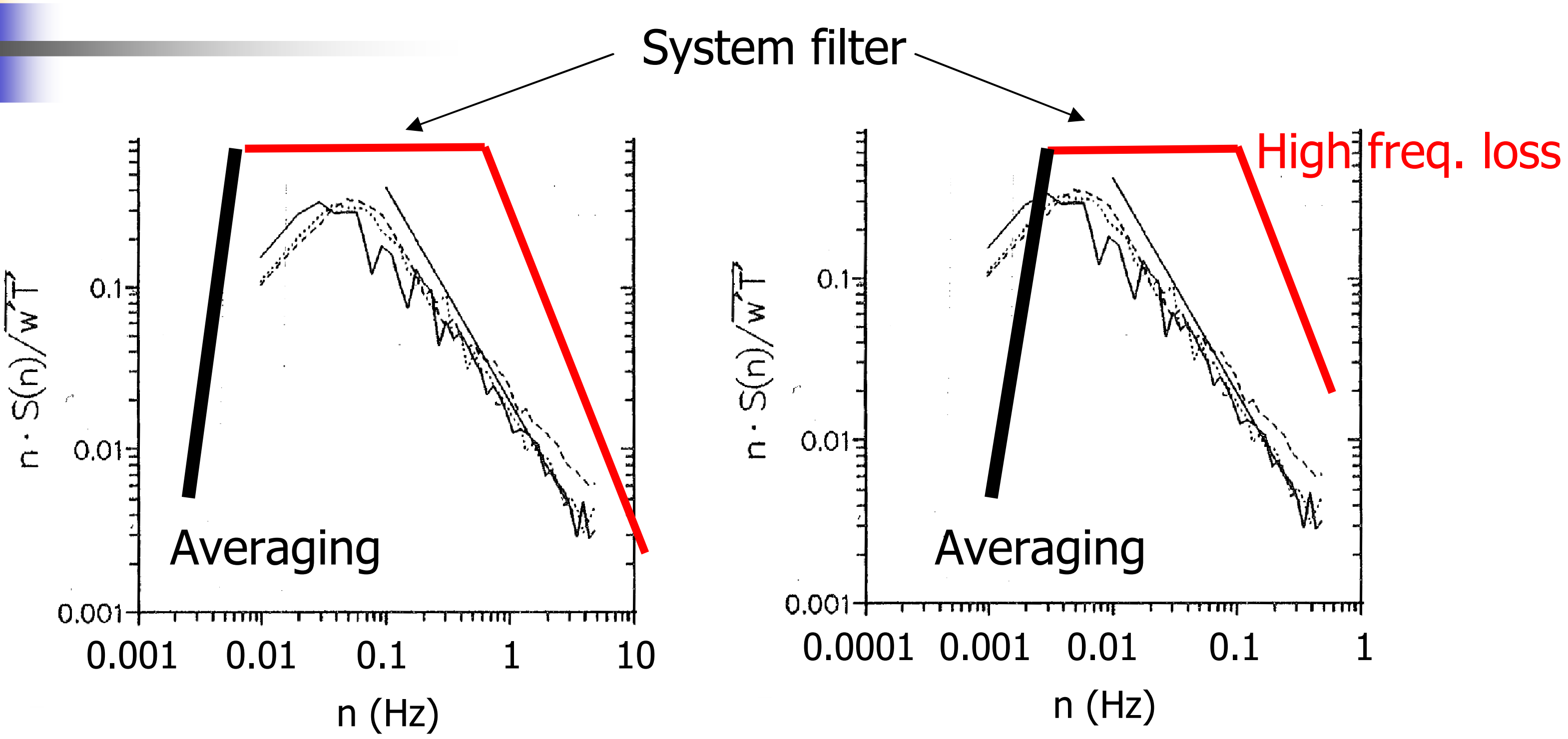
Frequency scaling & high frequency filtering



1/10 x freq. scale

z = 1 m → z = 10 m

Frequency scaling & high frequency filtering

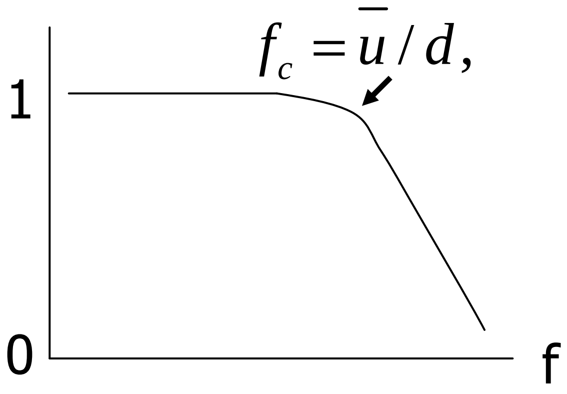


$u = 10 \text{ m s}^{-1}$ ← $u = 1 \text{ m s}^{-1}$

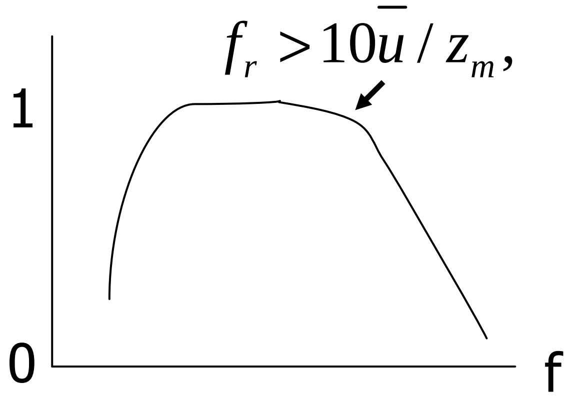
10 x freq. scale

Measurement height

- System filter
- Atmospheric turbulence



$$\geq$$



$$f_c \geq f_r \quad \rightarrow \quad z_m \geq 10d$$

Remember equilibrium layer

$$z_m \leq X/100$$

Low Frequency covariance

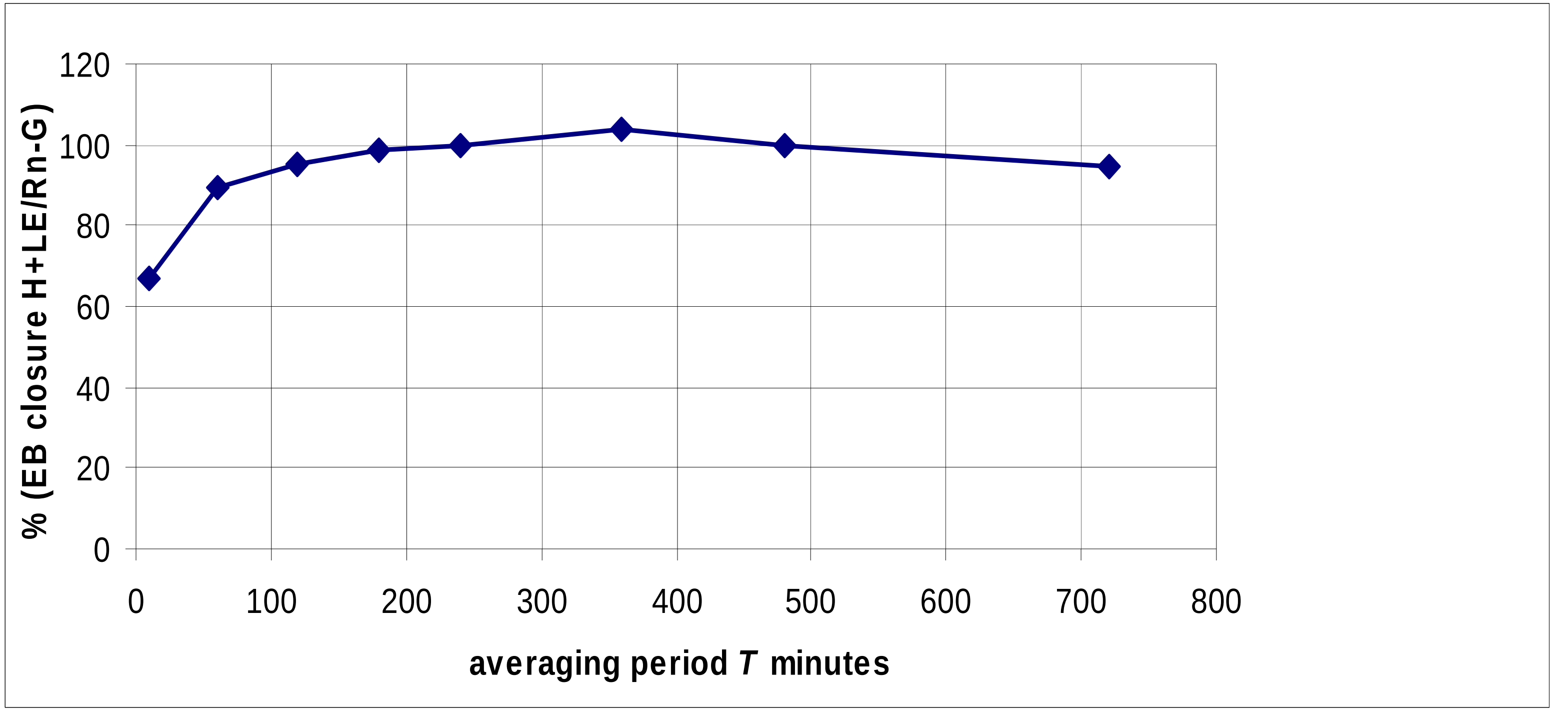
- Average for long enough to
  - include all significant low-frequency contributions to the covariance
- Averaging period increases with
  - measurement height
  - free convection (unstable boundary layers)
  - complex topography

Typical averaging periods 30 mins

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

Finnigan et al., (2001)

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

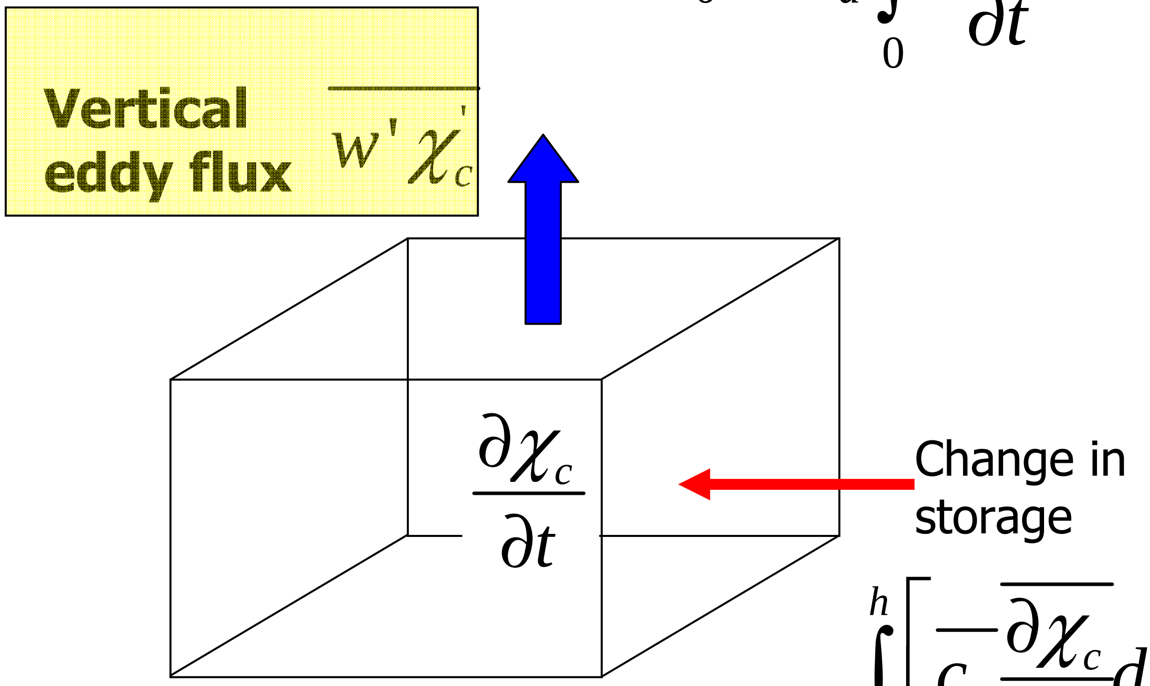


From theory to measurements

- Eddy fluxes
  - System design
  - Webb, Pearman & Leuning theory
    - Sonic anemometers
    - Open-path gas analysers
    - Closed-path gas analysers
- Change in heat & mass storage in canopy
  - Temperature profiles
- Other flux station instrumentation
- Checking energy balance closure

Measurements on a single tower

$$\overline{F_0} = \overline{c_d}\int_0^h \overline{\frac{\partial \chi_c}{\partial t}}dz + \overline{c_d}\,\overline{w^{'}\chi_c^{'}}$$



Vertical eddy flux $\overline{w'\chi_c'}$

$$\frac{\partial \chi_c}{\partial t}$$

Change in storage

$$\int_0^h \left[\overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}dt\right]dz$$

Sonic anemometer gives:

$$\overline{u}, \overline{v}, \overline{w} \quad u', v', w'$$

$$H = \rho \overline{c}_{pd} \overline{w' T_v'}$$

Where sonic virtual temperature is

$$T_v = T(1 + 0.514q)$$

Still require

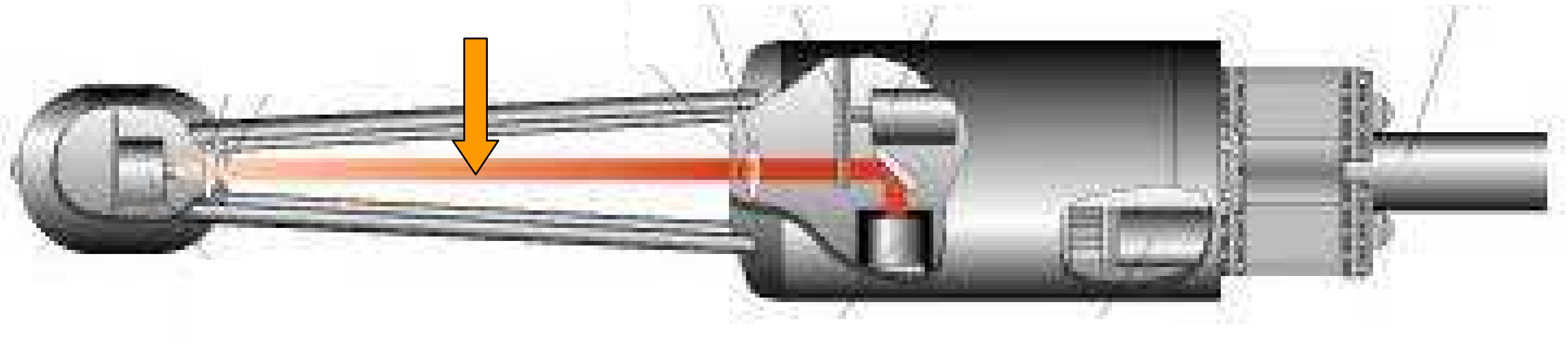
$$\lambda E = \lambda \overline{c}_d \overline{w' \chi_v'}$$

$$F_c = \overline{c}_d \overline{w' \chi_c'}$$

LI-7500 CO_2 and water vapour analyser

Measures mol m^{-3} in optical path,

not required mixing ratios χ_v χ_c



But! Eddy fluxes have been expressed in terms of mixing ratio. What to do?

