Workshop on

EddyUH: a software for eddy covariance flux calculation

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Eddy Covariance technique: flux corrections

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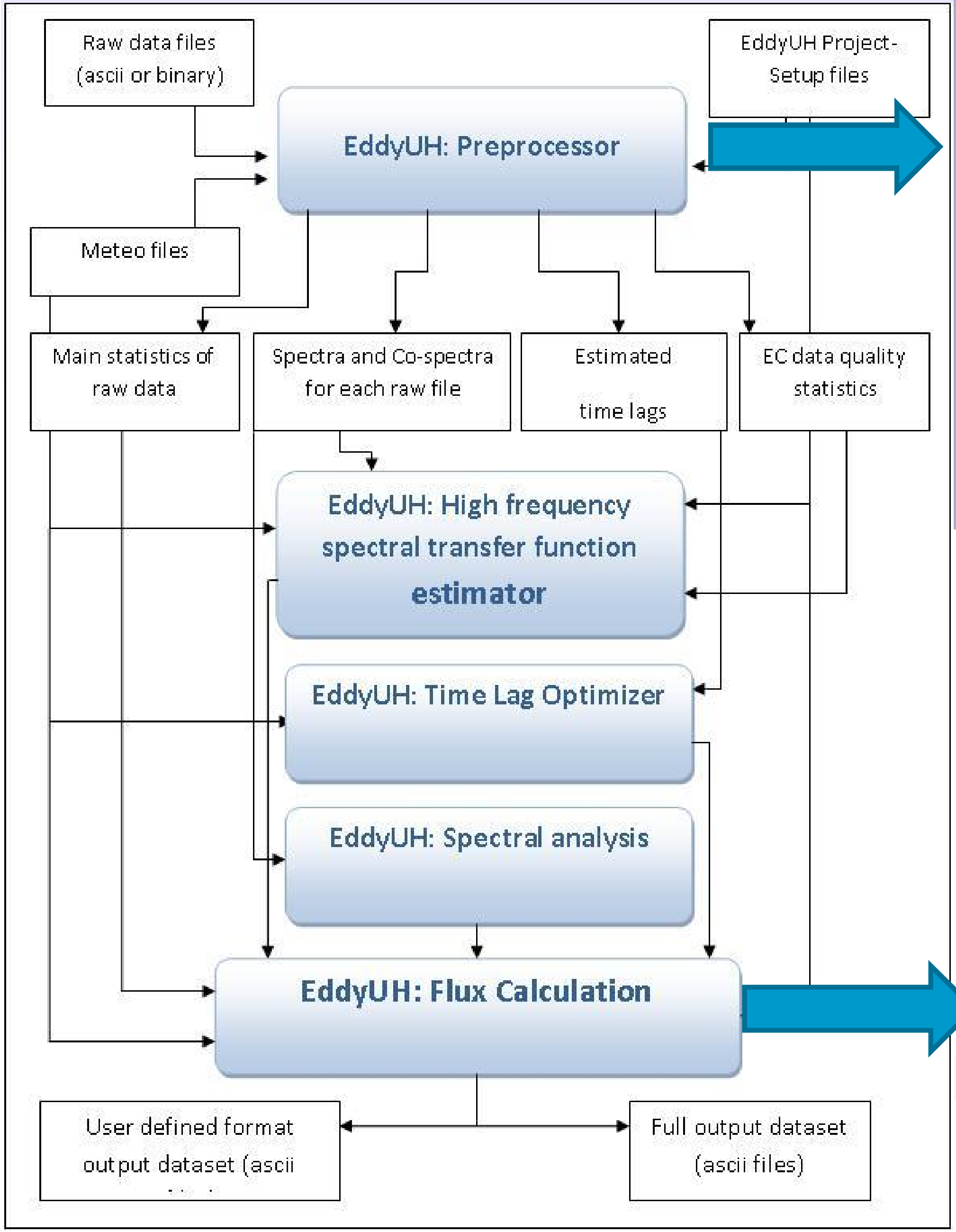
EddyUH: flowchart of p



