Eddy covariance at Otway: A tale of two analysers

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Bureau of Meteorology

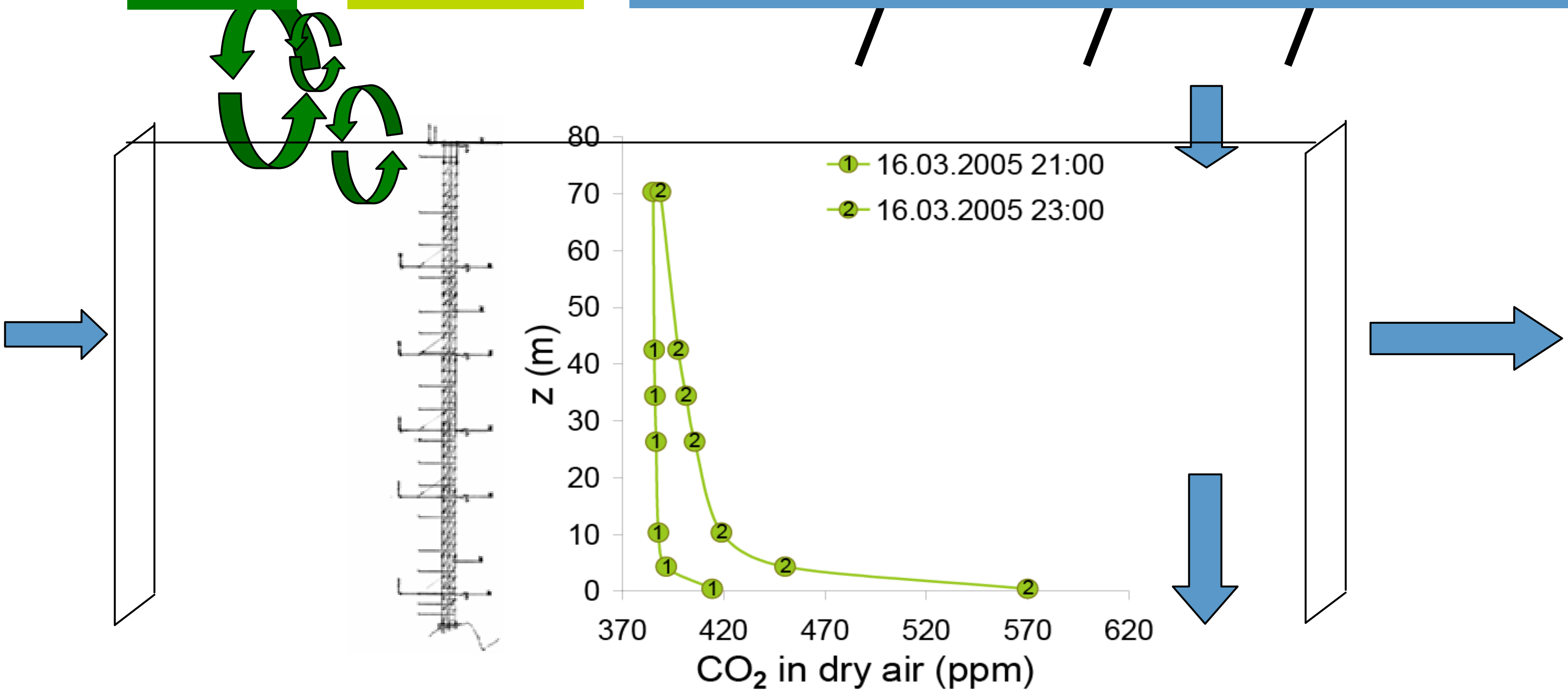
The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

CSIRO

With these assumptions

- Horizontally homogeneous flow

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



Eddy fluxes: 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

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

Require H_2O & CO_2

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

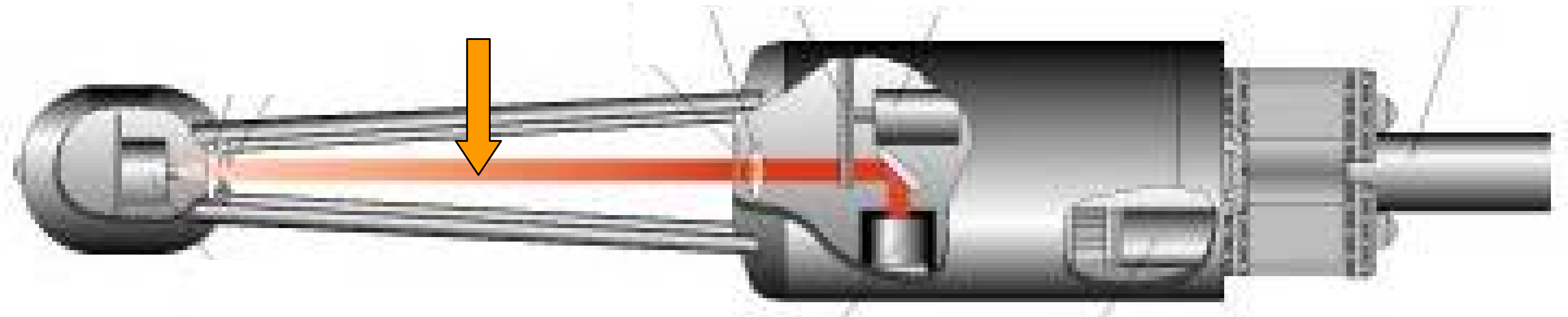
$$F_c = \overline{c}_d \overline{w' \chi_c'}$$

Note correlation of vertical velocity and mixing ratios

LI-7500 CO_2 and water vapour analyser

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

not required mixing ratios $\chi_v \quad \chi_c$



Eddy fluxes have been expressed in terms of mixing ratio.

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

What to do?

Eddy flux for trace gas - WPL theory (1980)

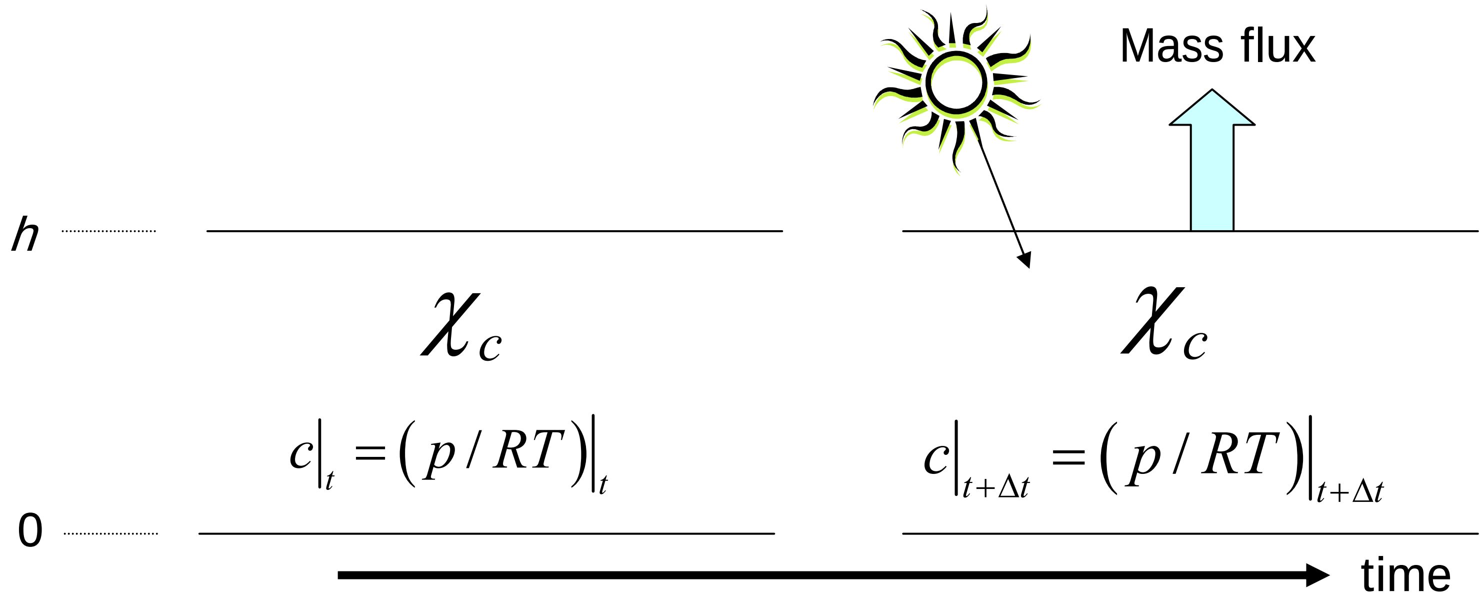
Steady state, horizontally homogeneous flow

- Open-path instruments

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

Raw CO_2 flux | Water vapor flux | Heat flux

What about non-steady state, horizontally homogeneous flow?