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

Webb, Pearman & Leuning (1980) theory Steady state, horiz. homogeneous flow

Can write trace gas flux using concentrations

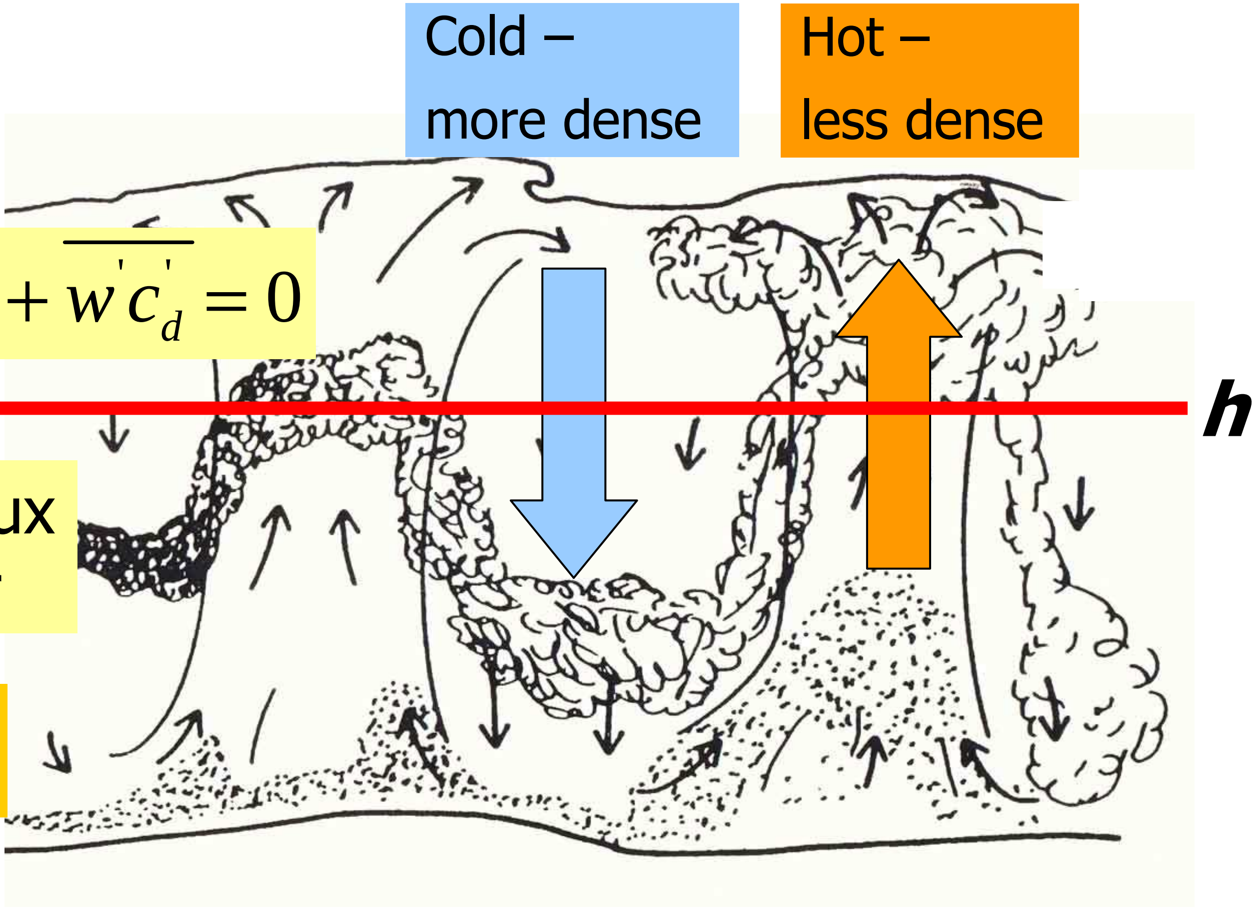
$\overline{F_c} = \overline{c_d}\,\overline{w'\chi_c'} \equiv \overline{wc_c} = \overline{w}\,\overline{c_c} + \overline{w'c_c'}$ **but** $\overline{w} \neq 0$

What is $\overline{w}$? WPL assumed no net flux of dry air

$$\overline{F_d} = 0 = \overline{w}\,\overline{c_d} + \overline{w'c_d'} \quad \Longrightarrow \quad \boxed{\overline{w} = -\overline{w'c_d'}\,/\,\overline{c_d}}$$

Why is there a $\overline{w}$?

Consider 'hot' and 'cold' eddies over dry surface



$$\overline{F_d} = \overline{w c_d} = \overline{w}\,\overline{c_d} + \overline{w' c_d'} = 0$$

No net flux of dry air

$$\overline{w} = -\overline{w' c_d'} \,/\, \overline{c_d}$$

WPL theory

$$\overline{w} = -\overline{w'c_d'}\ /\ \overline{c_d}$$

Need expression for c_d'

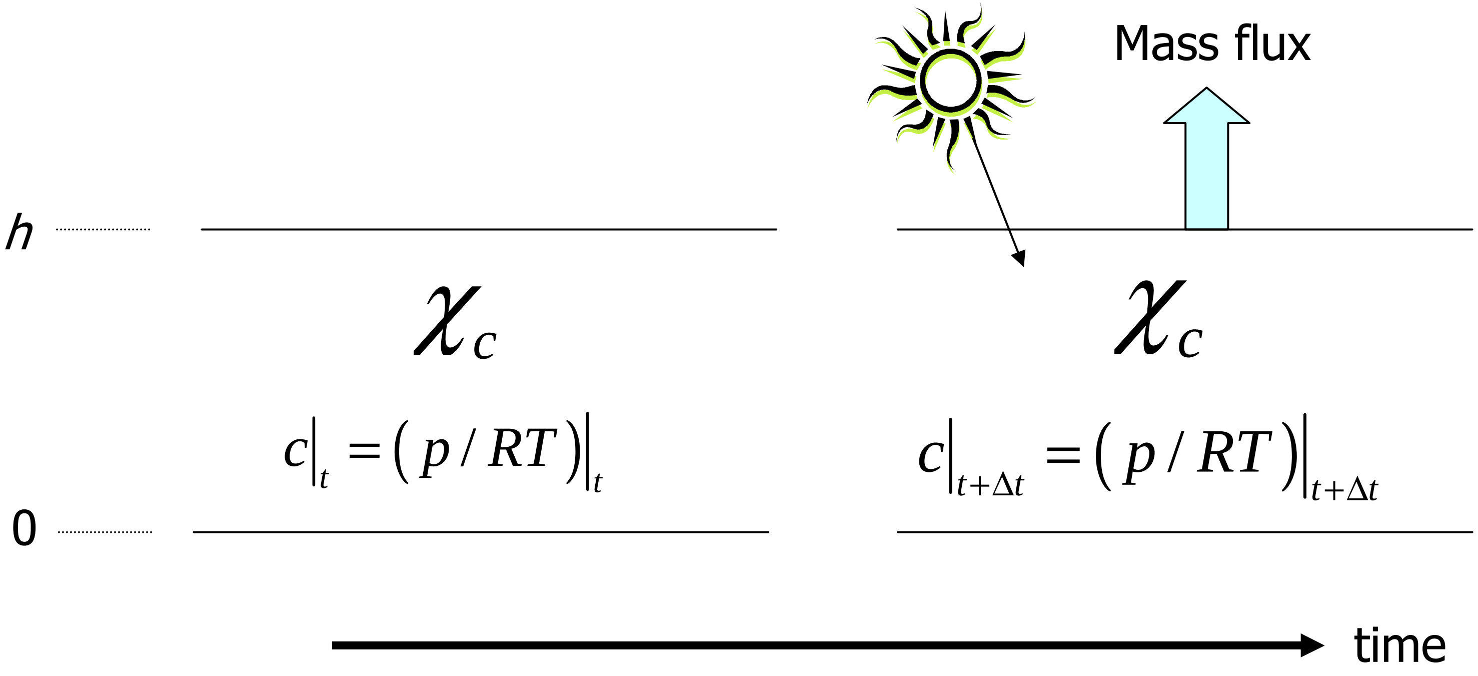
WPL showed

$$\overline{w} = \frac{1}{\overline{c}_d}\left[\underbrace{\overline{w'c_v'}}_{\text{Water vapor flux}} + \overline{c}\,\underbrace{\frac{\overline{w'T'}}{\overline{T}}}_{\text{Heat flux}}\right]$$

$< 3\ \mathrm{mm\,s^{-1}}$

Cannot measure $\overline{w}$ directly

What about non-steady state, horizontally homogeneous flow?



$$\chi_c$$

$$c\big|_t = (p/RT)\big|_t$$

$$\chi_c$$

$$c\big|_{t+\Delta t} = (p/RT)\big|_{t+\Delta t}$$

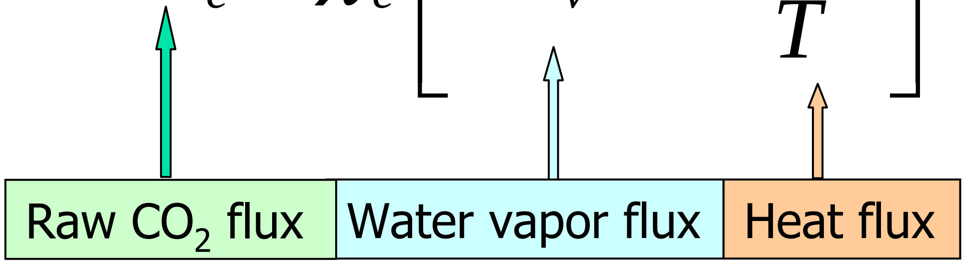
Change in concentration, but not mixing ratio

Eddy flux for trace gas

Leuning (2007) showed original WPL still correct

- No source/sink of dry air in the control volume

$$\overline{F_c} = \bar{c}_d\,\overline{w'\chi_c'} = \overline{w'c_c'} + \overline{\chi_c}\left[\overline{w'c_v'} + \bar{c}\,\frac{\overline{w'T'}}{\overline{T}}\right]$$