- Read EC rawdata and meteo files
- Units conversions
- Calibration
- Dilution correction (if needed)
- Despiking
- Coordinate rotation
- Appliyng detrending method
- Calculate statistics
- Correcting for time lag
- Calculate covariances

- Frequency response correction
- Conversion of buoyancy flux into SH flux
- WPL correction (if needed)
- Spectroscopic correction (if needed)
- Burba correction (if needed)
- Quality criteria and flag

Derivation of additional parameters from EC measurements

Stability parameter

$$\varsigma = \frac{z-d}{L}$$

$$u_* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$$

Obukhov length (units: m)

$$L = -\frac{T_0 u_*^3}{\kappa g \overline{w'T_v'}}$$

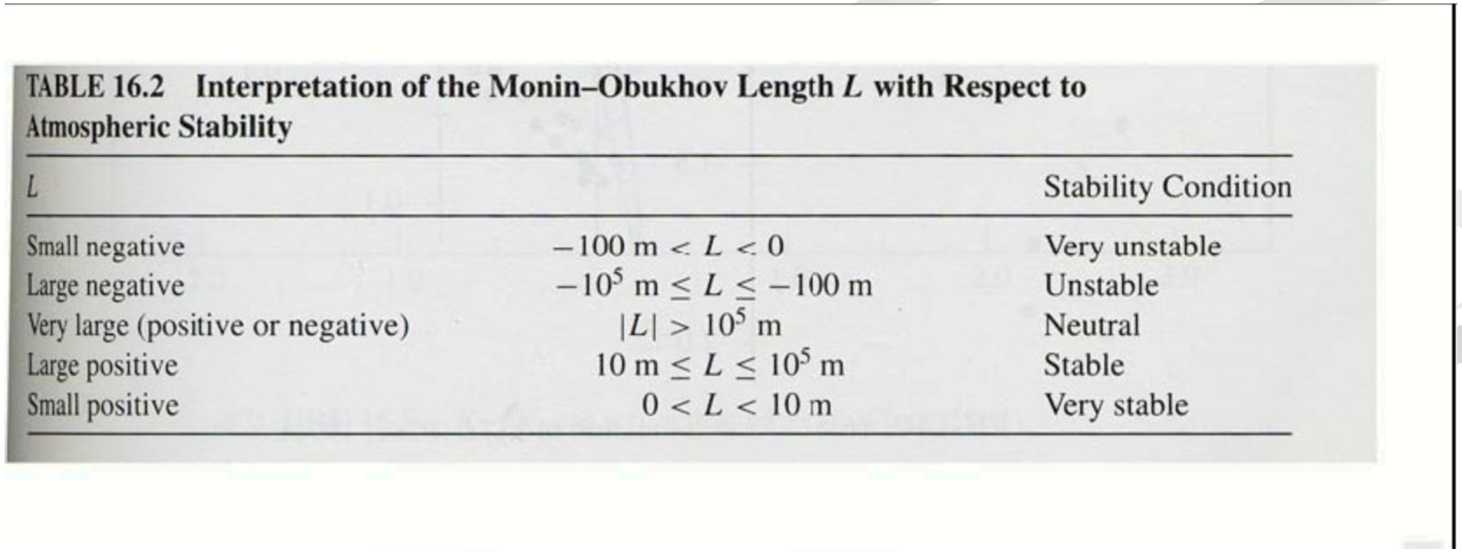


TABLE 16.2 Interpretation of the Monin–Obukhov Length L with Respect to Atmospheric Stability

L		Stability Condition
Small negative	$-100 \text{ m} < L < 0$	Very unstable
Large negative	$-10^5 \text{ m} \leq L \leq -100 \text{ m}$	Unstable
Very large (positive or negative)	$\lvert L \rvert > 10^5 \text{ m}$	Neutral
Large positive	$10 \text{ m} \leq L \leq 10^5 \text{ m}$	Stable
Small positive	$0 < L < 10 \text{ m}$	Very stable