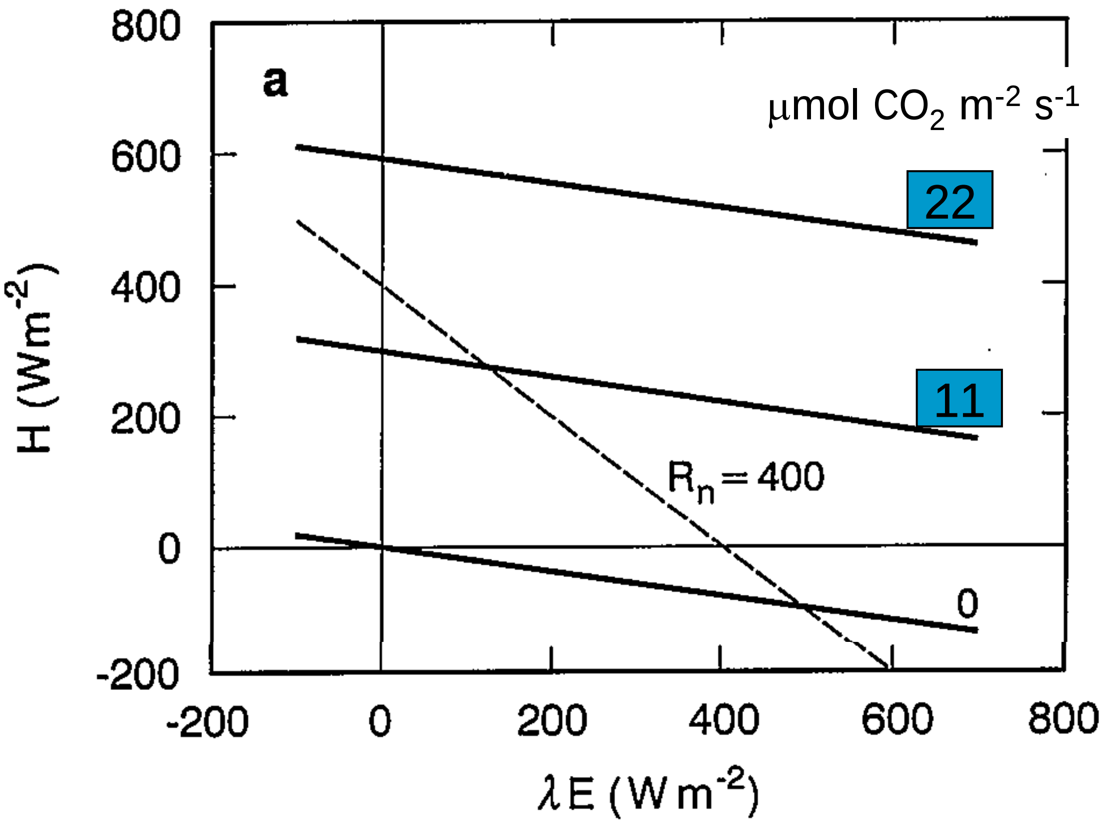


Change in concentration, but **not** mixing ratio

Leuning (2007) showed original WPL still OK

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

Magnitude of WPL corrections for CO_2 – add to raw flux



Leuning & Judd, 1996

Frequency domain - Covariance

Covariance

= eddy flux

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

Time domain   Frequency domain

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

Approximation because calculations are over a finite time interval Δt

Instrument array is a low-pass frequency filter

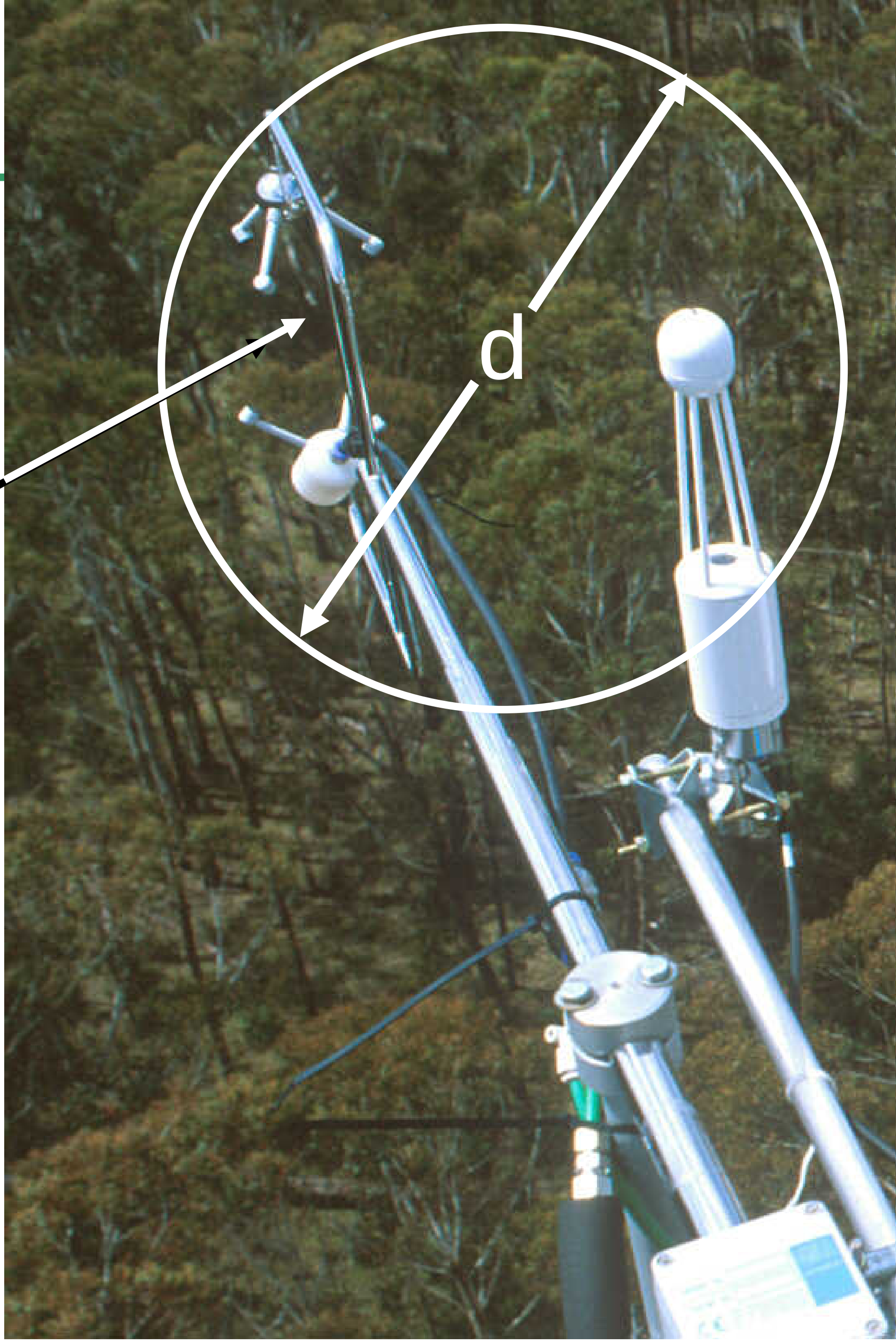
Line-averaging along instrument path

– loss of variance

Spatial separation between instruments