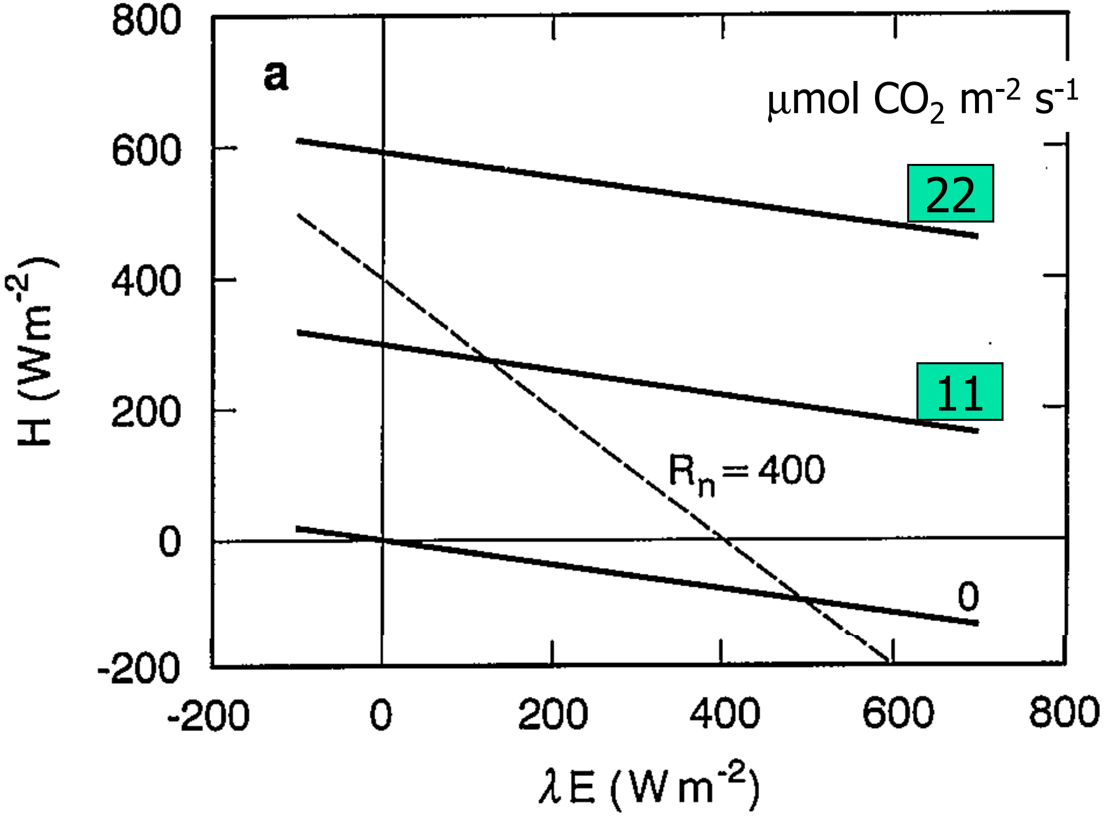


Raw CO_2 flux

Water vapor flux

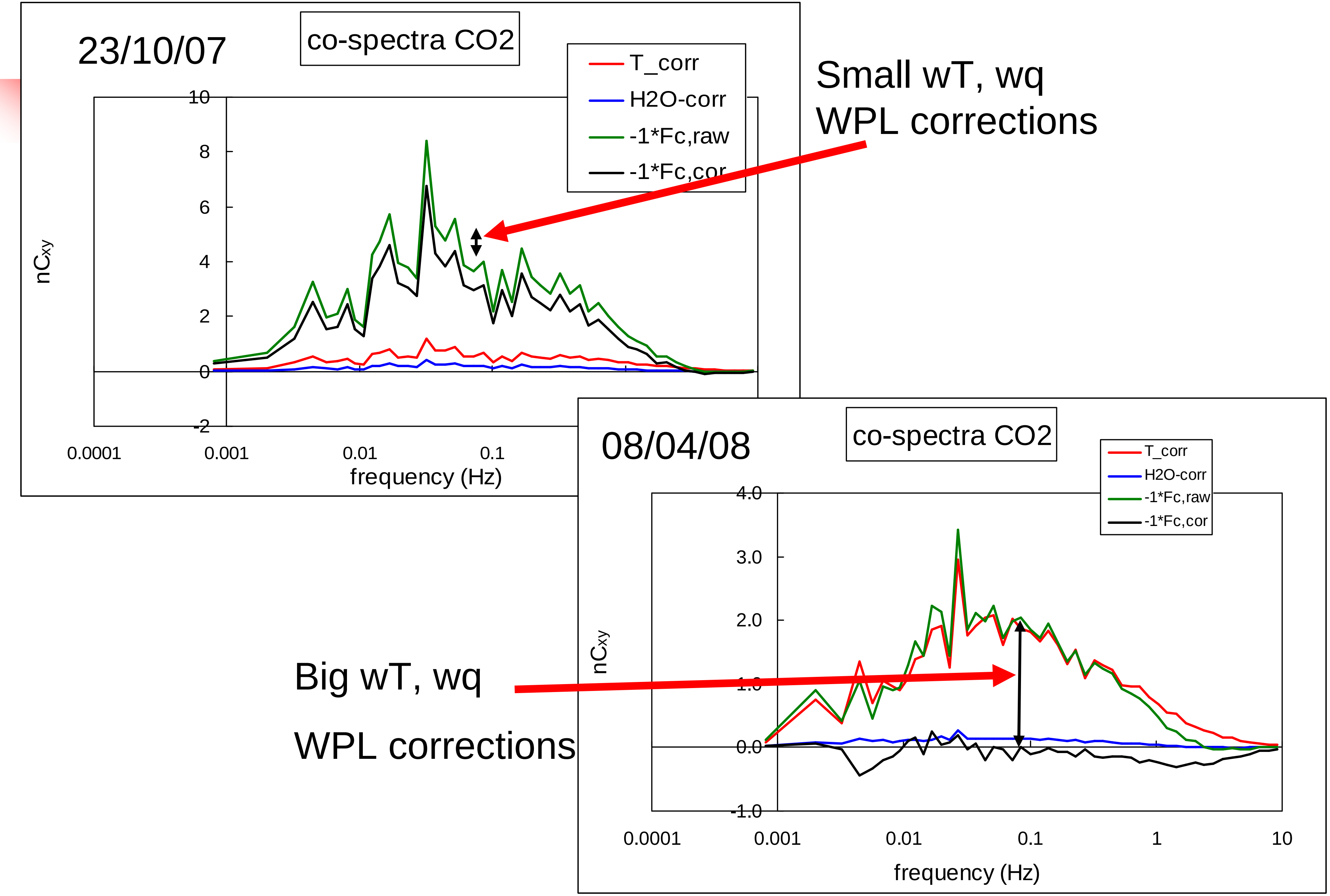
Heat flux

Magnitude of WPL corrections – add to raw flux



Leuning & Judd, 1996

WPL corrections to open path



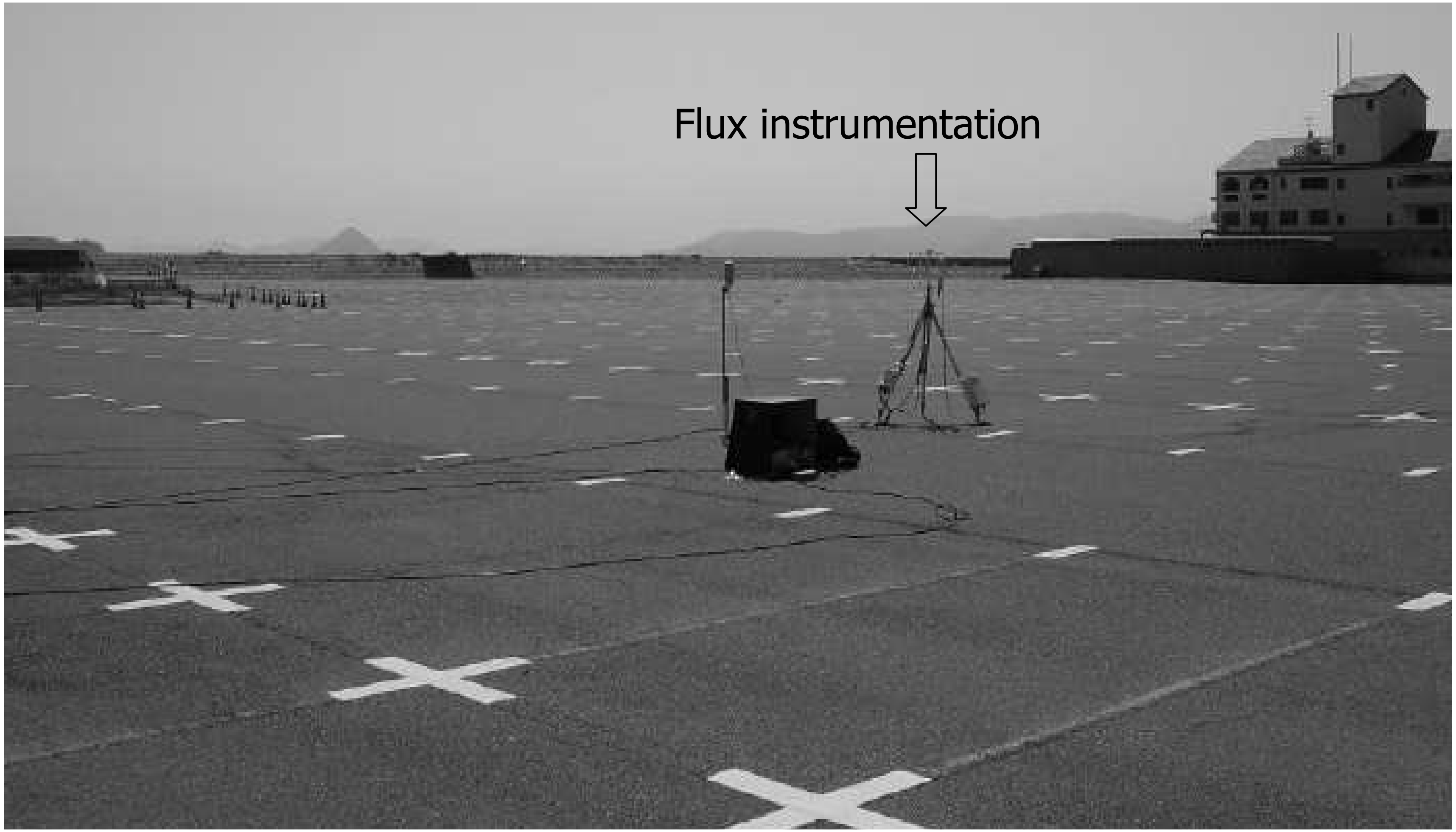
Small wT, wq
WPL corrections

Big wT, wq

WPL corrections

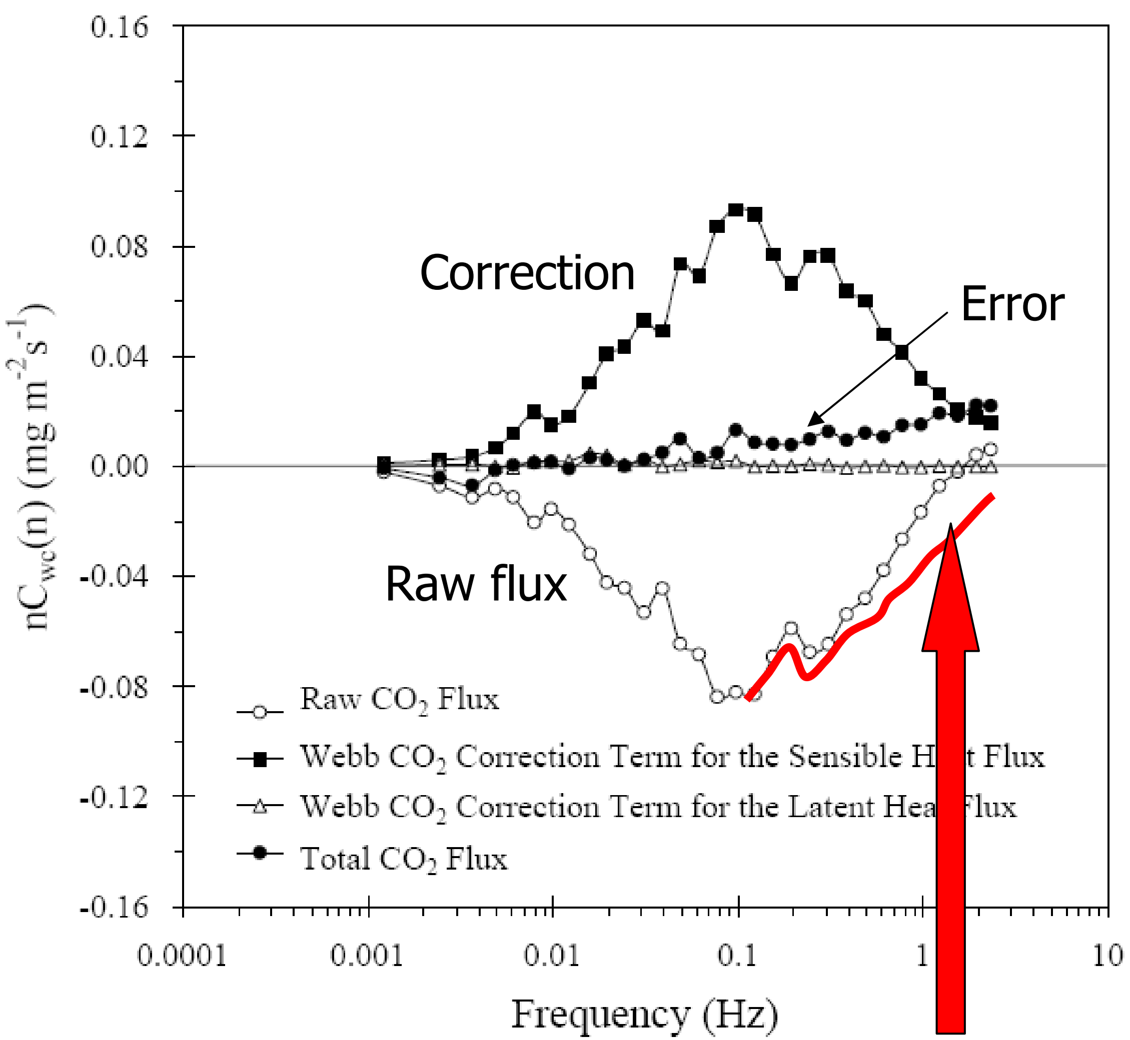
Testing Webb Pearman & Leuning 2007 – zero CO_2 flux over a tarmac

Kondo and Tsukamoto (pers comm)



Cospectra

Error due to differing frequency responses for cospectra of wT and wc_c



Need to correct for loss of covariance before WPL correction

Frequency Response Corrections

Define correction factor

$$C_F = \frac{\int_0^\infty C_{wc}(f)df}{\int_0^\infty G_{wc}(f)C_{wc}(f)df}$$

‘true’ cospectrum

filtered cospectrum

filter function

$C_F > 1$, typically

(Leuning and Moncrieff, 1990; Leuning & Judd 1996)

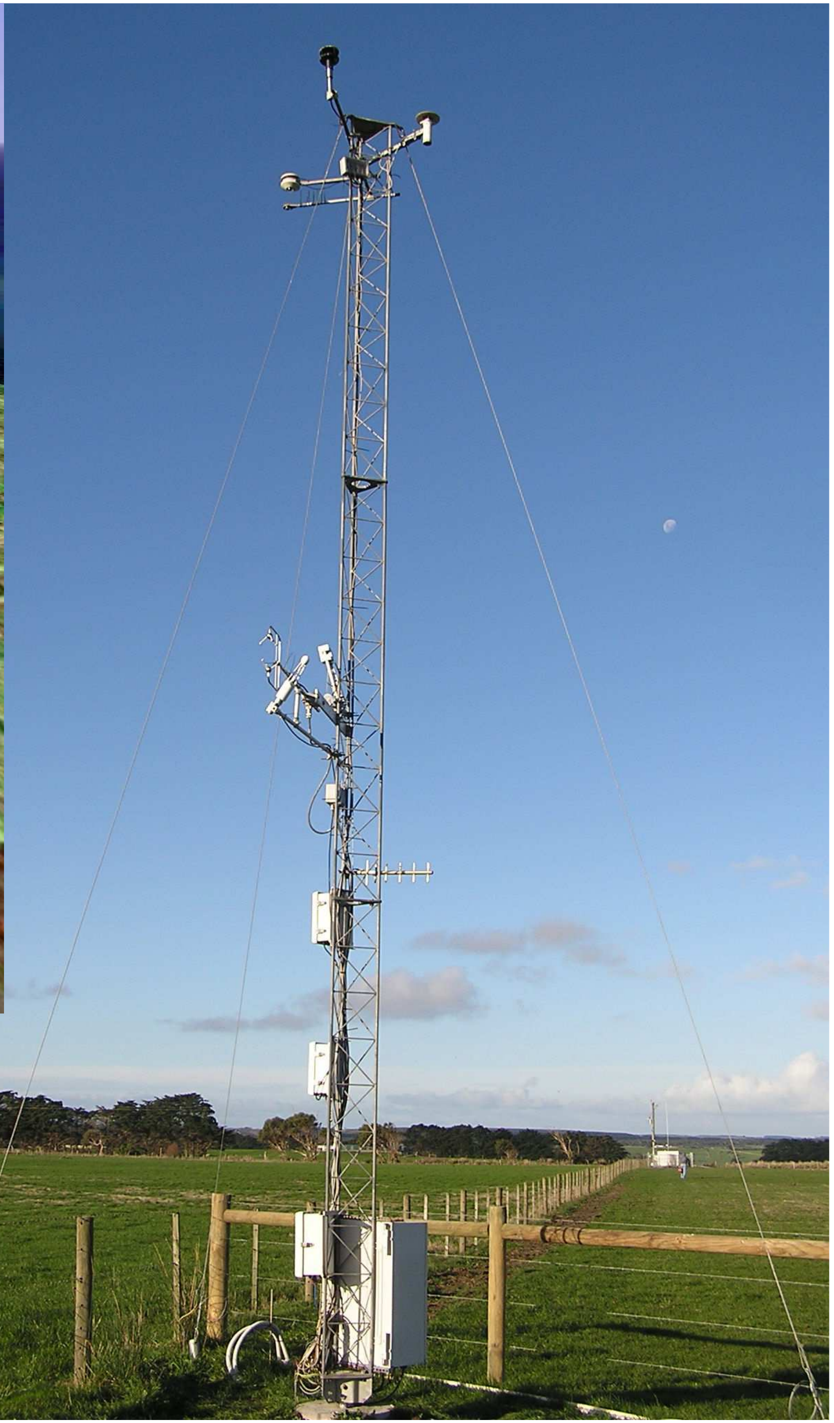
Open path measurements – calculation sequence

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

2) $$\overline{E} = (1+\overline{\chi}_v)\left[\overline{w'c_v'} + \frac{\overline{c}_v}{\overline{T}}\frac{\overline{H}}{\overline{\rho} c_p}\right]$$

3) $$\overline{F}_c = \overline{w'c_c'} + \overline{c}_c\left[\frac{\overline{E}}{\overline{c}} + \frac{\overline{H}}{\overline{\rho}\, c_p \overline{T}}\right]$$

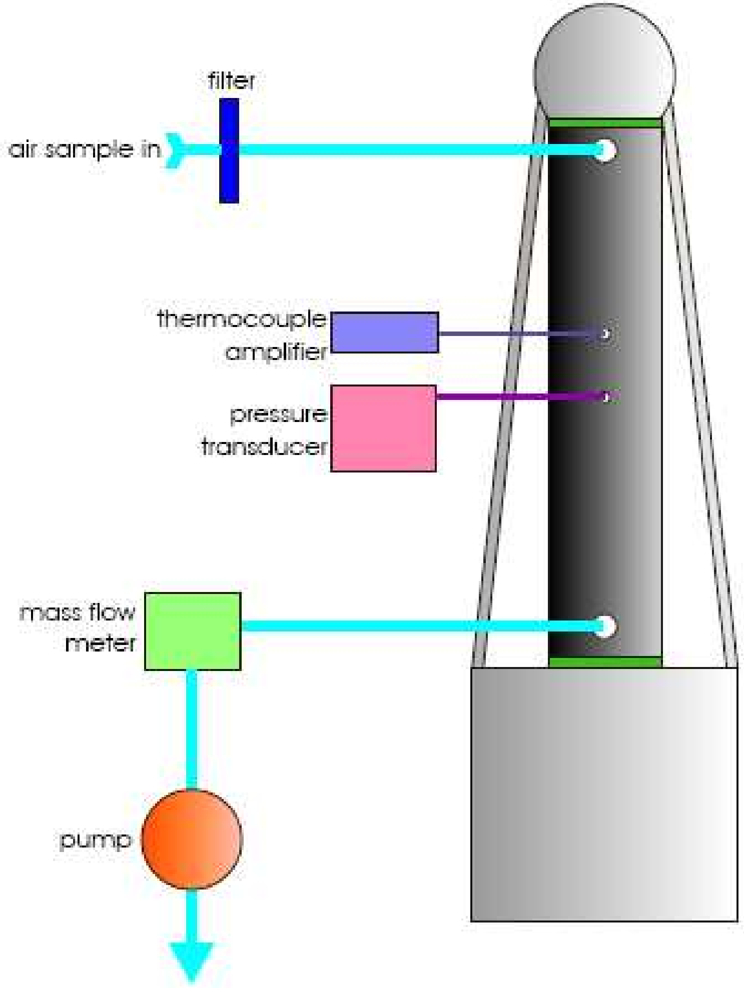
Assumes *H*, *E* & F_c have already been corrected for high & low frequency filtering