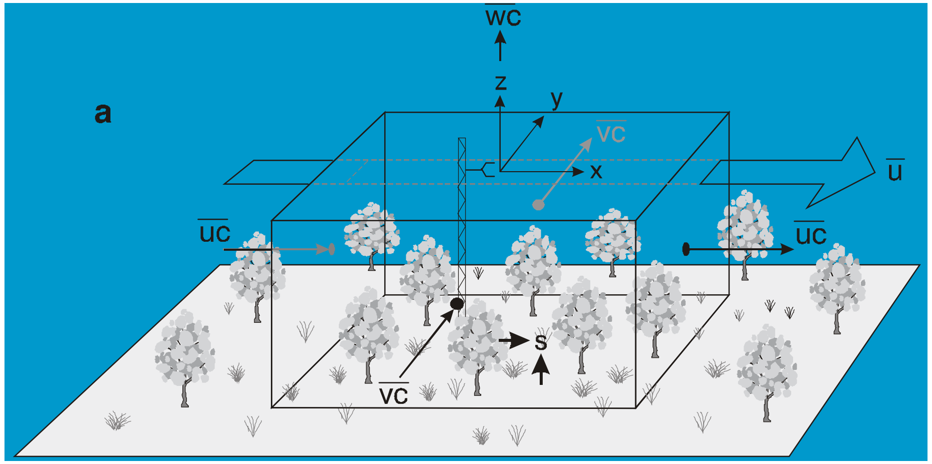
Concentration definitions

- Mass density ($\boldsymbol{\rho}_s$, kg m^{-3}) and Molar density (c_s mole m^{-3}) represent the mass and the number of moles of *s* per volume of air, respectively.
- Mole fraction (mole $mole^{-1}$) is the ratio of the moles of *s* divided by the total number in the mixture (also equal to the ratio of the constituent partial pressure to the total pressure)
- molar mixing ratio ($\boldsymbol{\chi}_{s,m}$, mole $mole^{-1}$) is the ratio of the constituent mole number to those of dry air.
- mass mixing ratio ($\boldsymbol{\chi}_s$, kg kg^{-1}) is the ratio of the mass of the constituent to the mass of dry air. These variables are related by the perfect gas law.

The integral scalar budget equation

The connection between surface exchange and eddy flux of a scalar quantity *s* is achieved by integrating over a conceptual control volume the one point time-averaged conservation equation previously derived.

In homogeneous surface layer, terms II and III are assumed negligible.



$$\frac{1}{4L^2}\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\left[\underbrace{\overline{\rho_d}\frac{\partial\overline{\chi_s}}{\partial t}}_{I}+\cancel{\underbrace{\overline{\rho_d}\,\overline{u}\frac{\partial\overline{\chi_s}}{\partial x}+\overline{\rho_d}\,\overline{v}\frac{\partial\overline{\chi_s}}{\partial y}+\overline{\rho_d}\,\overline{w}\frac{\partial\overline{\chi_s}}{\partial z}}_{II}}+\cancel{\underbrace{\frac{\partial\overline{\rho_d}\,\overline{u'\chi_s'}}{\partial x}+\frac{\partial\overline{\rho_d}\,\overline{v'\chi_s'}}{\partial y}}_{III}}+\underbrace{\frac{\partial\overline{\rho_d}\,\overline{w'\chi_s'}}{\partial z}}_{IV}\right]dz\,dx\,dy$$

$$=\frac{1}{4\rho L^2}\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\underbrace{\overline{S_b}\,dz\,dx\,dy}_{V}$$

In homogeneous surface layer

$$\underbrace{\int_0^{h_m} \overline{\rho}_d \overline{\frac{\partial \chi_s}{\partial t}} dz}_{I} + \underbrace{\overline{\rho}_d \overline{w' \chi_s'} \Big|_{h_m}}_{IV} = \underbrace{NEE}_{V}$$

Net Ecosystem Exchange(V) = EC flux at h$_m$(IV) + Storage change flux(I)

This equation is at the basis of EC method!

Cross-wind correction

- Schotanus et al. 1983 & Liu et al. 2001
- Problem
  - Sonic temperature is defined using transit times of sonic pulses along the three axes in a sonic anemometer
  - The path that a sonic pulse takes between a pair of transducers is distorted by winds oriented across its axis, giving rise to cross-wind contamination of sonic temperature measurements.