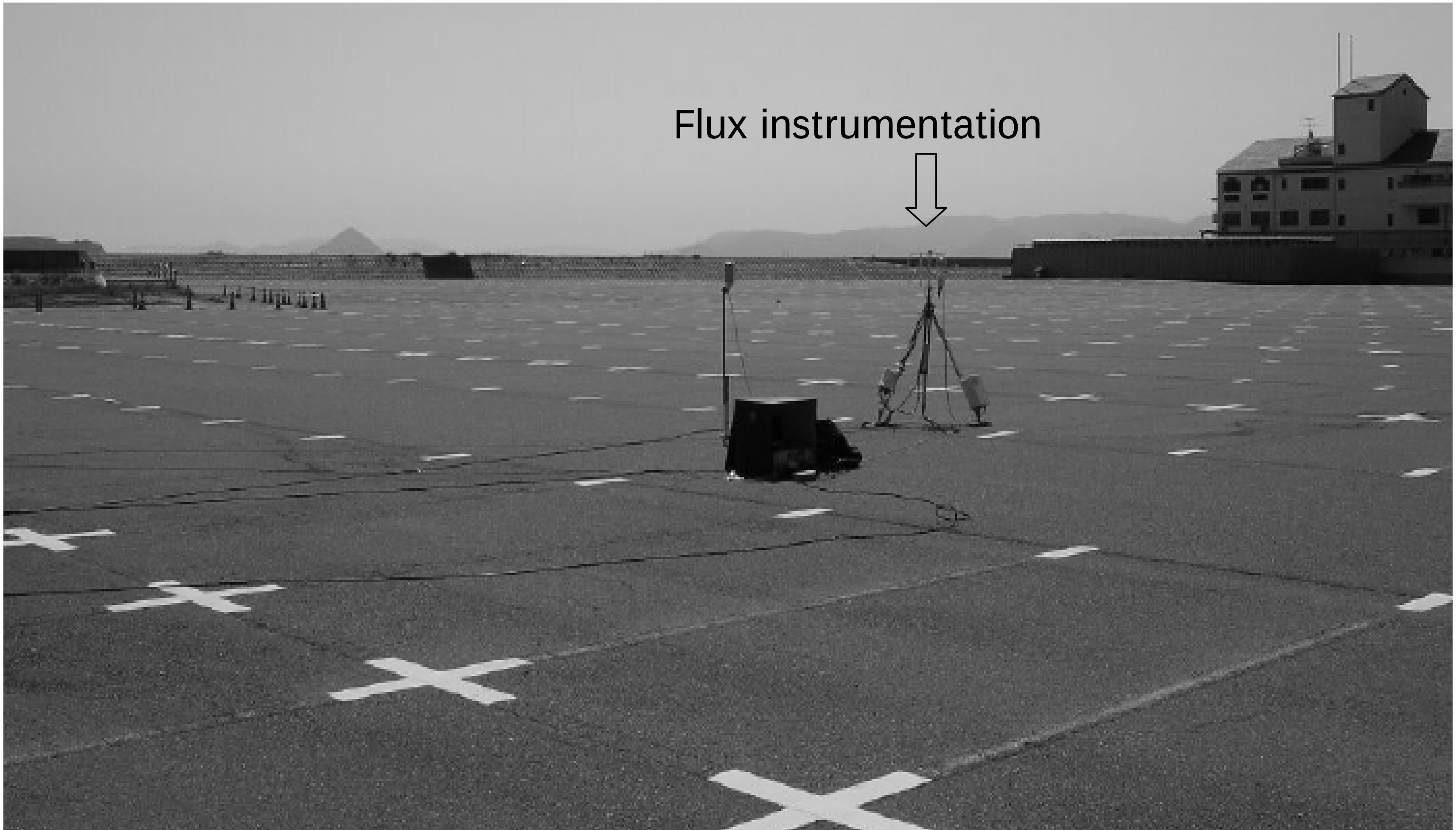
– loss of covariance

- Samples eddies > ~2d



A case study – zero CO_2 flux over a car park

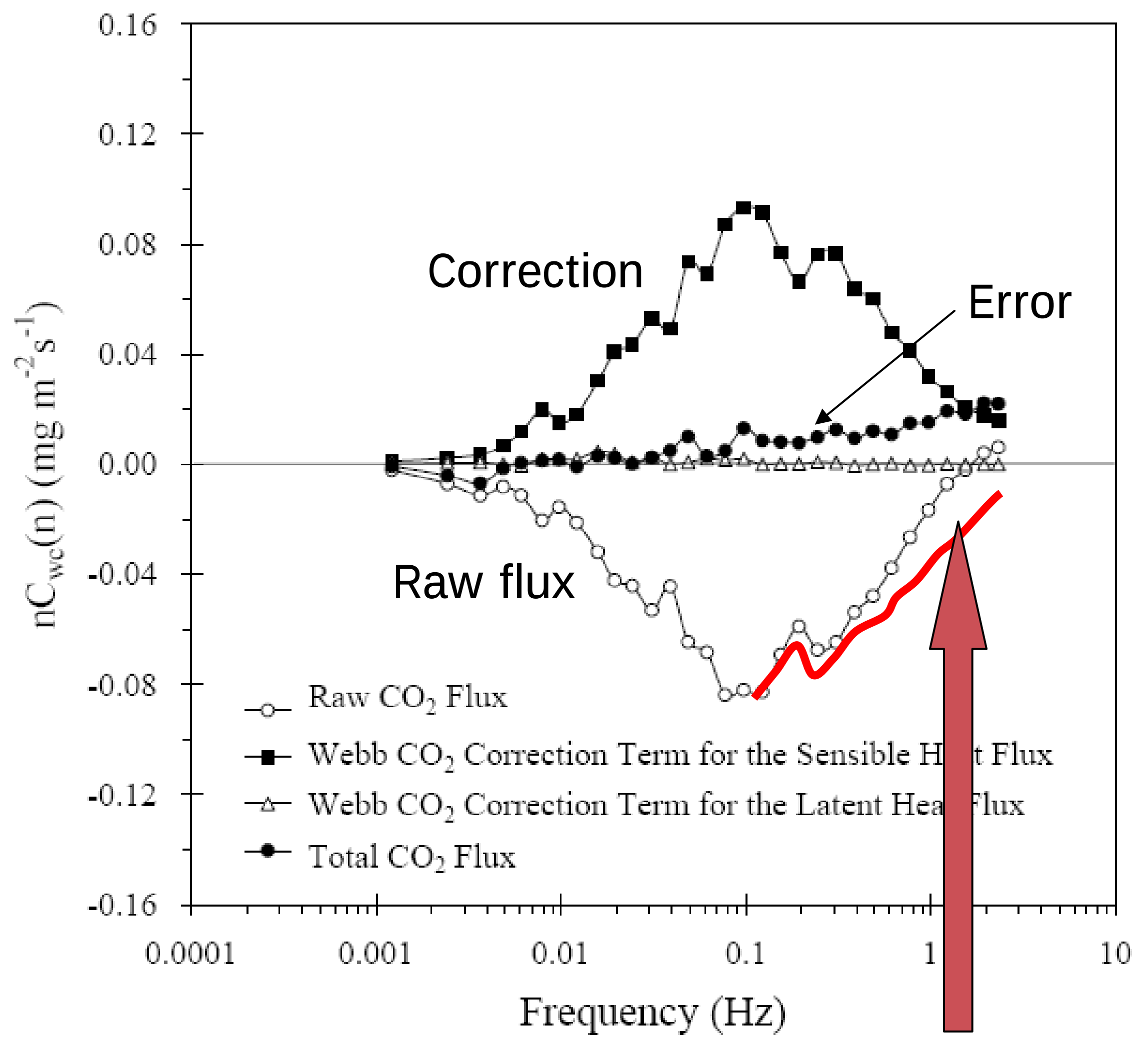
Kondo and Tsukamoto (2008)



WPL correction

Correction may be larger than true flux

Measurements of heat and water vapor fluxes must be accurate and have same frequency response as open-path CO_2 system



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, eg w’T’

filtered cospectrum

filter function

$C_F > 1$, typically

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

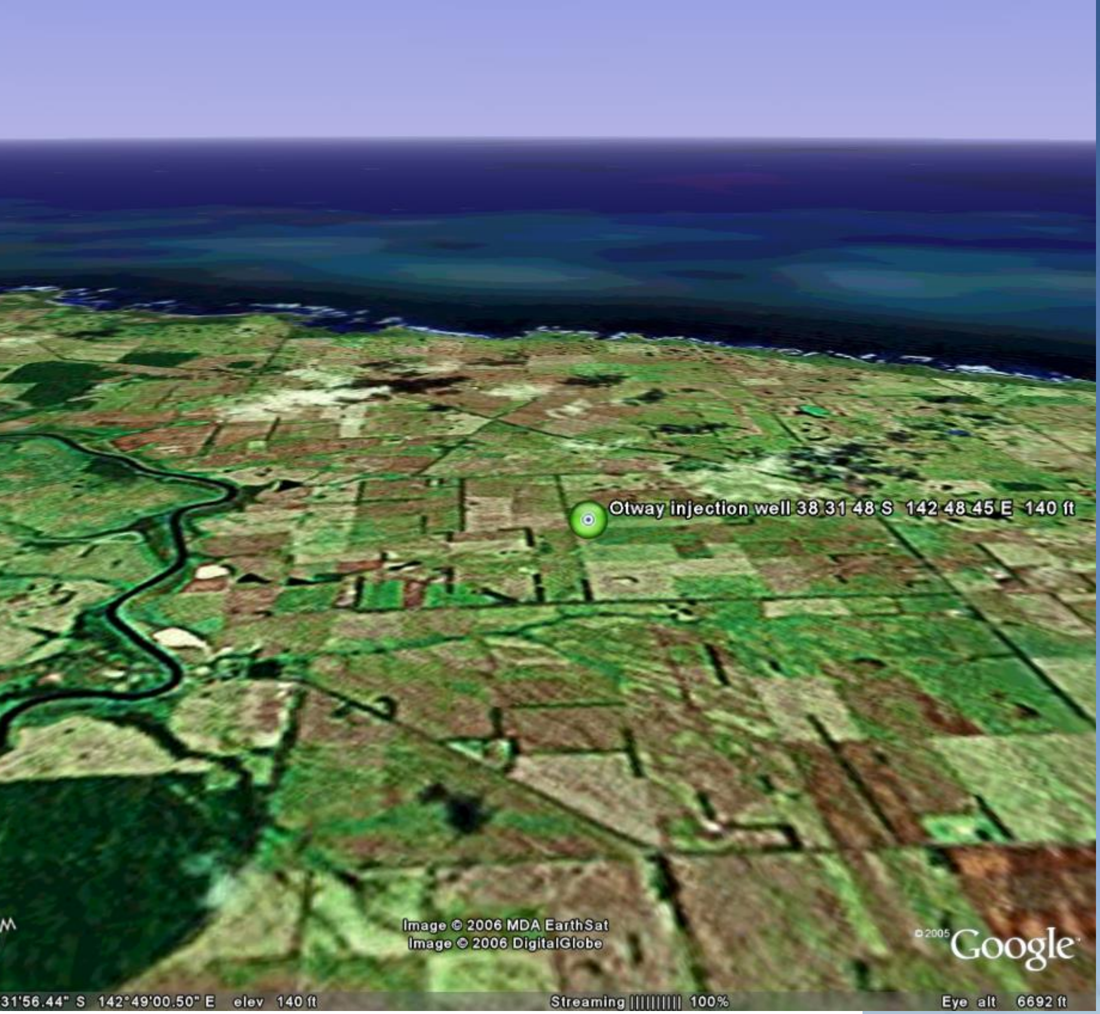
Open path measurements – calculation sequence

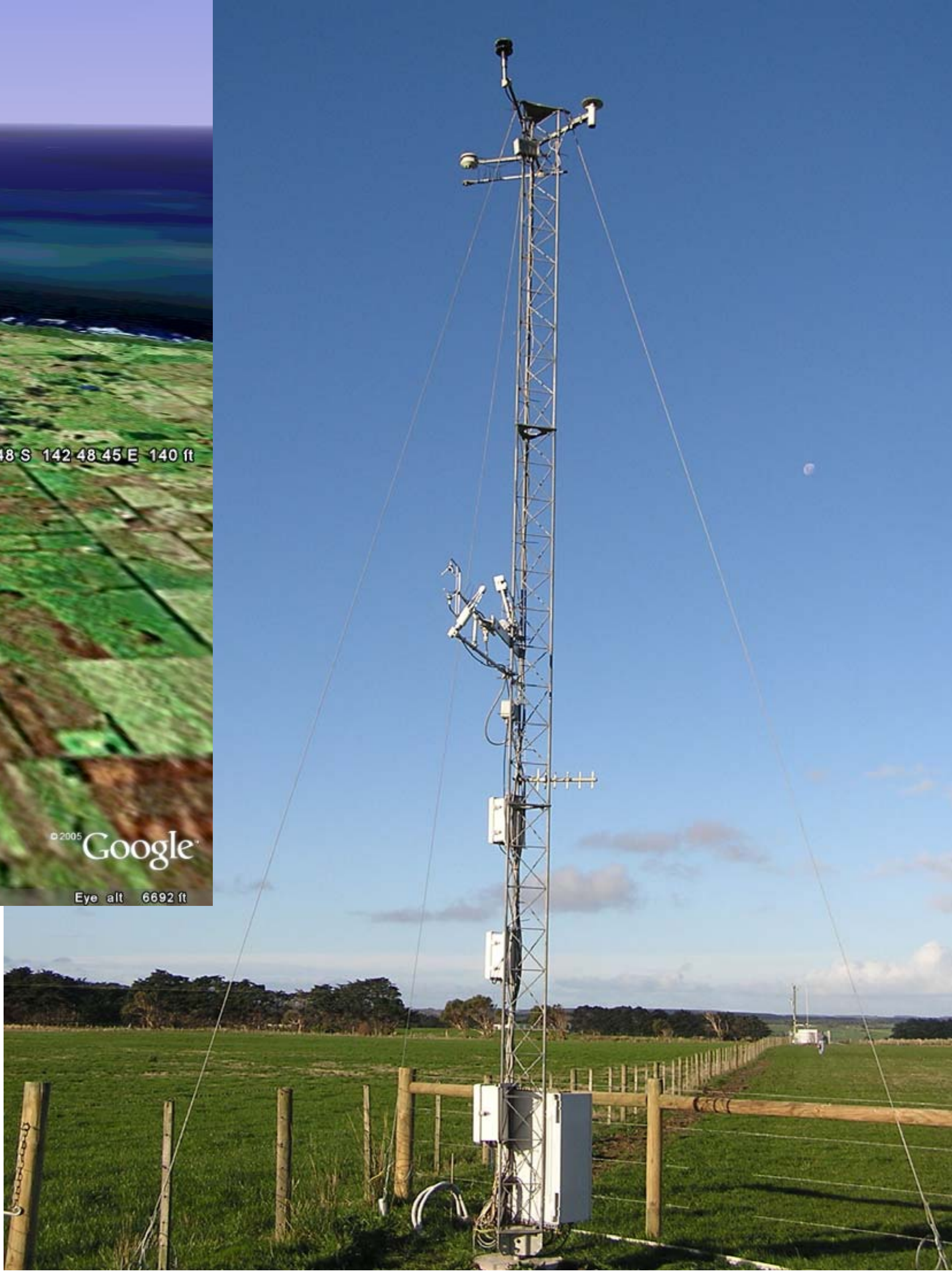
$$1)\quad \overline{H} = \overline{\rho} c_p \overline{w' T'}$$