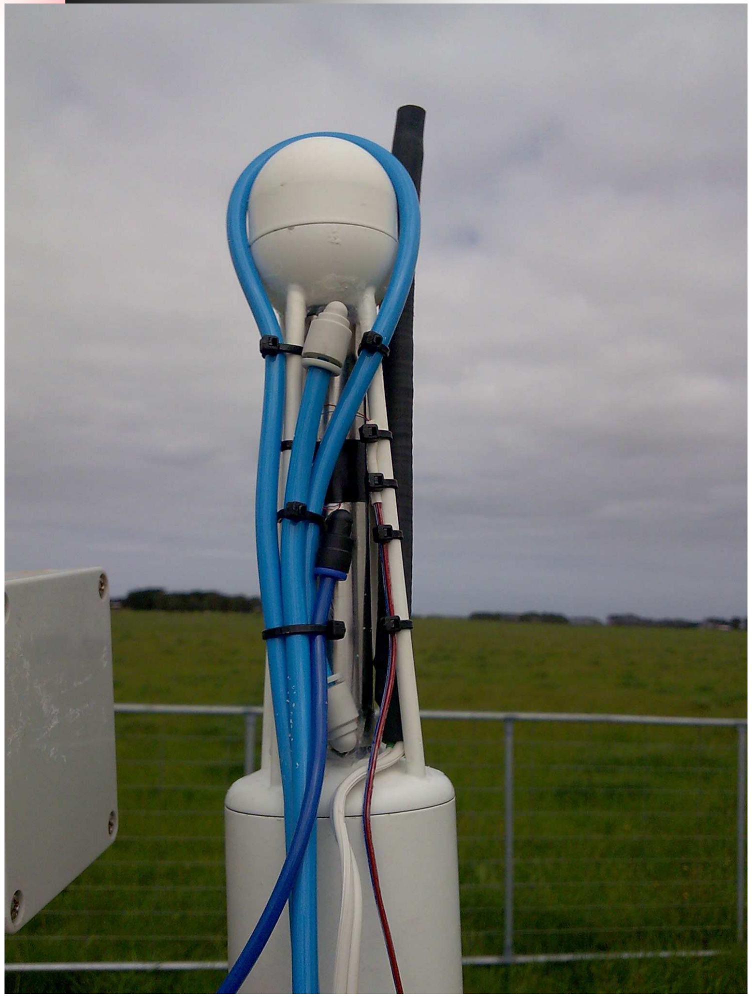
Otway flux station

Much loss of data - mist & rain

Conversion of LI7500 to closed-path analyser



Modified LI7500



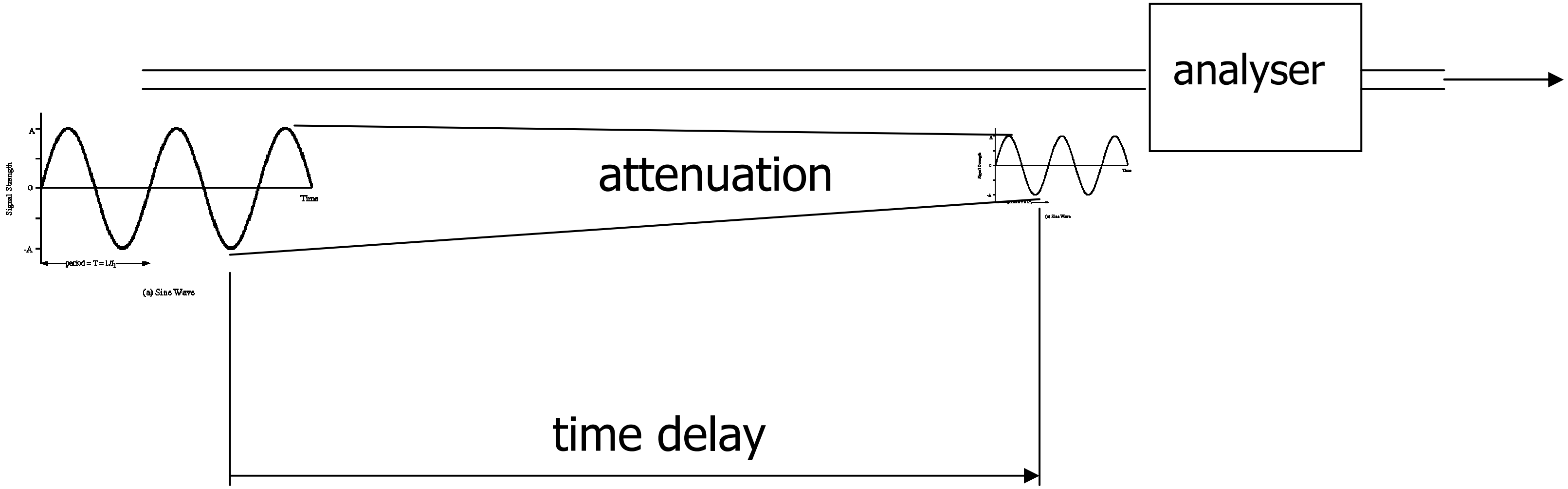
Closed-path analyser

- Measure c_c, c_v, T & P simultaneously in gas analyser and calculate mixing ratio at sampling rate used for eddy covariance

$$\chi_v = \frac{c_v}{P_i/(RT_i) - c_v}, \quad \chi_c = \frac{c_c}{P_i/(RT_i) - c_v}$$

- Must also consider
  - Time-lag
  - Hi-frequency attenuation by air flow in tubing

Closed-path gas sampling



analyser

attenuation

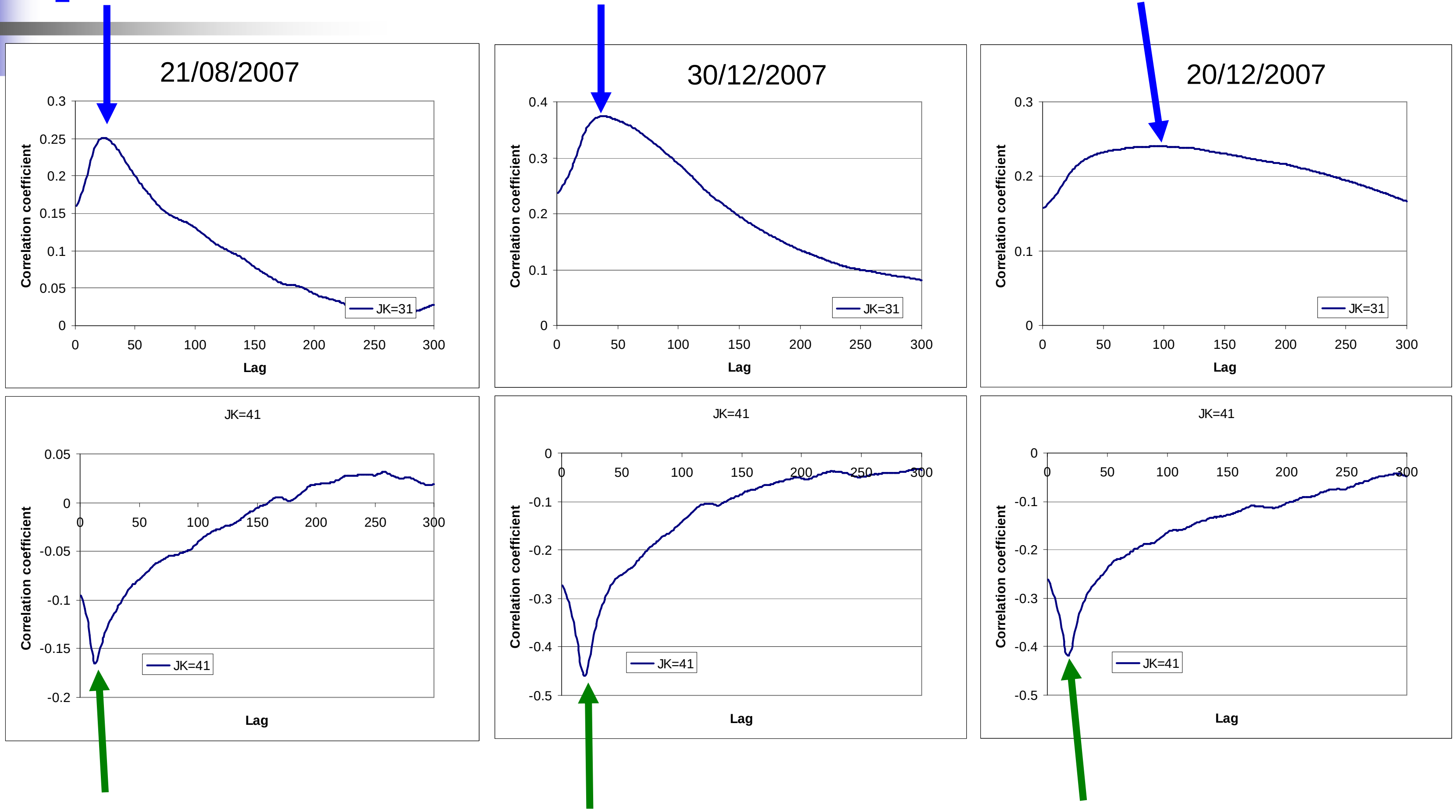
time delay

Lag at maximum correlation for closed path

H_2O lag @ max. correlation function of flow rate & rel. humidity

H_2O

CO_2

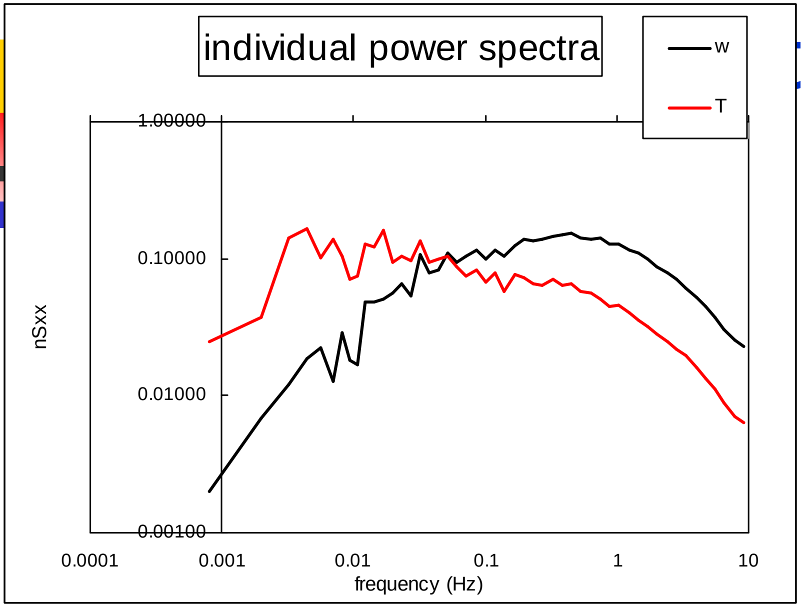


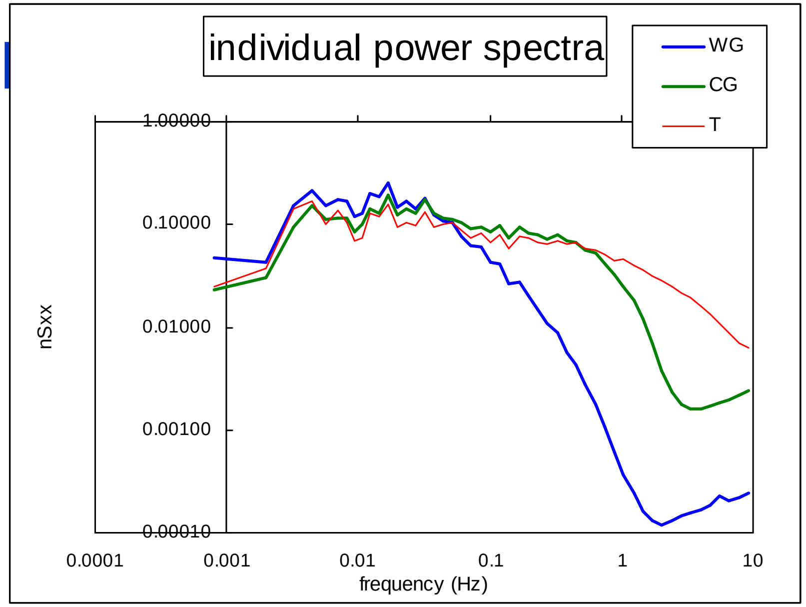
CO_2 lag @ max. correlation function of flow rate only

High Frequency Attenuation - Closed path

- Tubing acts like a low-pass filter by mixing the air
- Higher frequencies strongly attenuated – depends on:
    - Flow rate through tube
    - Tube diameter, length and material