- Schotanus et al.1983 for sonic measuring

sonic temperature along <u>one path</u>

$$\overline{w'T'}_{SCH} = \overline{w'T'} + \frac{2}{403}\bar{u}\overline{u'w'}$$

- Liu et al. 2001 give coefficients for different types of sonics

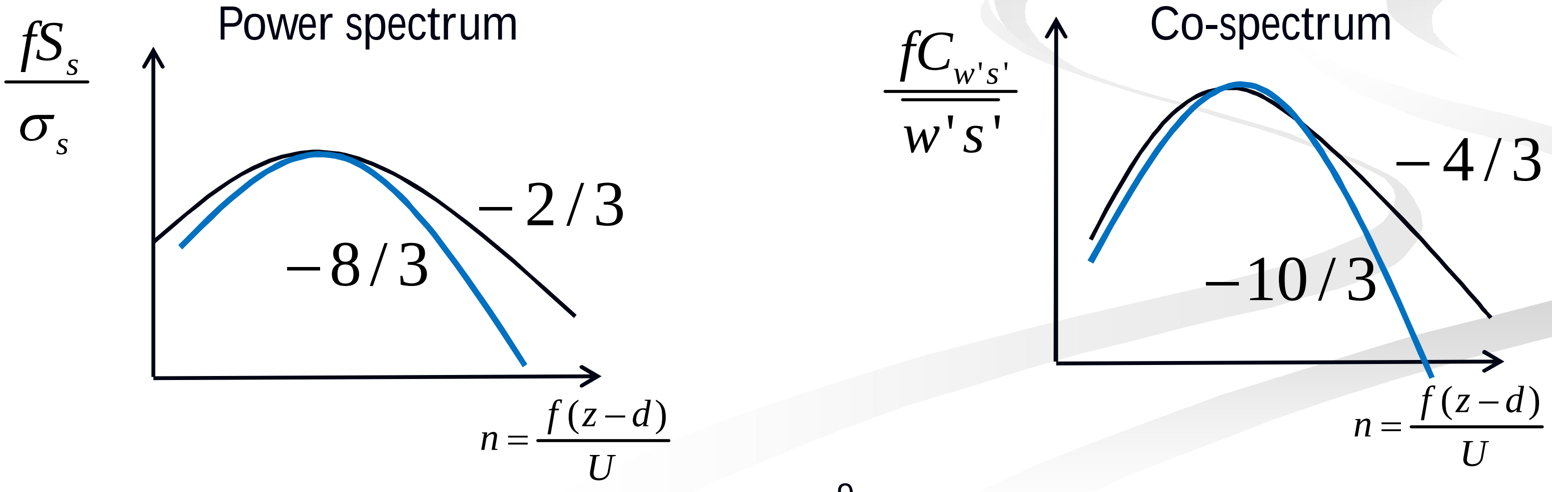
$$\overline{w'T'}_{LIU} = \overline{w'T'} + \frac{2}{403}\left(A\bar{u}\overline{u'w'} + B\bar{v}\overline{v'w'}\right)$$

Applied online	Correction needed during post-processing
Campbell CSAT3	Gill Solent R2
Gill Solent HS and R3	ATI K-Probe
METEK USA-1 if use of the flux “hf”	METEK USA-1 if covariance calculated from high frequency raw data or use of the covariance “zTcov”
Young 81000	

Frequency response corrections (Spectral corrections)

- Problem
  - Flux loss at high frequency due to the incapability of the measurement system to detect small scale variation
  - Flux loss at low frequency due to limited averaging period (30 min) and trend removal
- Correction always increases flux!
- Correction may be done theoretically or experimentally
- Correction is different for $\overline{u'w'}, \overline{w'T'}, \overline{w's'}$ (also different for open- and closed-path)