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

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

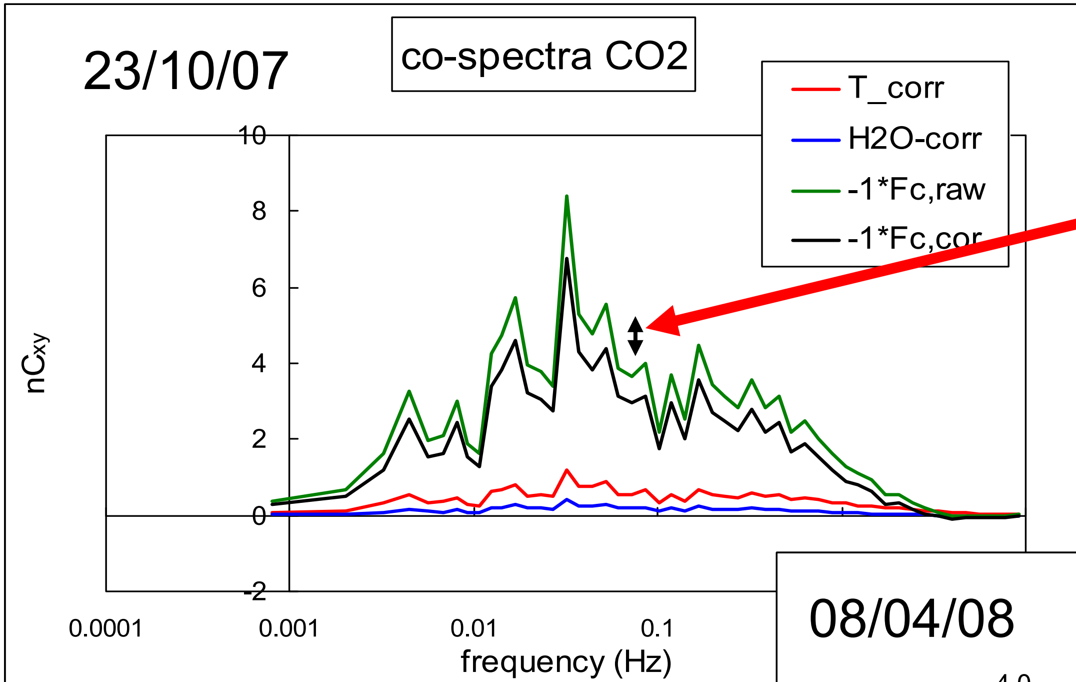
Assumes *H*, *E* & F_c have already been corrected for high & low frequency filtering