(Leuning and Moncrieff, 1990; Leuning & Judd 1996)


individual power spectra
w
T
nSxx
1.00000
0.10000
0.01000
0.00100
0.0001
0.001
0.01
0.1
1
10
frequency (Hz)


individual power spectra
WG
CG
T
nSxx
1.00000
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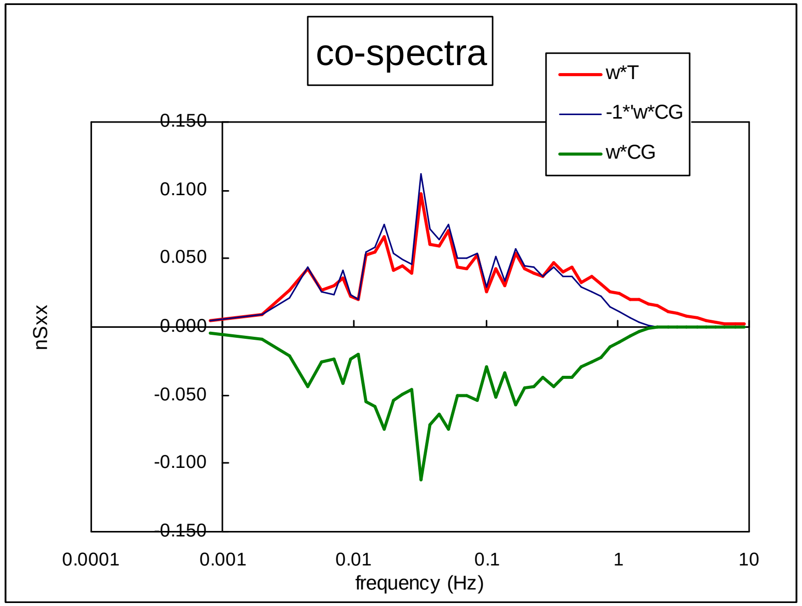
0.01000
0.00100
0.00010
0.0001
0.001
0.01
0.1
1
10
frequency (Hz)


co-spectra
w*T
-1*w*CG
w*CG
nSxx
0.150
0.100
0.050
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-0.050
-0.100
-0.150
0.0001
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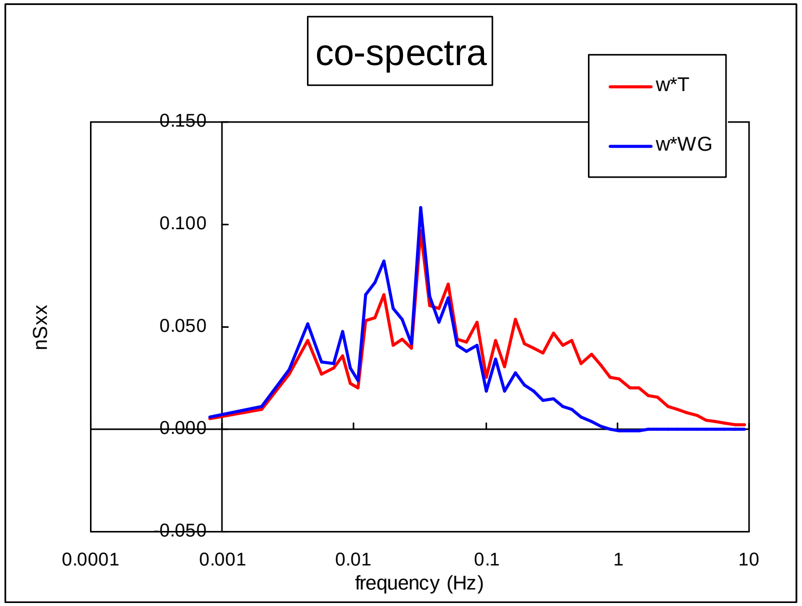
1
10
frequency (Hz)


co-spectra
w*T
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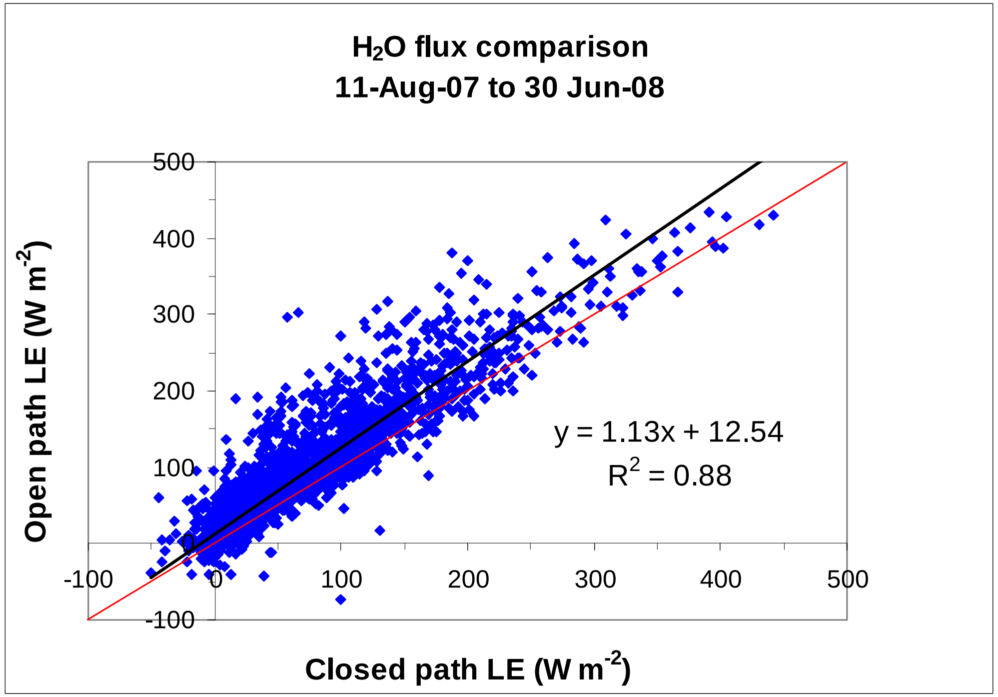
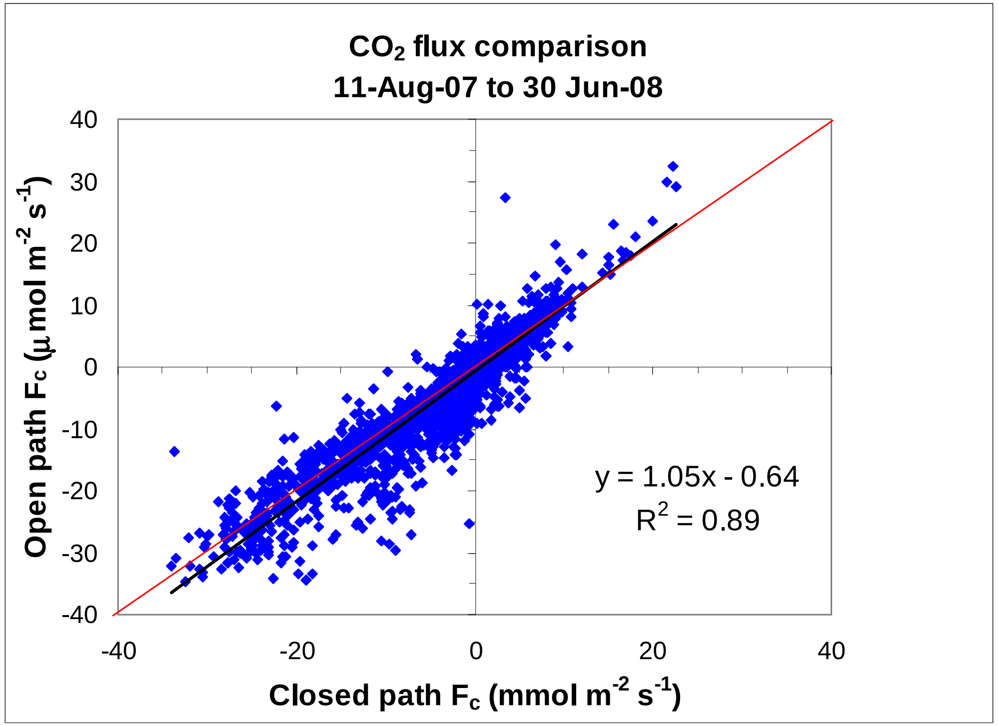
0.0001
0.001
0.01
0.1
1
10
frequency (Hz)

Open vs closed path instruments

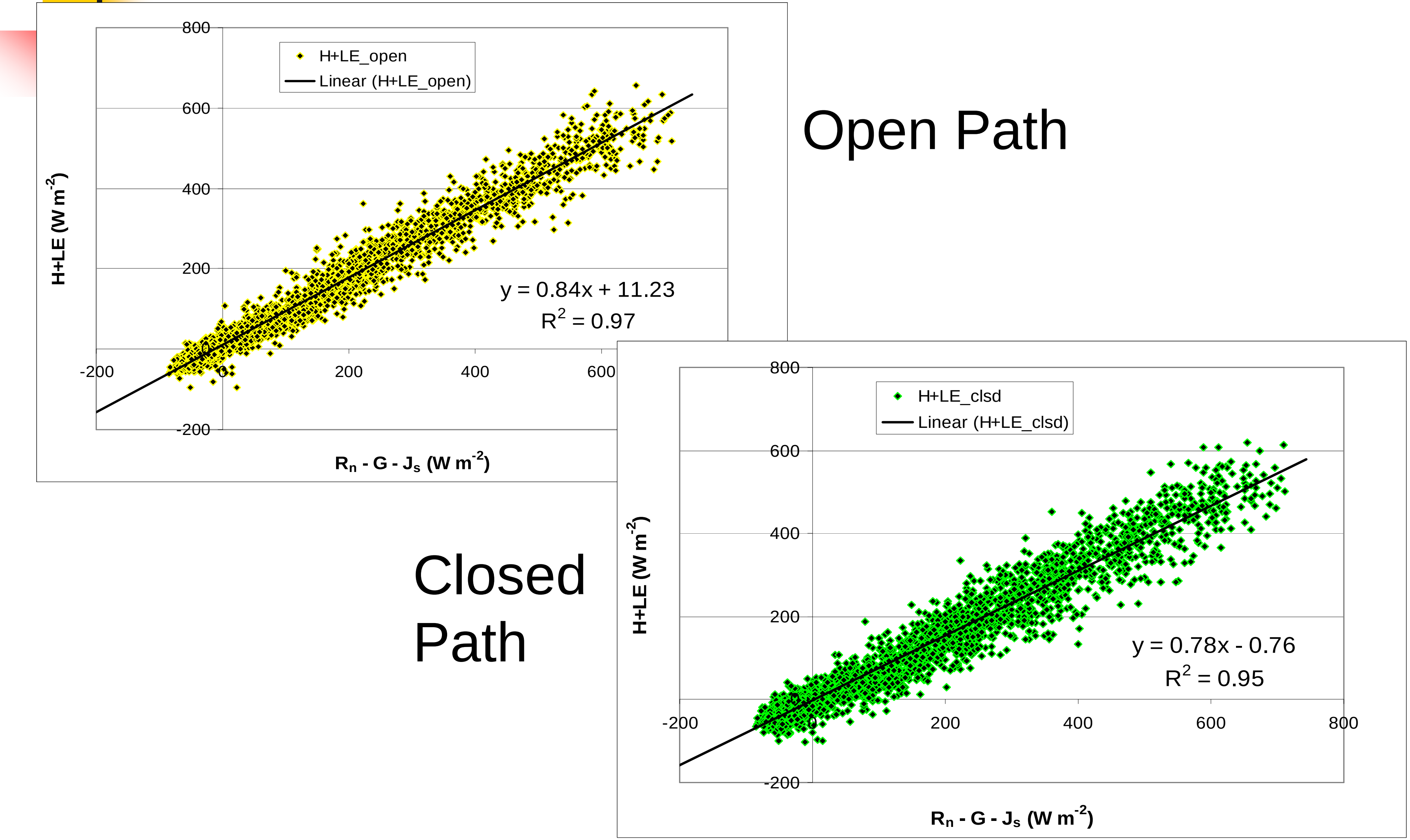
H_2O



CO_2



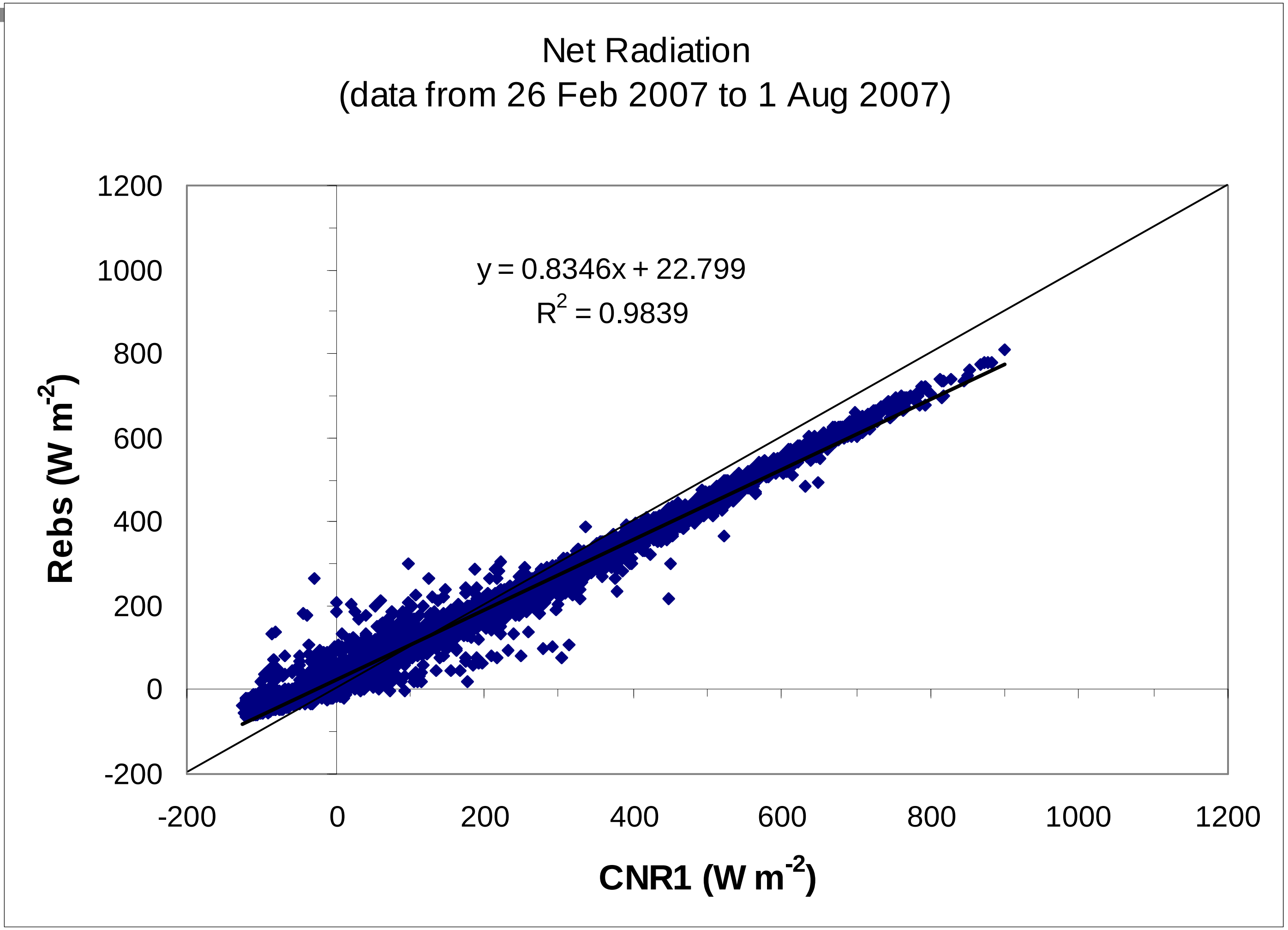
Energy balance



Open Path

Closed Path

Uncertainties in net radiation!