Example of low and high frequency loss



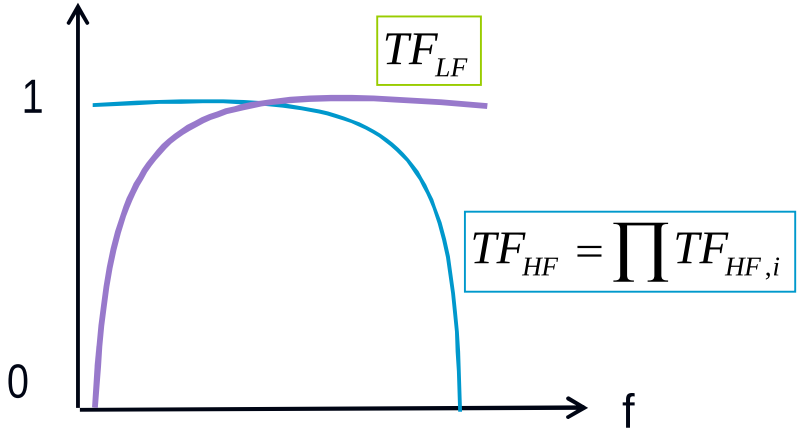
- The relationship between the measured and the real covariance is the flux attenuation (F_a). The relationship is described by a frequency dependent transfer function (*TF*)

$$F_a = \frac{\overline{w's'}_{meas}}{\overline{w's'}_{real}} = \frac{\int_0^\infty TF(f)C_{ws}(f)df}{\int_0^\infty C_{ws}(f)df}$$

C_{ws} is here the normalized model co-spectrum

Denominator =1 according to its definition

- The transfer function consists of a low frequency and high frequency part



$$TF_{HF} = \prod TF_{HF,i}$$

$$TF = TF_{LF} TF_{HF}$$

Cut-off frequency is defined as the point where TF=$2^{-1/2}$

- Transfer functions are needed in order to do the spectral correction!

Low frequency correction

- Depends on the type of averaging (mean removal, linear de-trending, non-linear de-trending)
- Correction is performed theoretically
- For linear de-trending (Rannik and Vesala, 1999)

$$TF_{LF,LD} = 1 - \left[\frac{\sin(\pi f T)}{\pi f T} \right]^2 - 3 \frac{\left(\sin(\pi f T) - \pi f T \cos(\pi f T) \right)^2}{\left(\pi f T \right)^4}$$

- For mean removal (block averaging) (e.g. Lee at al. 2004, p.15)

$$TF_{LF,MR} = \left[\frac{\sin(\pi f T)}{\pi f T} \right]^2$$

T = averaging time
f = natural frequency

- Causes an addition to flux of 0.7-6.1% (Aubinet et al. 2000)

High frequency correction: theoretical approach

- Superposition of terms representing different causes of flux loss (Moore 1986, Leuning and Judd 1996, Moncrieff et al., 1997)