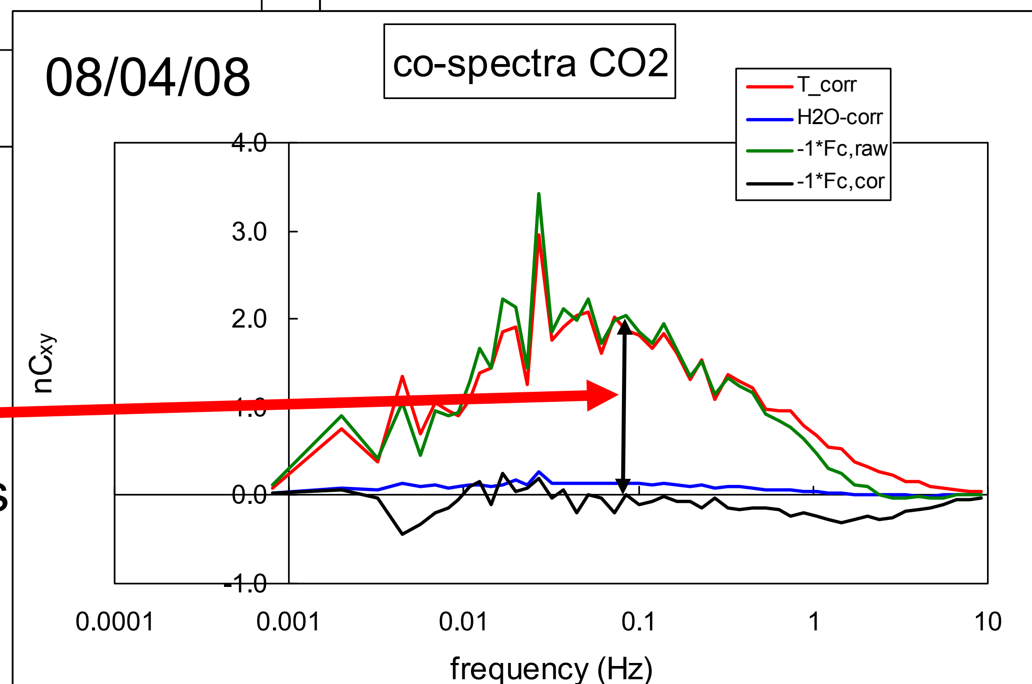


Otway flux station

WPL corrections to open path measurements



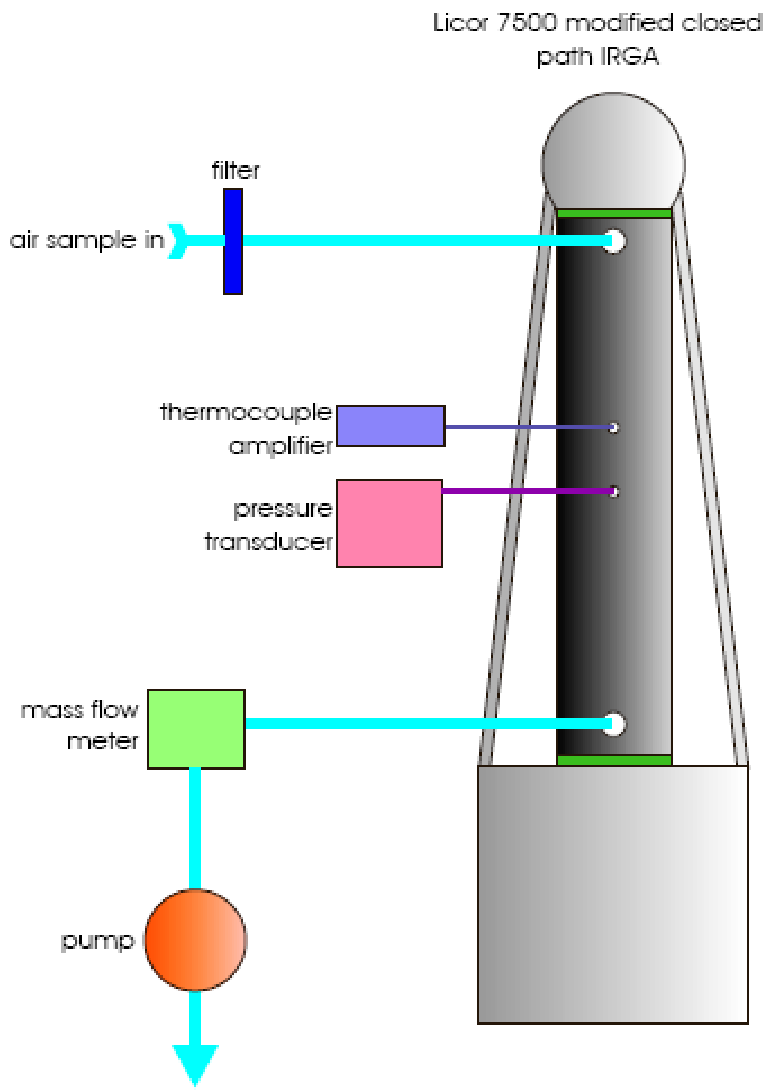
Small wT, wq
WPL corrections



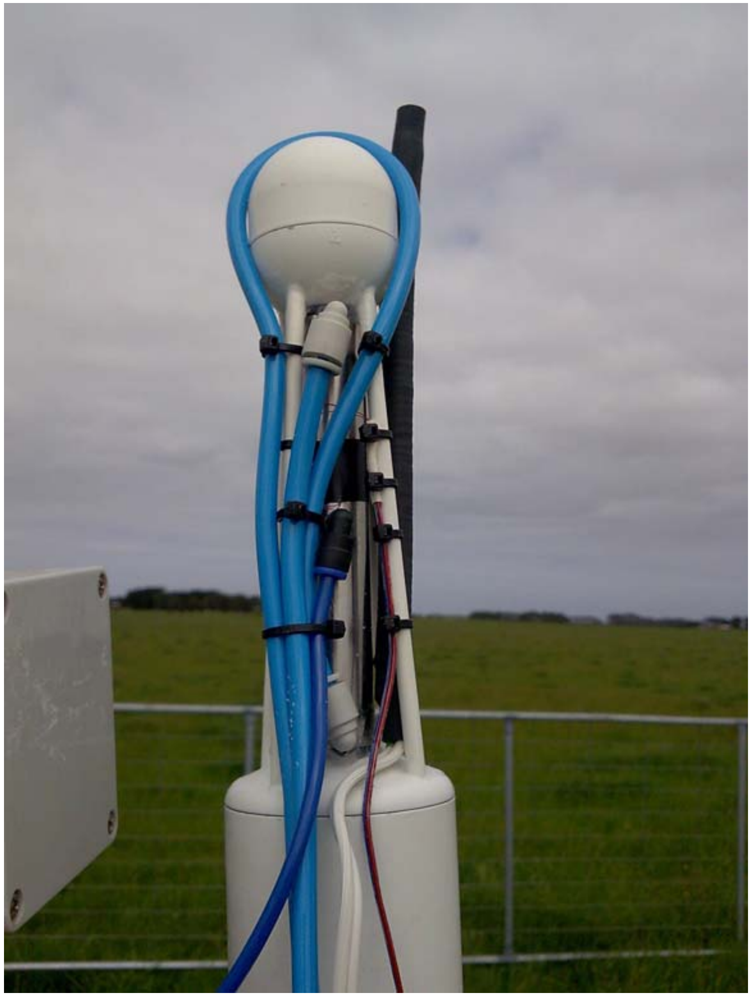
Big wT, wq

WPL corrections

Conversion of LI7500 to closed-path analyser



Modified LI7500



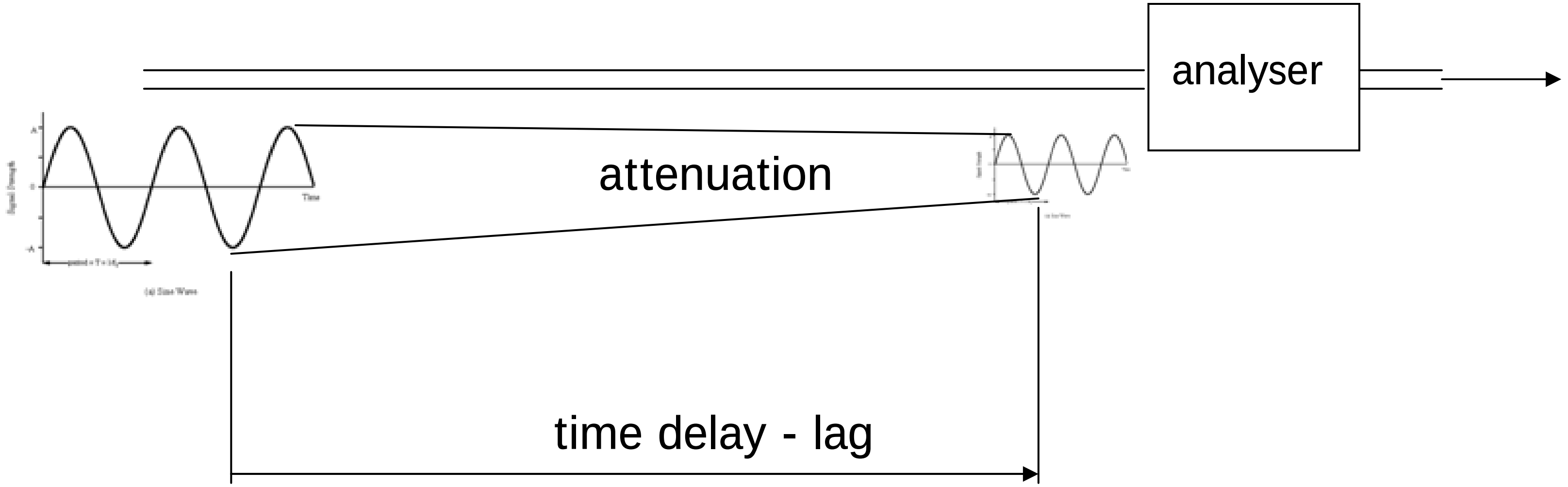
Closed-path analyser

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

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

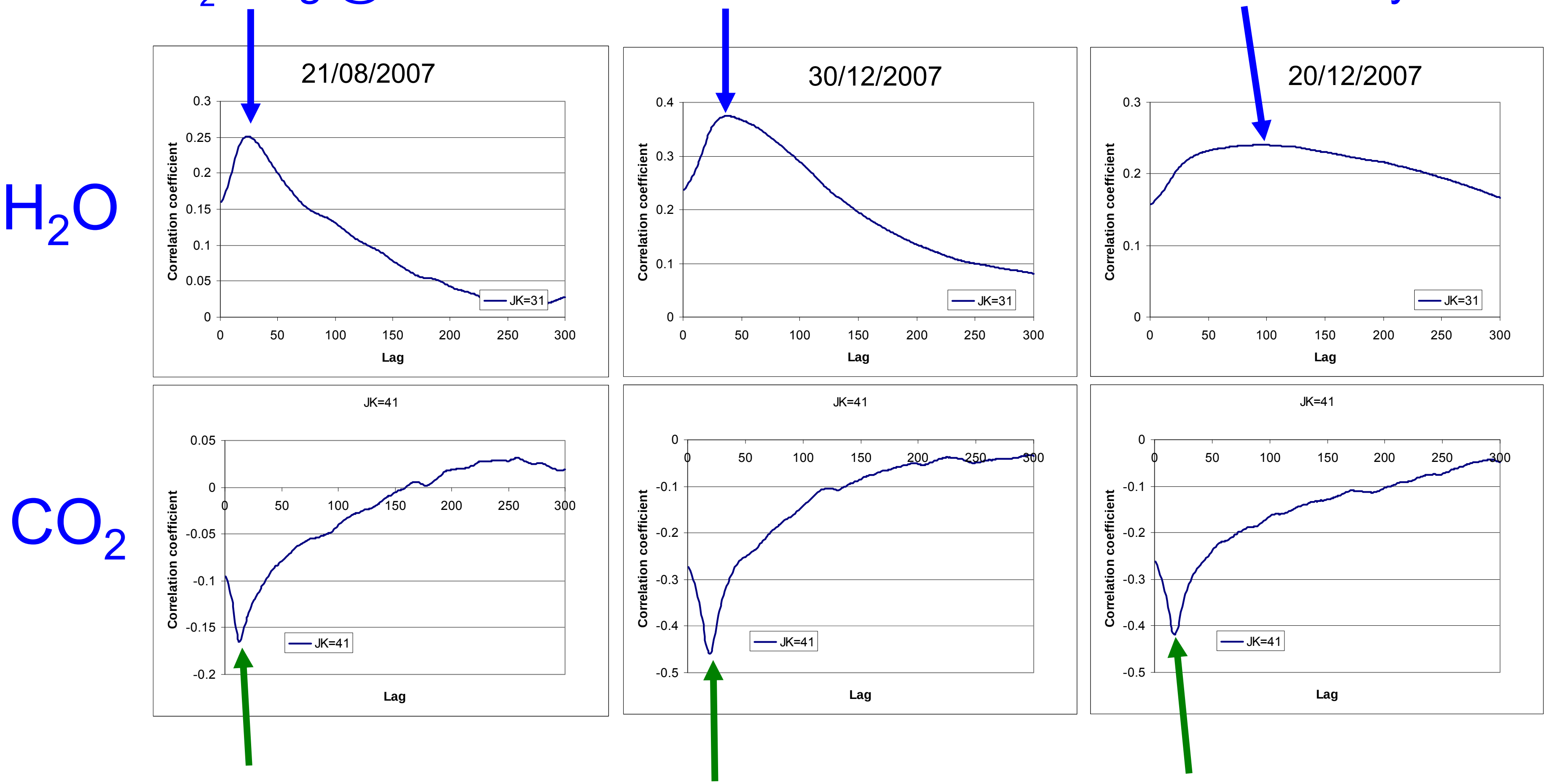
- Must also consider
  - Time-lag
  - Hi-frequency attenuation by air flow in tubing

Closed-path gas sampling



Lag at maximum correlation for closed path

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



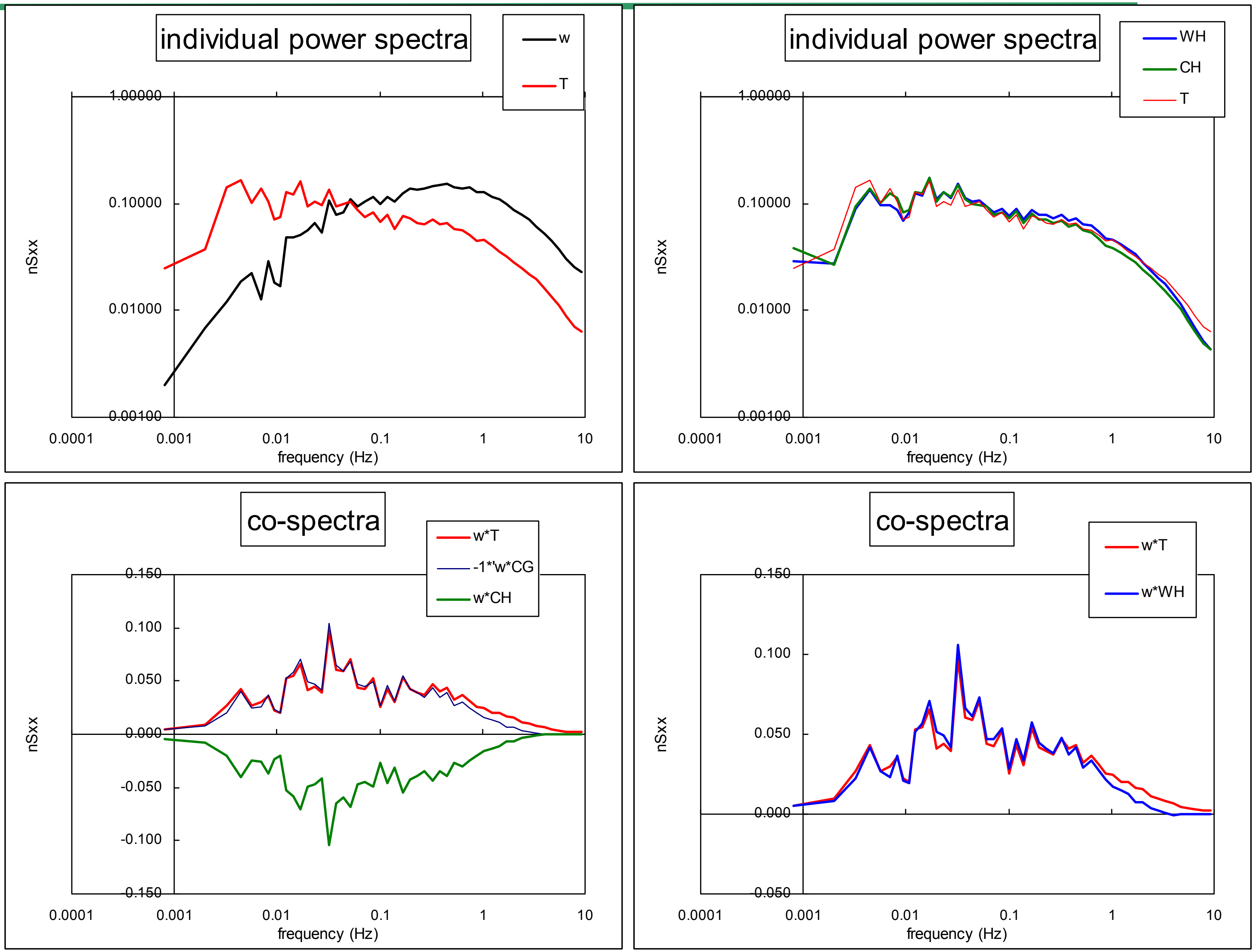
CO_2 lag @ max. correlation function of flow rate only