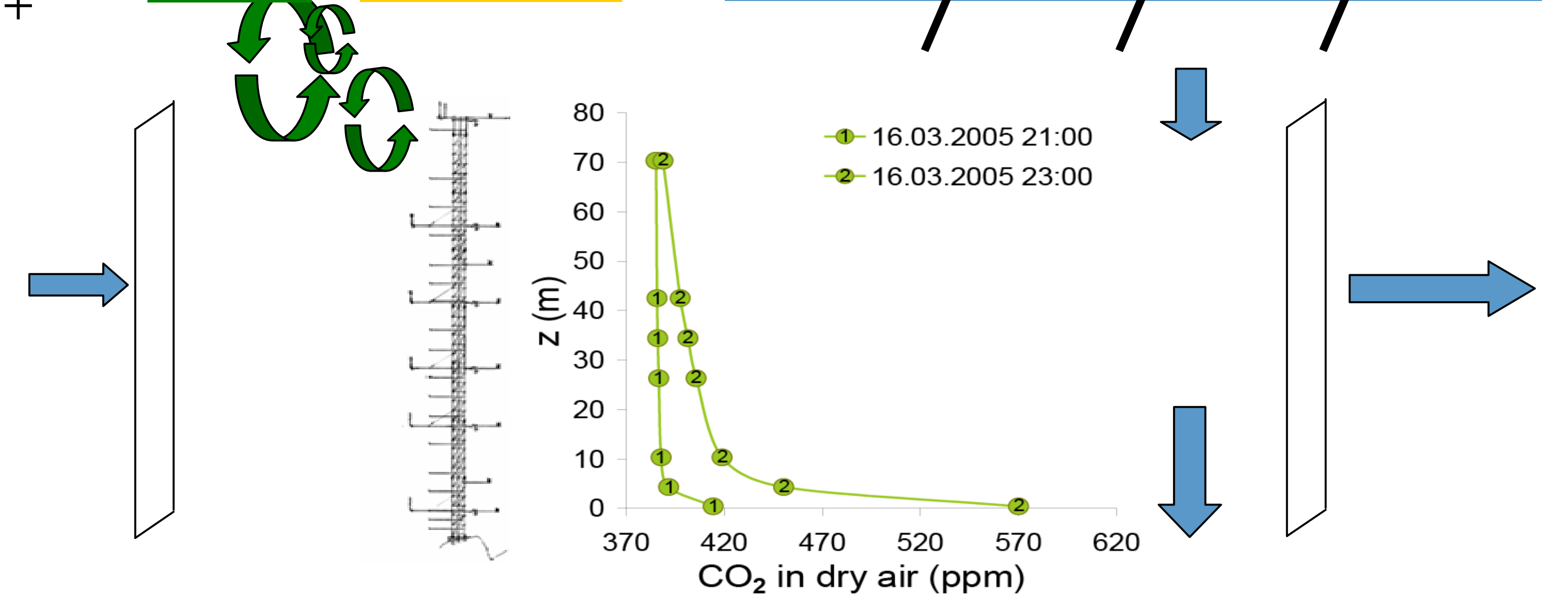


Reminder of assumptions

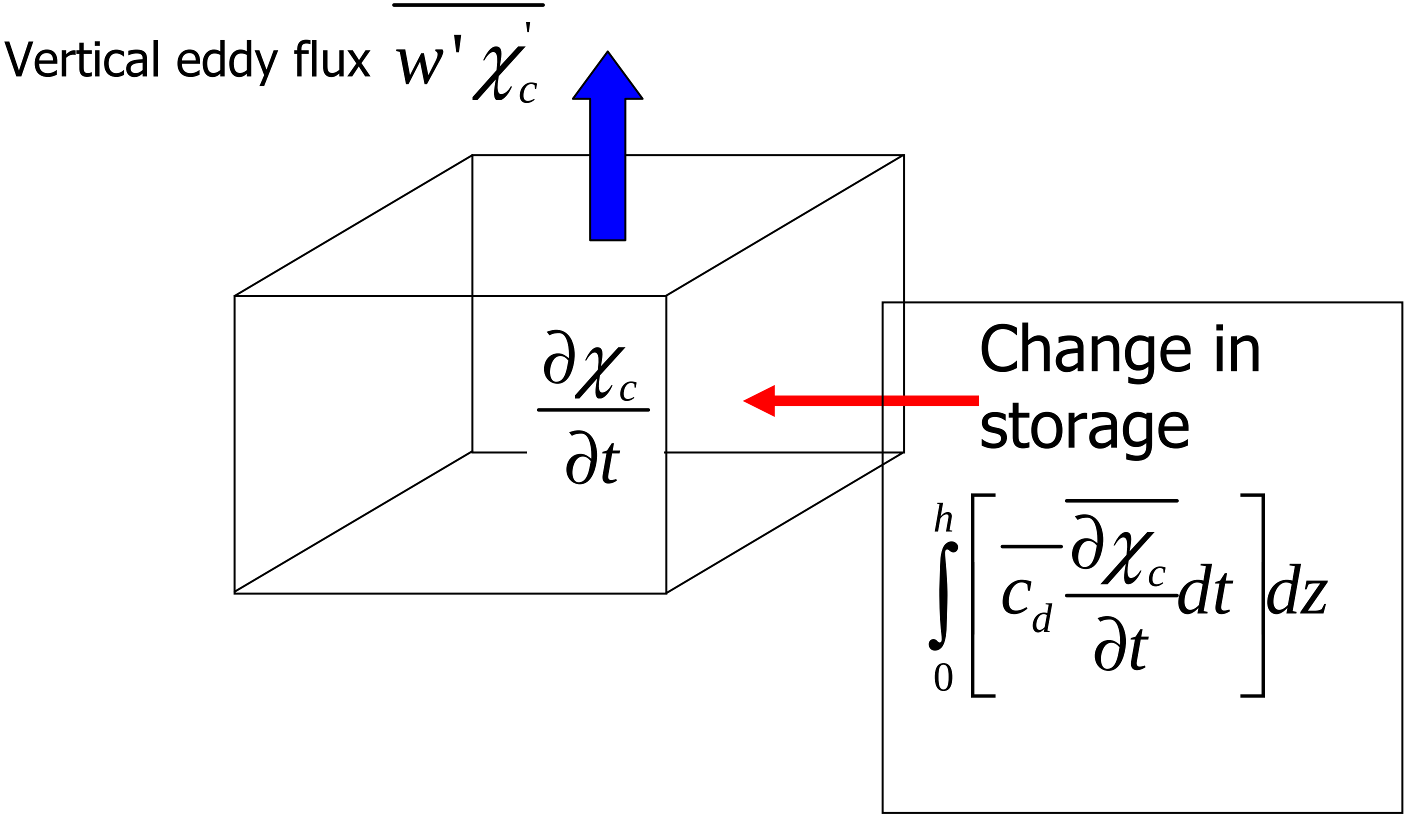
- horizontally homogeneous flow
- advection neglected

$$NEE = \overline{c_d}\,\overline{w'\chi_c'} + \int_0^{h_r} \overline{c_d}\,\frac{\partial \overline{\chi_c}}{\partial t}\,dz + \frac{1}{L^2}\int_0^L\int_0^L\int_0^{h_r}\left[\cancel{\overline{u}\,\overline{c_d}\,\frac{\partial \overline{\chi_c}}{\partial x}} + \cancel{\overline{v}\,\overline{c_d}\,\frac{\partial \overline{\chi_c}}{\partial y}} + \cancel{\overline{w}\,\overline{c_d}\,\frac{\partial \overline{\chi_c}}{\partial z}}\right]dxdydz$$

+



Measurements on a single tower – change in storage term



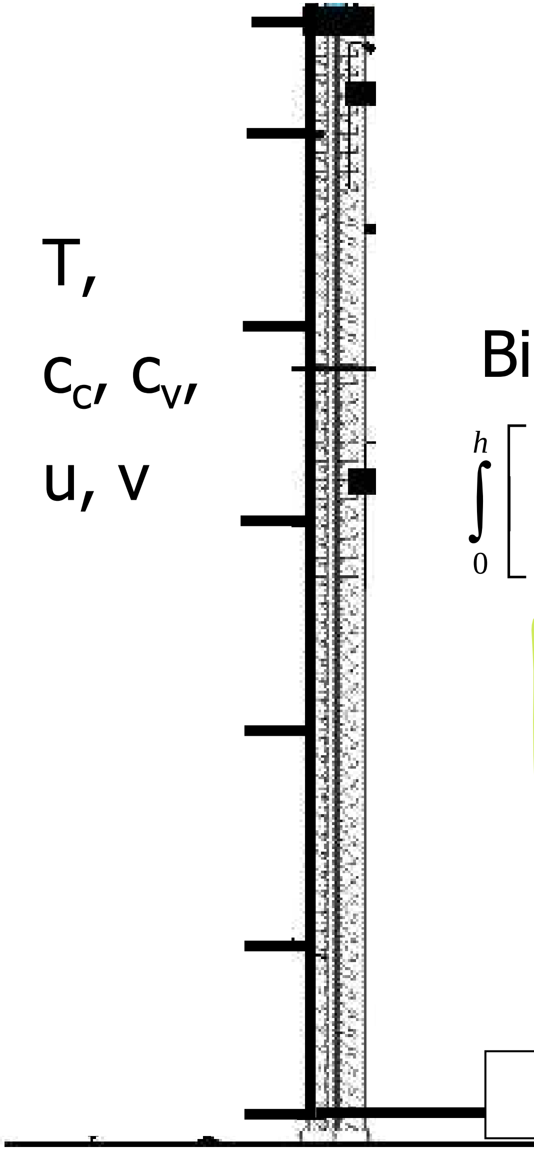
Vertical eddy flux $\overline{w'\chi_c'}$

$$\frac{\partial \chi_c}{\partial t}$$

Change in storage

$$\int_0^h \left[\overline{c_d}\,\overline{\frac{\partial \chi_c}{\partial t}}dt\right]dz$$

Profiles



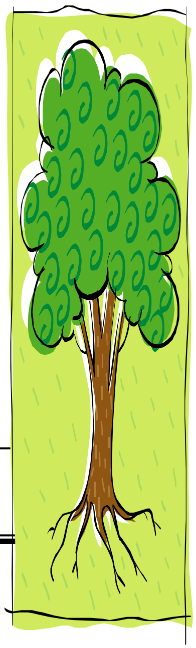
T,

c_c, c_v,

u, v

Biomass

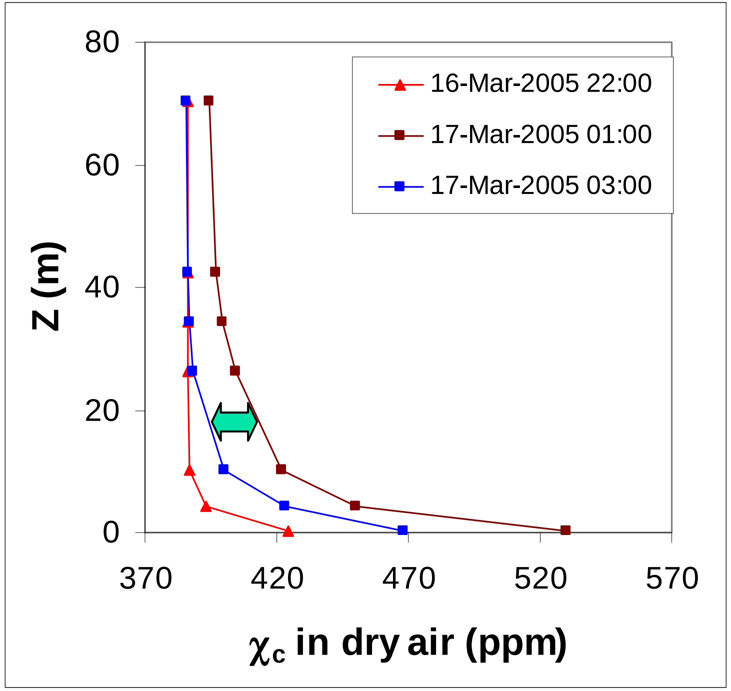
$$\int_0^h \left[\frac{\overline{\partial T}}{\partial t} dt \right] dz$$

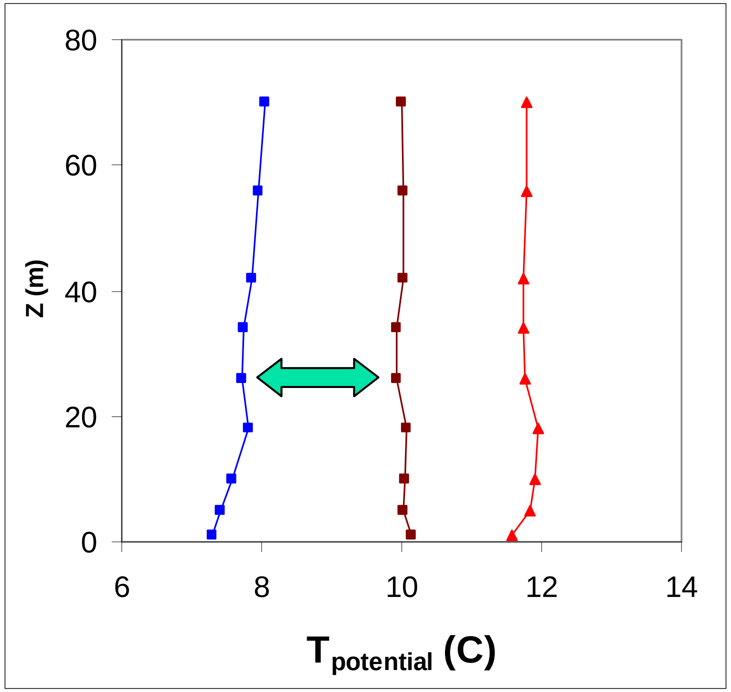


CO_2 & H_2O

CO_2 & T profiles – change in storage term

$$F_{\Delta storage} = \frac{\bar{c}_d}{\Delta t}\left[\int_0^h \chi_c dz \Big|_{t=\Delta t} - \int_0^h \chi_c dz \Big|_{t=0} \right]$$





Summary (1):

- Mass balance of a control volume
- Time vs spatial averaging concepts
- Time domain
  - Reynolds decomposition & averaging
  - Covariance
  - Coordinate system
  - Flux calculation
- Frequency domain
  - Variance, covariance
  - High-cut filtering
  - High-pass filtering & averaging

Summary (2):

- Measuring trace gas concentrations
  - Open and closed-path gas analysers
- Webb, Pearman & Leuning corrections
  - Correcting for system high and low frequency response
- The change in storage term
- Advection and night time respiration