High Frequency Attenuation - Closed path

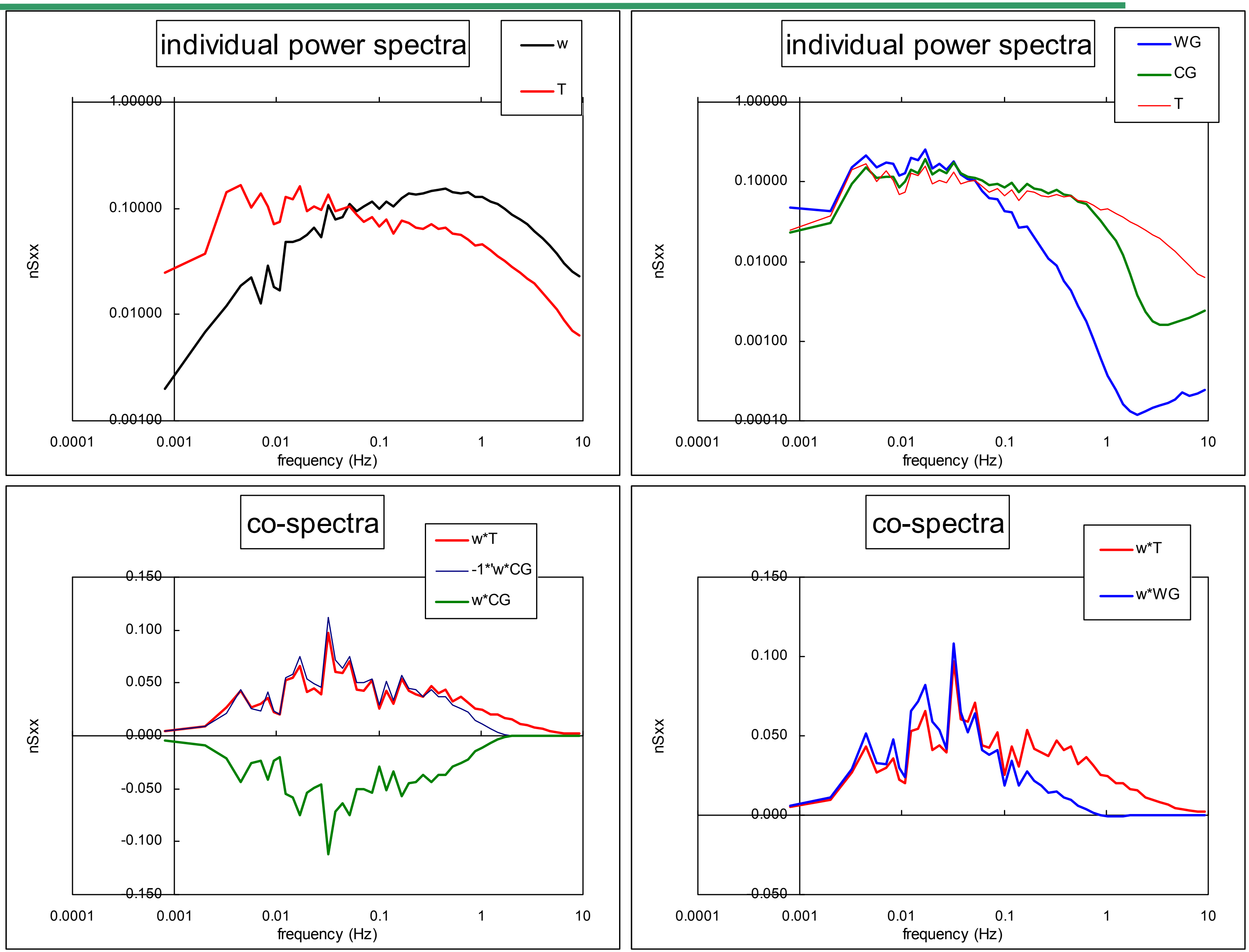
- Tubing acts like a low-pass filter by mixing the air
- Higher frequencies strongly attenuated – depends on:
  - Flow rate through tube
  - Tube diameter, length and material
  - Adsorption/desorption of gases on filter tubing walls

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

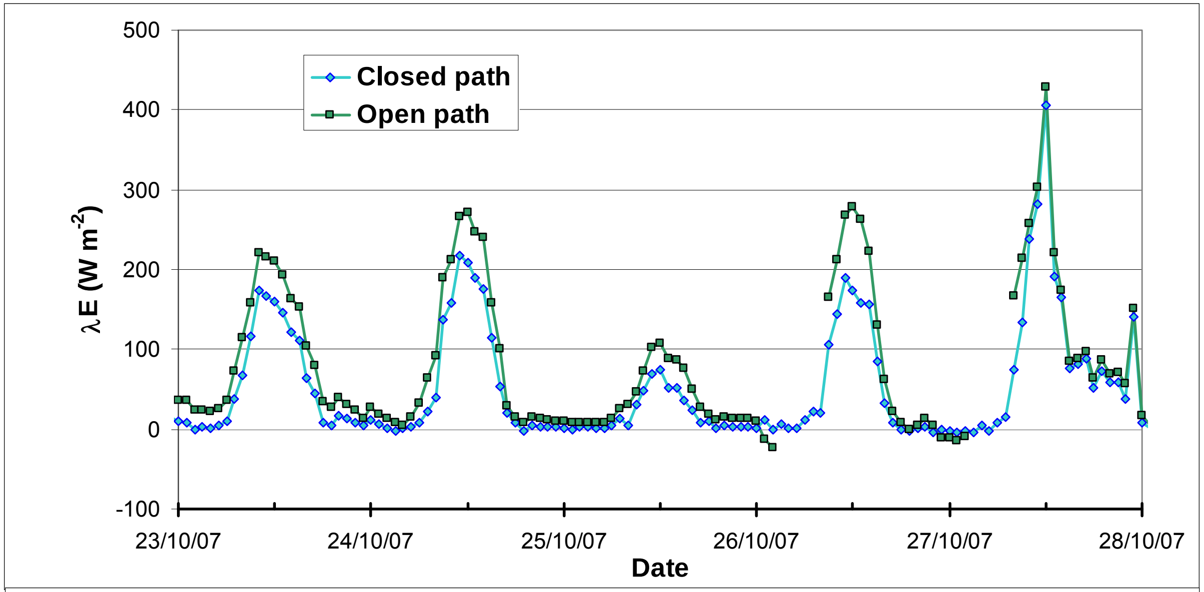
Open path spectra and co-spectra

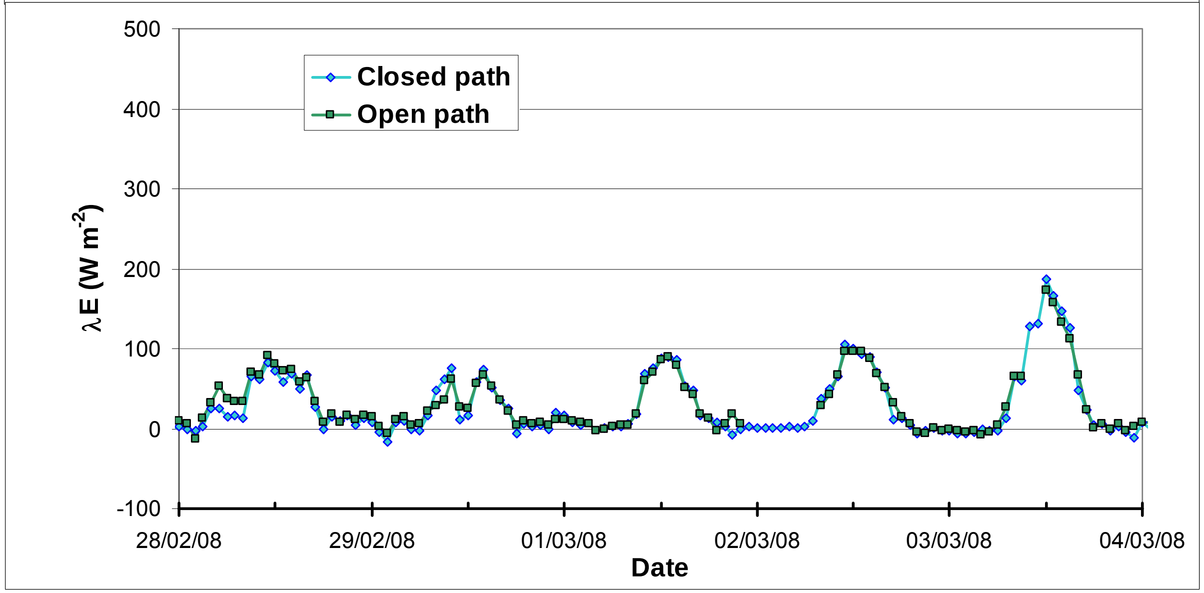


Closed path spectra and co-spectra

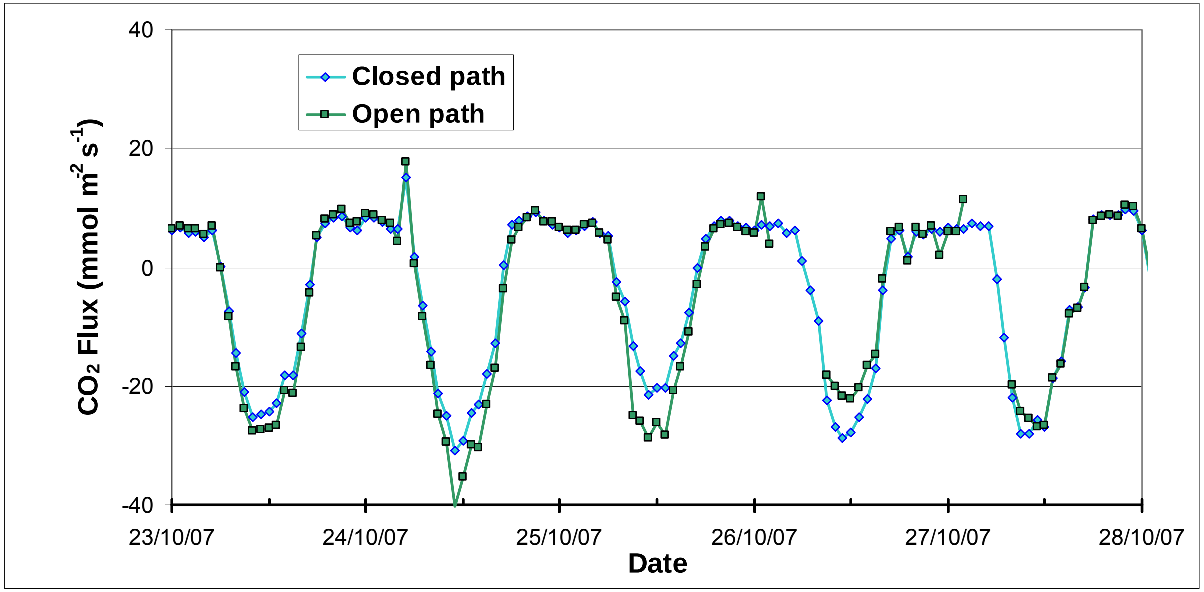


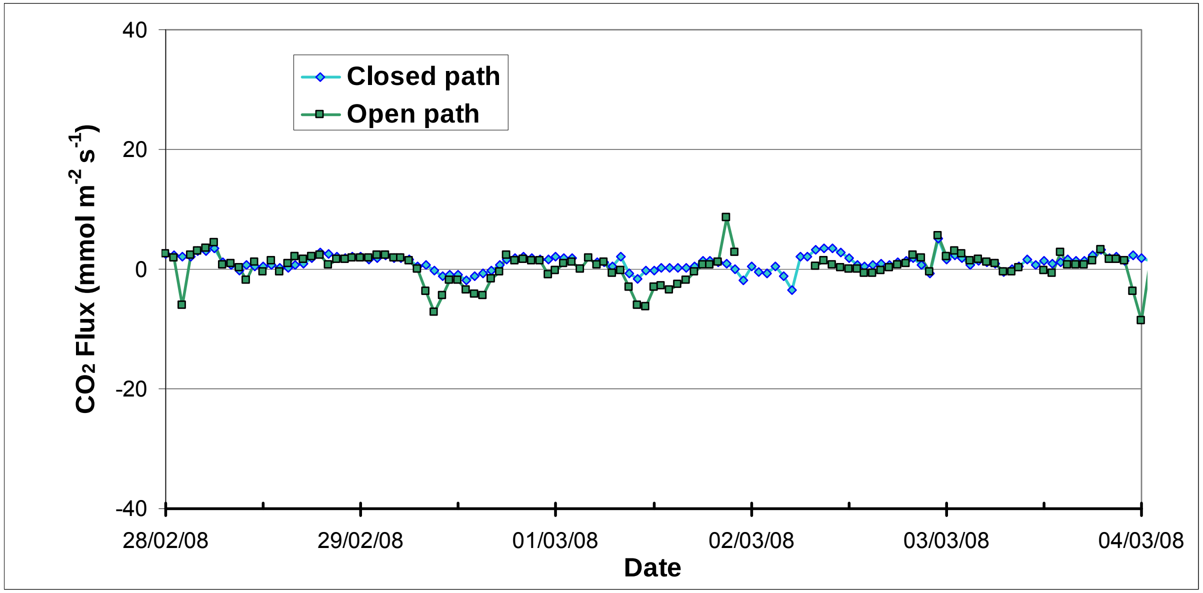
Time series of λE





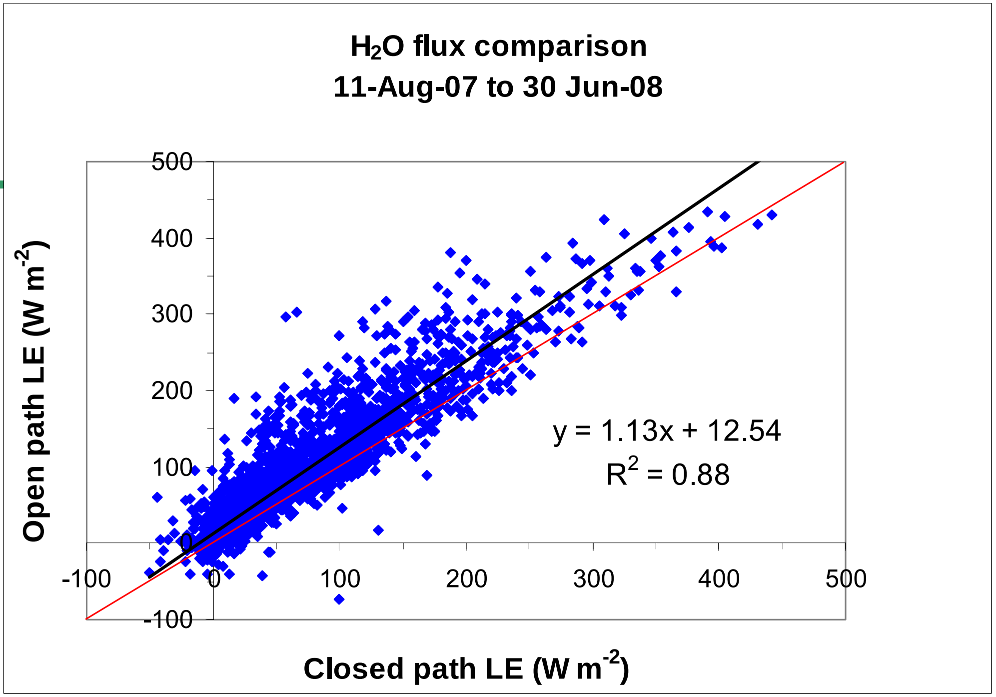
Time series of F_c



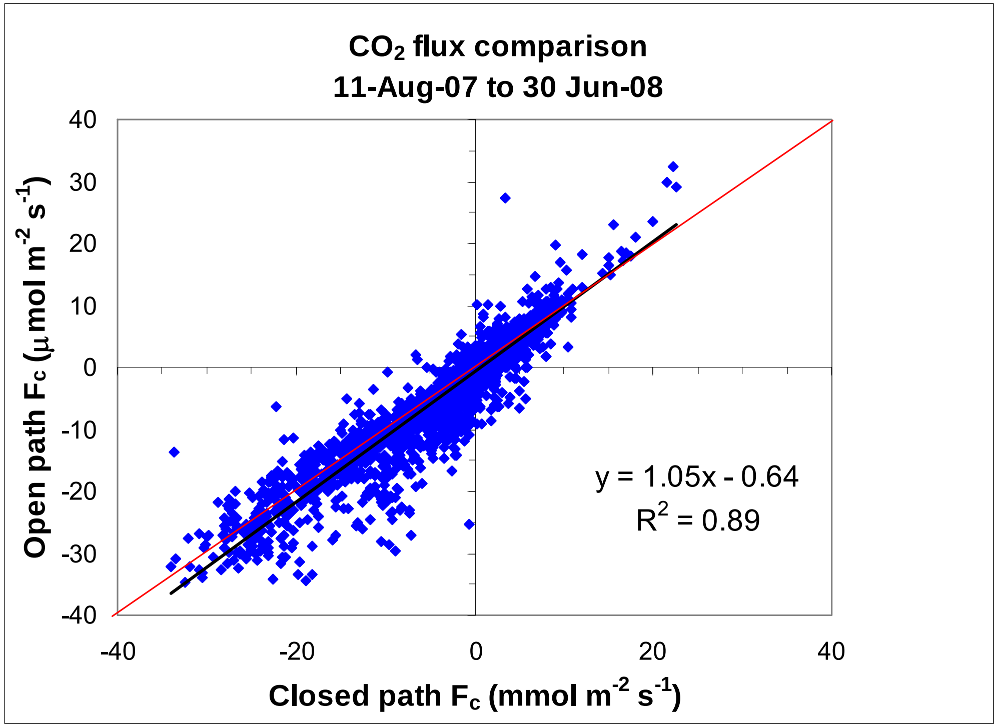


Open vs closed path instruments

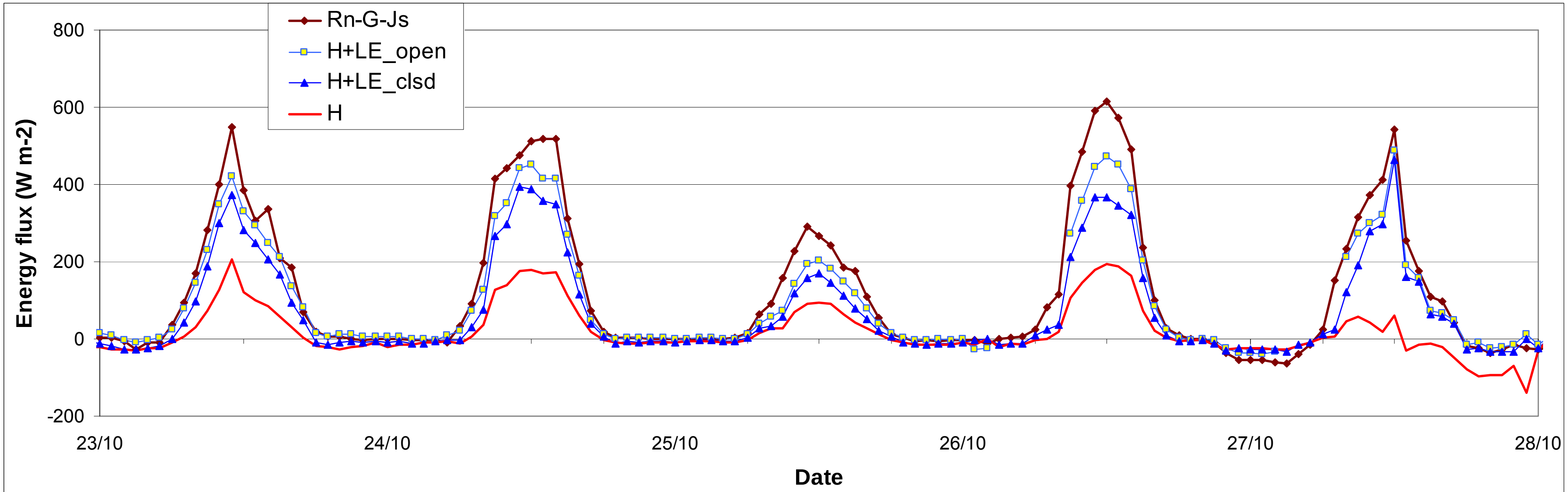
H_2O

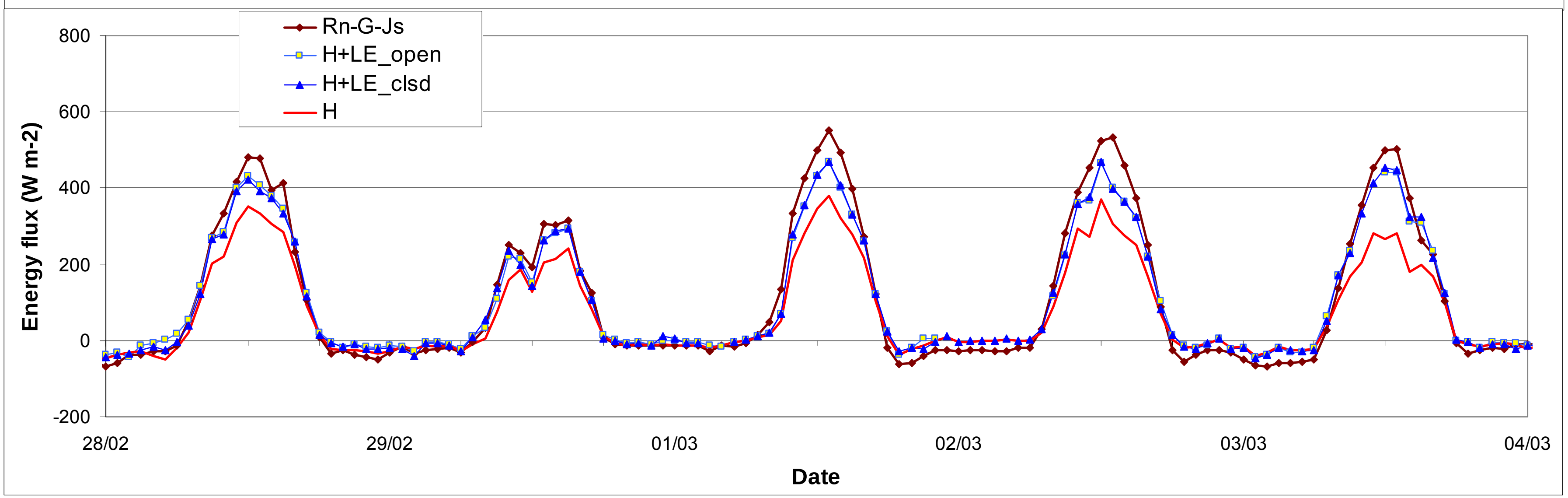


CO_2

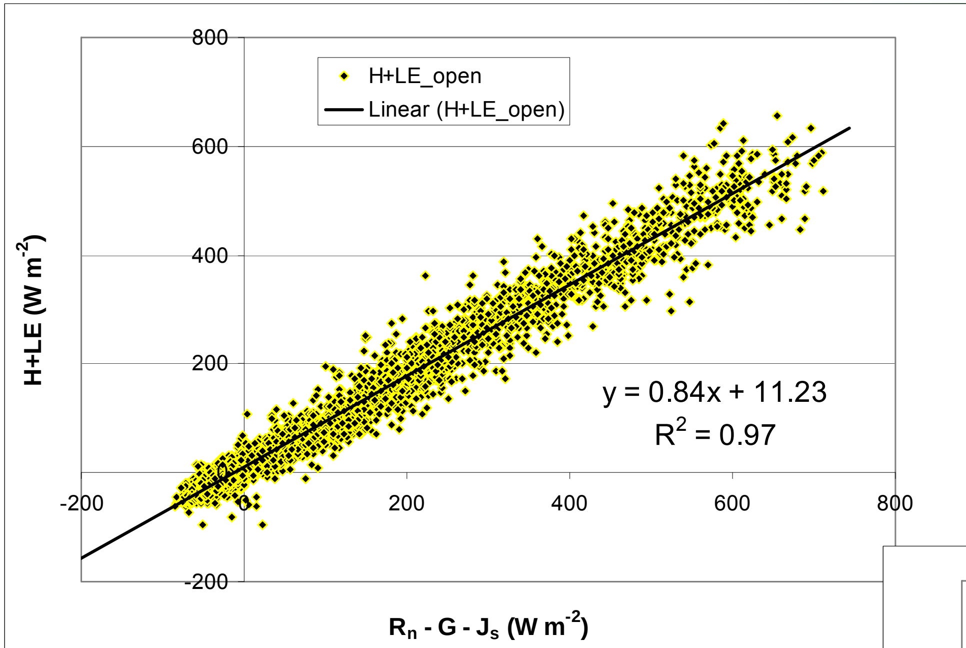


Time series of R_n-G-J_s, H + LE & H





Energy balance

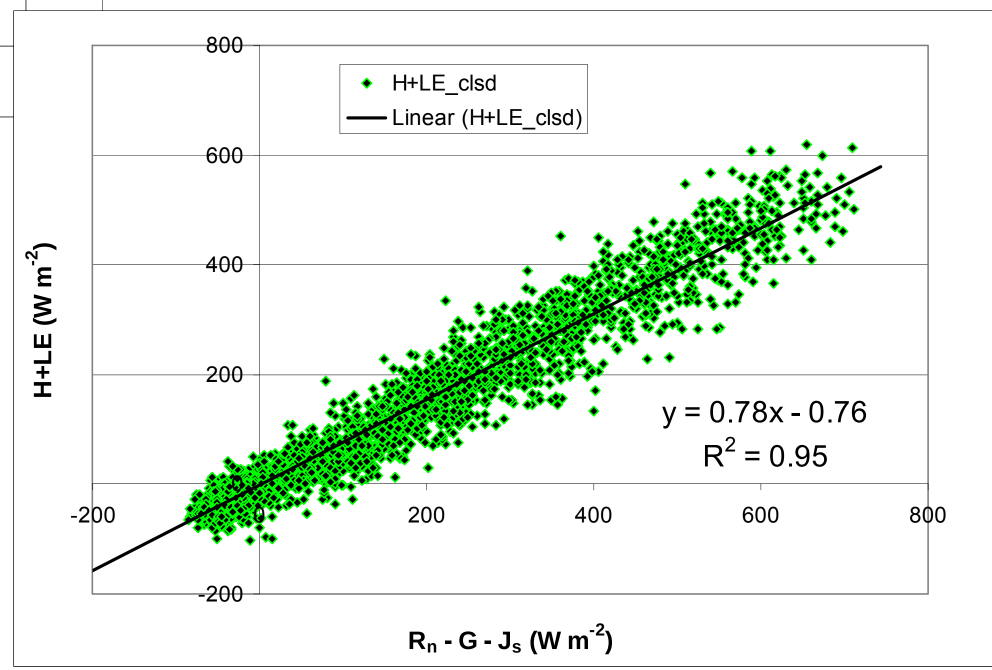


Open Path

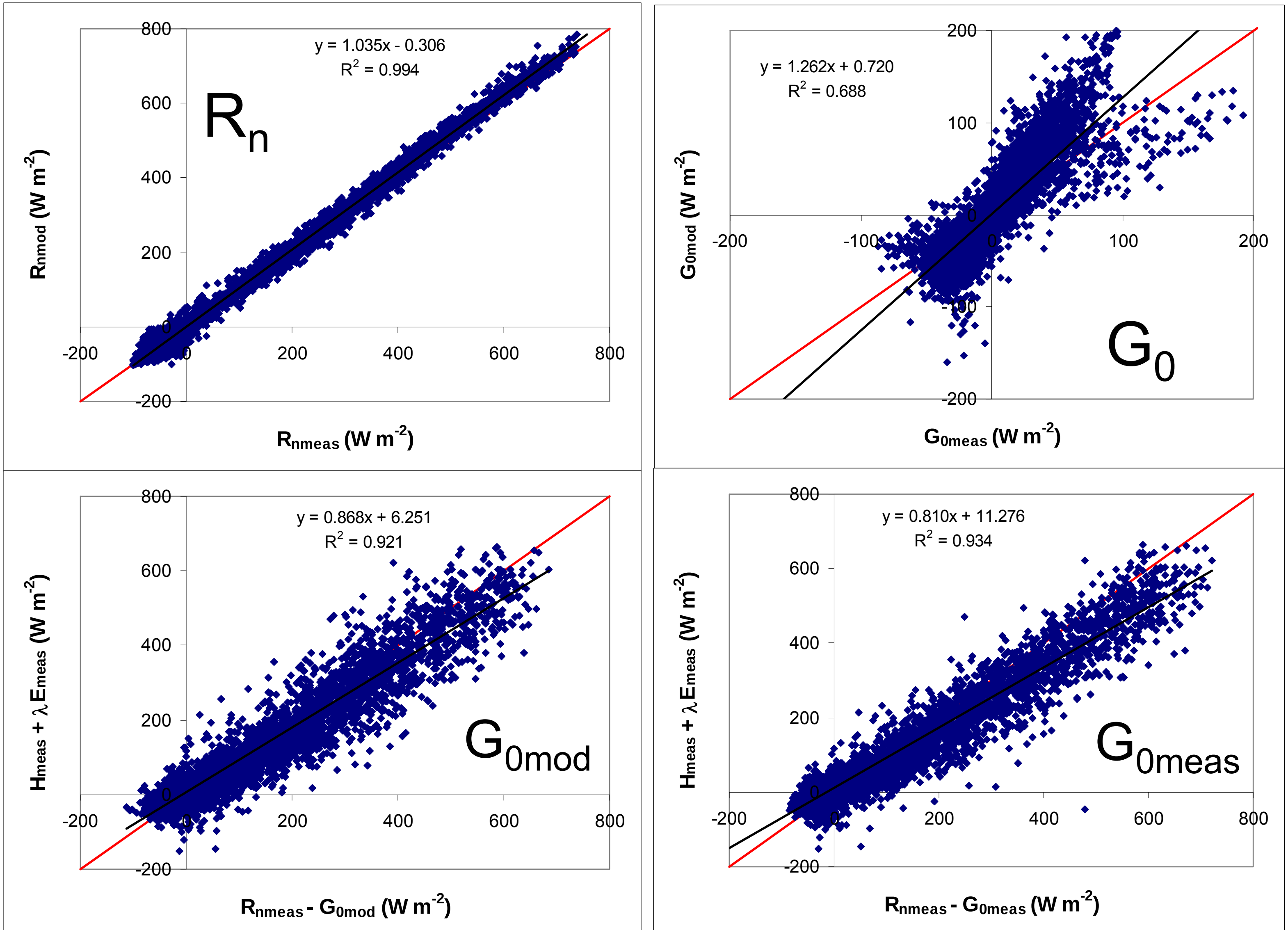
sma slope	0.850
lower b	0.845
upper b	0.854

Closed Path

sma slope	0.801
lower b	0.795
upper b	0.807



Modelling with CABLE



Summary (1):

- Open path analyser
- Strengths
  - Excellent spectral & cospectral response compared to temperature
  - Little need for high frequency correction due to line-averaging and instrument separation when measurements made at 4.5 m
- Weakness
  - High rates of data loss at Otway – mist, rain …
  - WPL corrections to CO_2 fluxes very large when H is large

Summary (2):

- Closed path analyser
- Low rate of data loss due to rain, mist …
- Calculate mixing ratios in real time – no WPL correction needed
- Strengths:CO_2
  - Good spectral & cospectral response compared to temperature
  - Well-defined lag as a function of flow rate
  - Close agreement with open path instrument

Strengths:H_2O

Agreement with open path instrument can be obtained with correction for loss of covariance at high frequencies

- Weakness
  - Poor spectral & cospectral response compared to temperature
  - Variable lag time @ maximum correlation – depends on flow rate and rel. humidity

Summary (3):

- Lack of energy closure
  - Better closure for open than closed path instruments
  - Change in energy storage term on layer above soil heat flux plates is very important but does not explain lack of energy closure
  - Advection?
    - Horizontal temperature gradients -> advection < 5 W m^{-2}
    - Vertical advection – needs non-zero mass flux of dry air