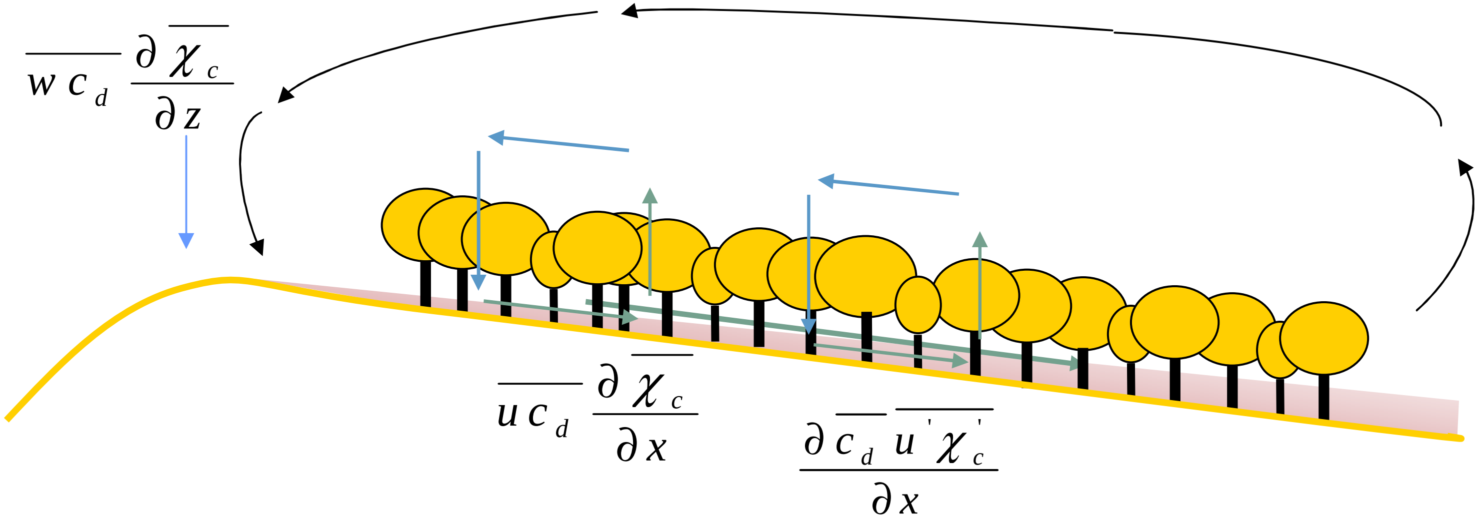
Pause

Advection and night time fluxes

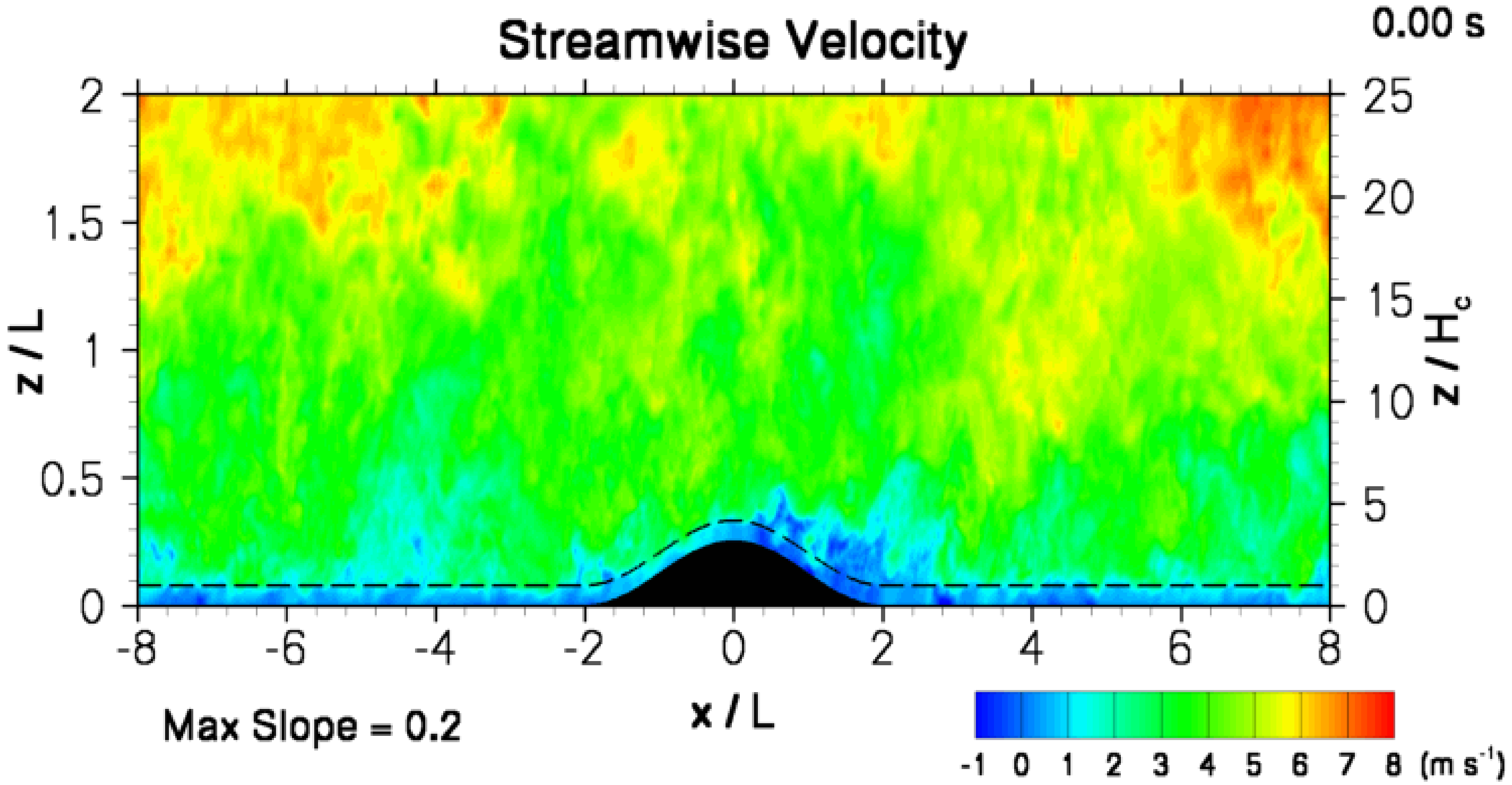
- Eddy flux underestimates night time fluxes at many sites
- Stable stratification causes decoupling of flow above and within canopy
- Drainage flows cause advection – not measured
- Most groups apply ‘u*-filter’ to select windy nights when advection is small

Dynamics of advection

Once drainage flows commence, the down flowing air has to be replaced with air from above. Entrainment of CO_2 poor air leads to development of horizontal CO_2 gradients.



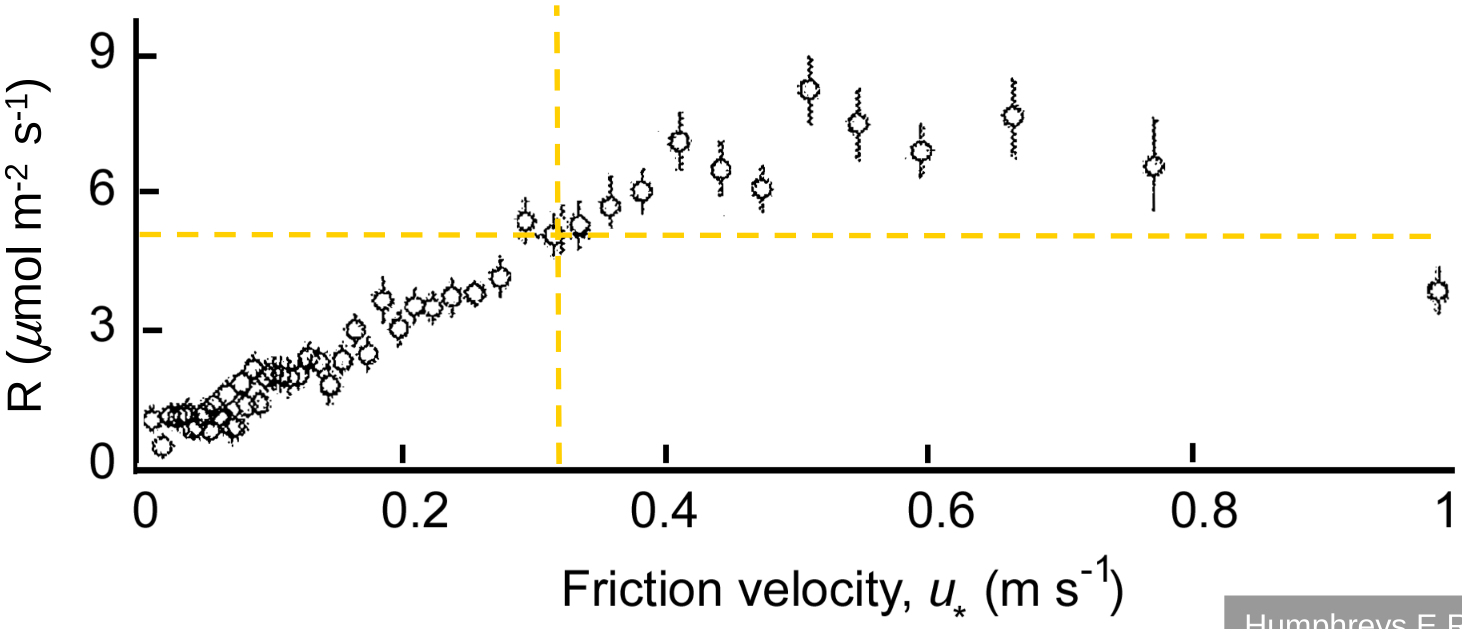
Complex terrain – flow over hills



Courtesy Dr Ned Patton, NCAR

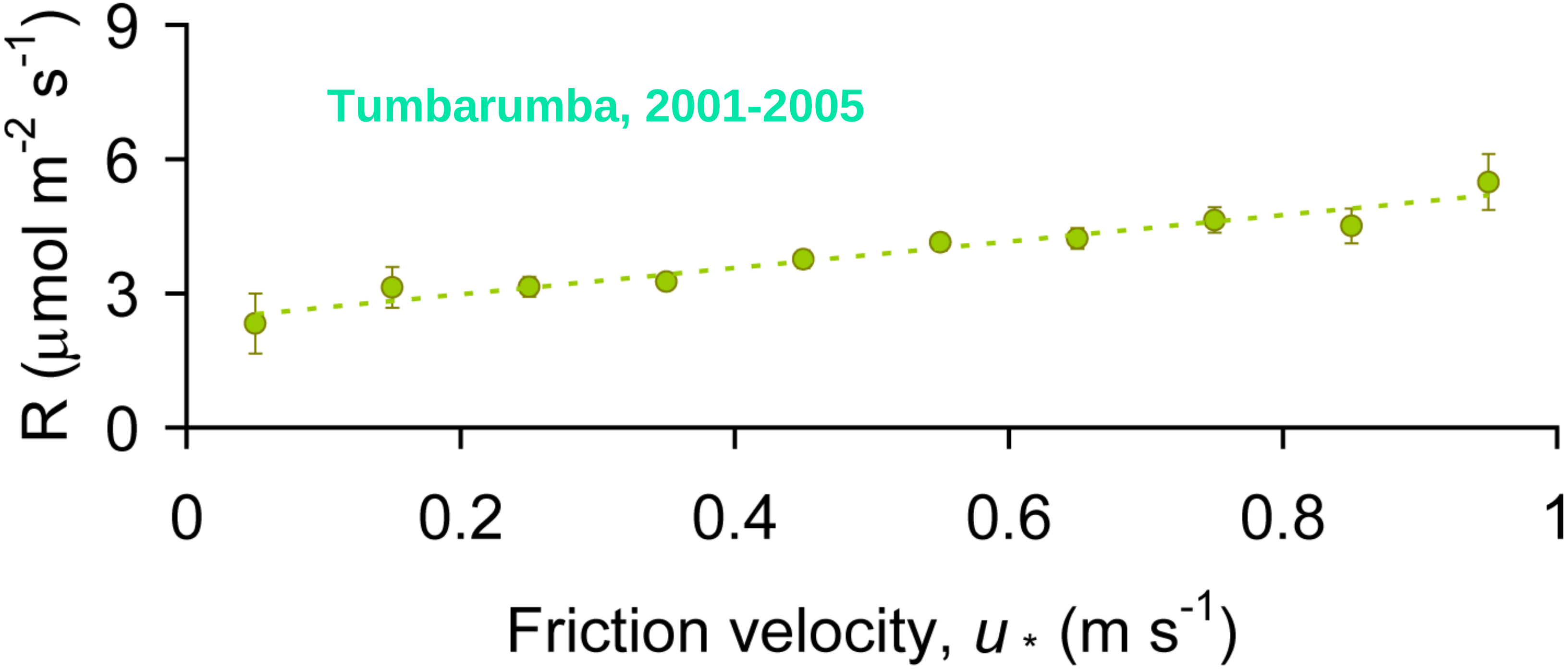
The u_* threshold

To estimate respiration - use u*-threshold to select periods when eddy flux and change in storage terms are important but not advection term

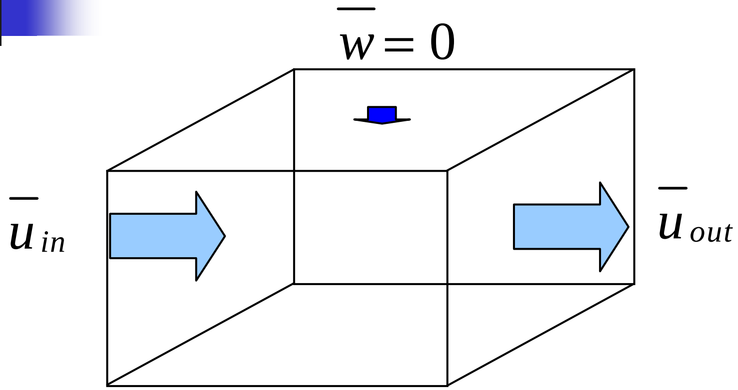


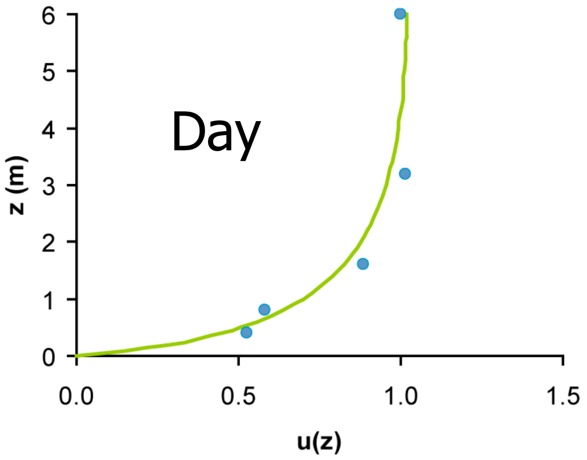
Humphreys E.R. et al. (2006)

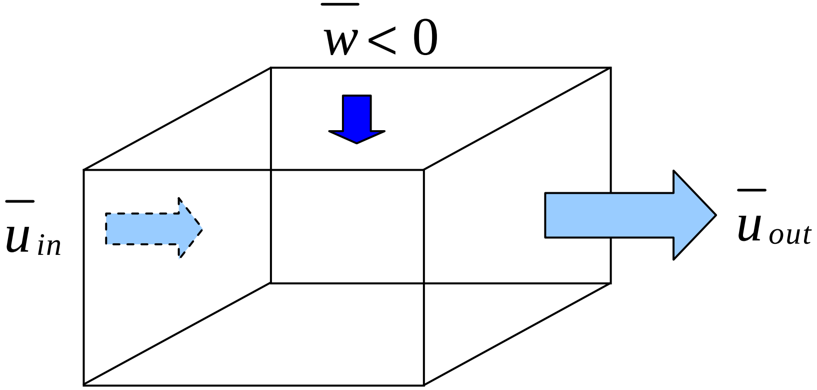
But, there are sites with no unique *u**-threshold

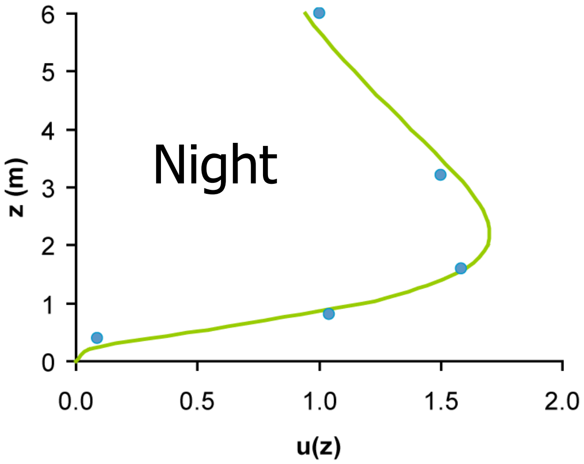


Drainage flow at forest floor

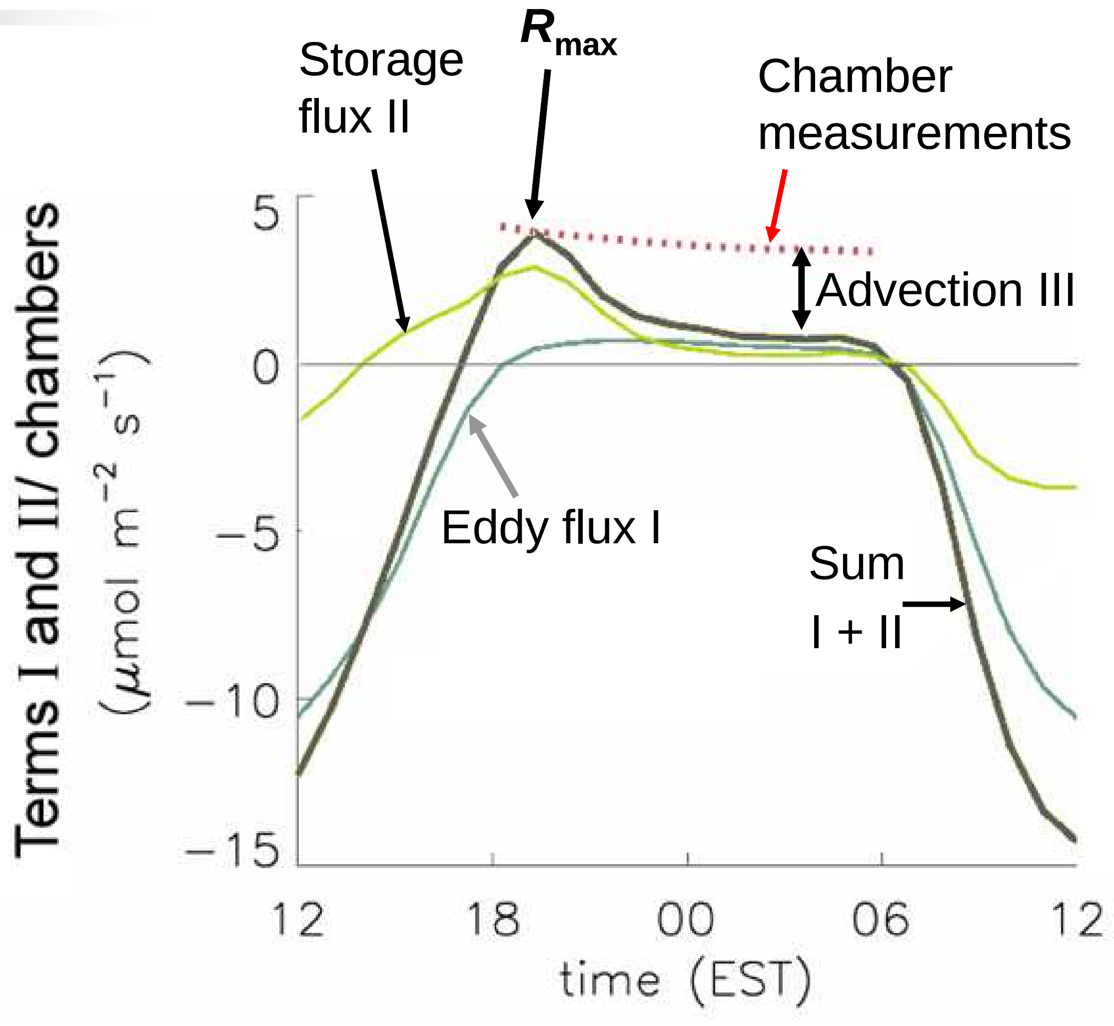




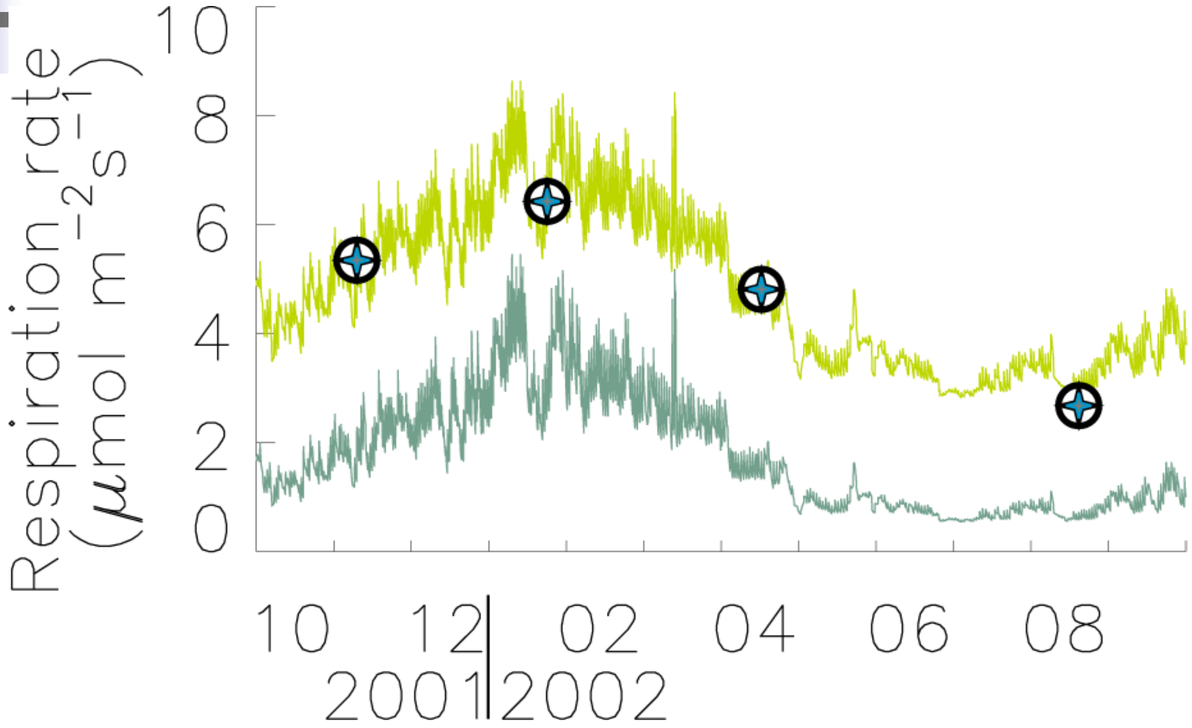




Early evening maximum of *R*

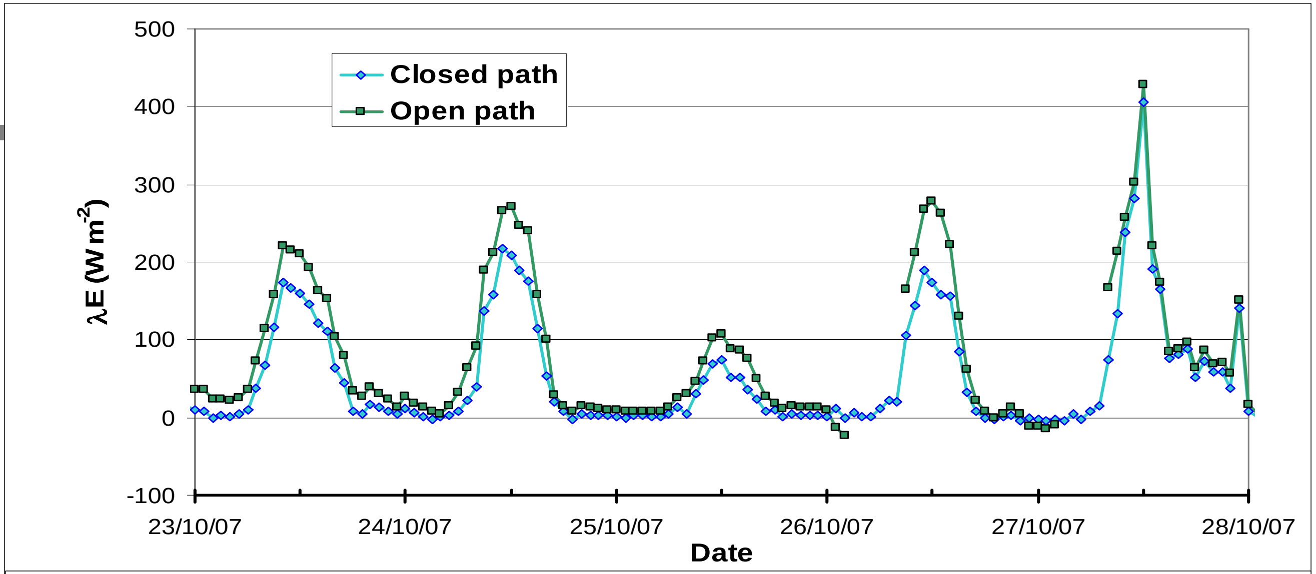


Results from alternative approach:

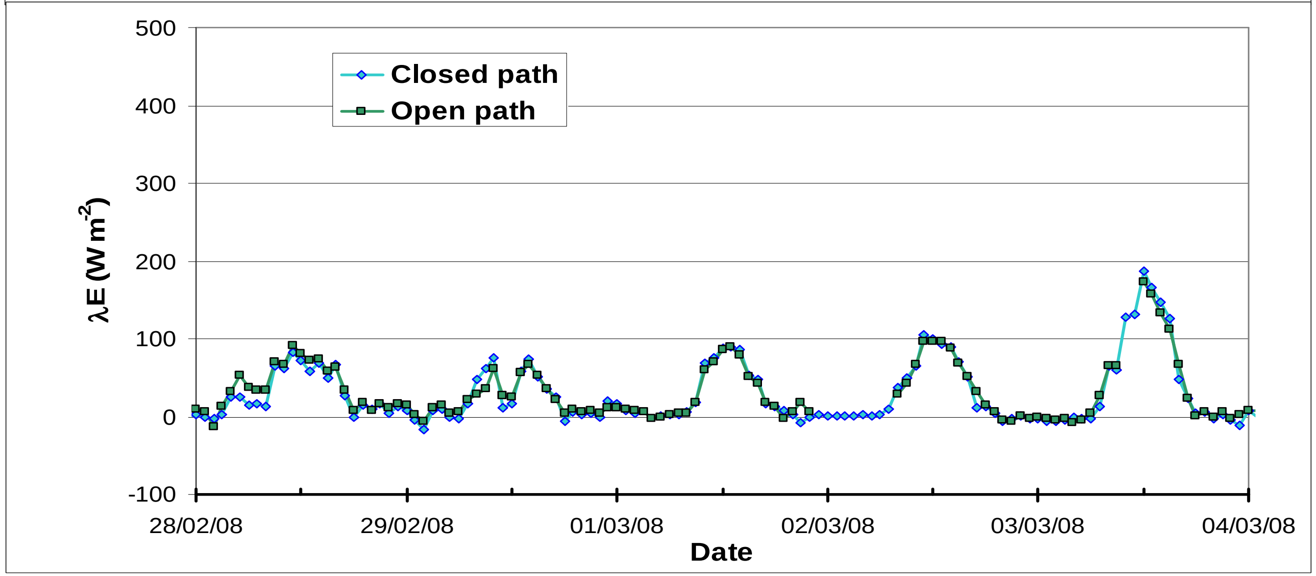


Comparison with independent methods shows that R_{Rmax}, the **maximum** of the sum of eddy flux and storage term measured in the early evening, provides the most accurate data to derive temperature response functions for ecosystem respiration.

Time series of λE

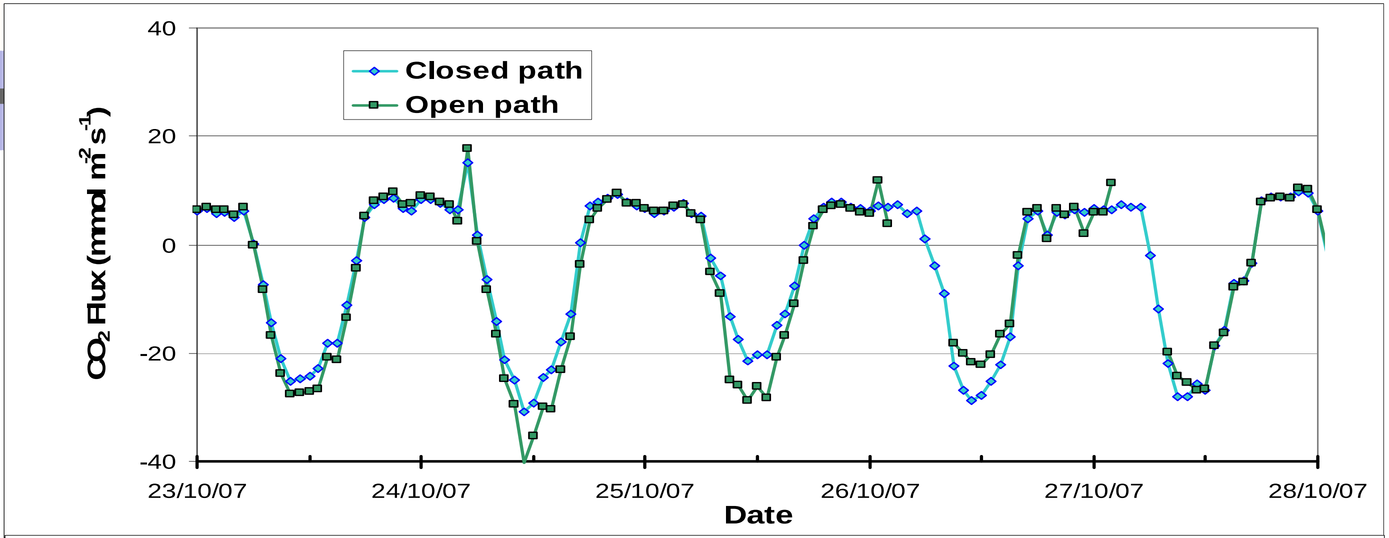


Spring

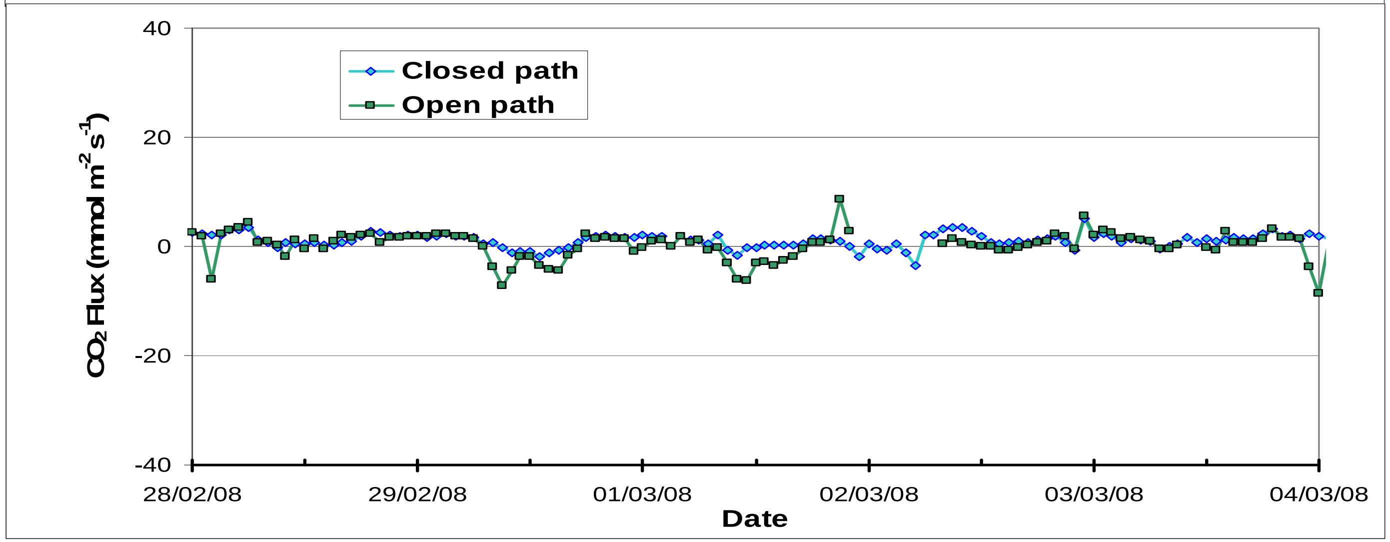


Summer

Time series of F_c



Spring



Summer