$$TF_{HF,wu} = TF_{d,S}(f)\,TF_{w}(n_p)$$

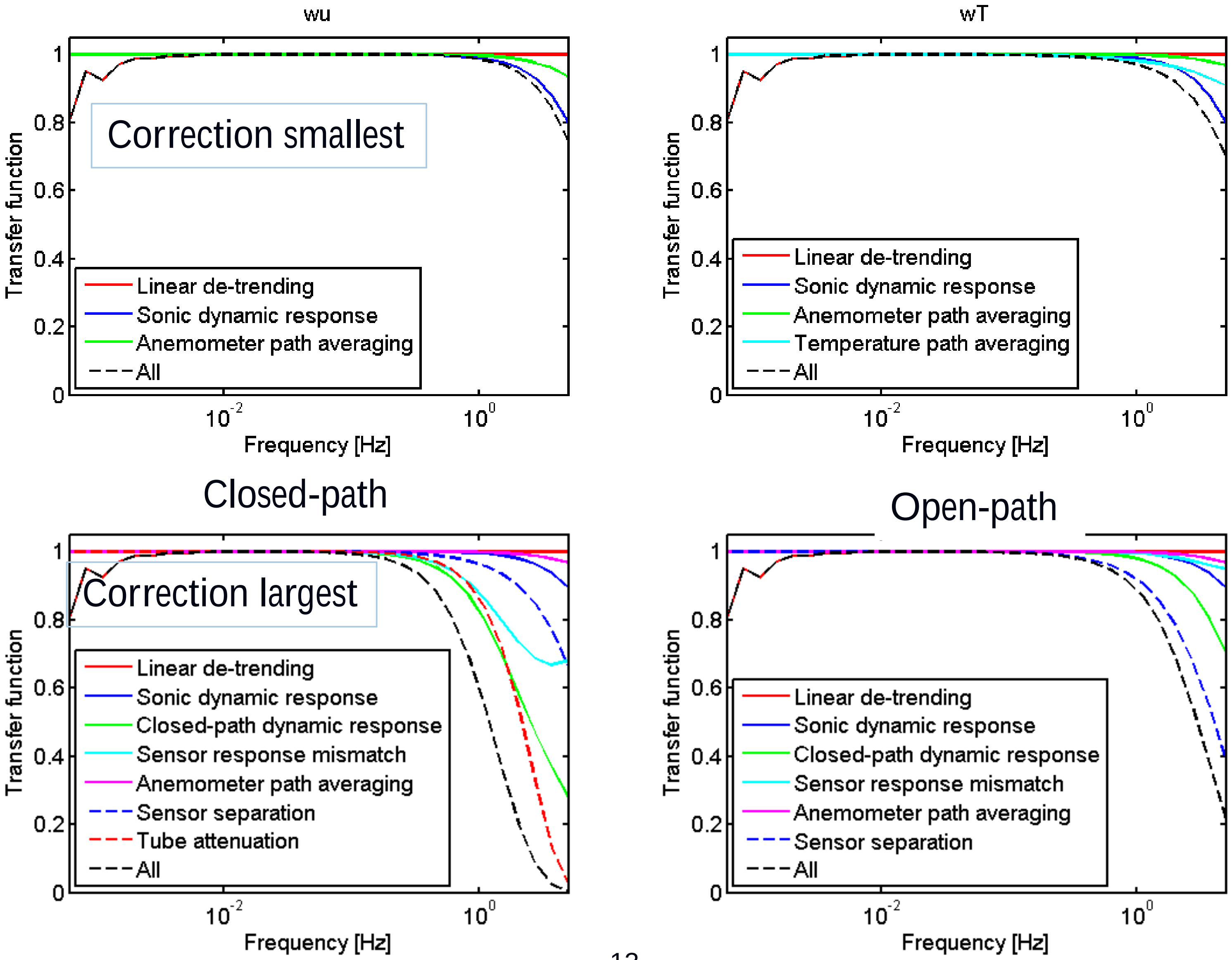
$$TF_{HF,wT} = TF_{d,S}(f)\,TF_{t}(f)\,TF_{w}(n_p)$$

$$TF_{HF,ws,OP} = TF_{d,OP}(f)\,TF_{d,S}(f)\,TF_{m}(f)\,TF_{w}(n_p)\,TF_{s}(n_s)$$

$$TF_{HF,ws,CP} = TF_{d,CP}(f)\,TF_{d,S}(f)\,TF_{m}(f)\,TF_{w}(n_p)\,TF_{s}(n_s)\,TF_{a}(f)$$

Dynamic response
Path averaging
Sensor response mismatch
Sensor separation loss
Attenuation in tube

Theoretical transfer functions at SMEARIII (from Annika Nordbo)



Correction smallest

Closed-path

Correction largest

Open-path

Empirical approach

- Theoretical determination works ok for $\overline{w'T'}$ and open-path gas fluxes but not for closed-path (e.g. Aubinet et al. 2000)
- The goal is to determine the total TF_{HF} from average measured co-spectra.
- The co-spectrum of $\overline{w'T'}$ is used as the ideal un-attenuated co-spectrum. Similarity between scalars assumed.
- TF_{HF} for water vapour depends on relative humidity (e.g. Mammarella et al. 2009)

  → different TF_{HF} for different RH classes

Transfer function derived from measured cospectra

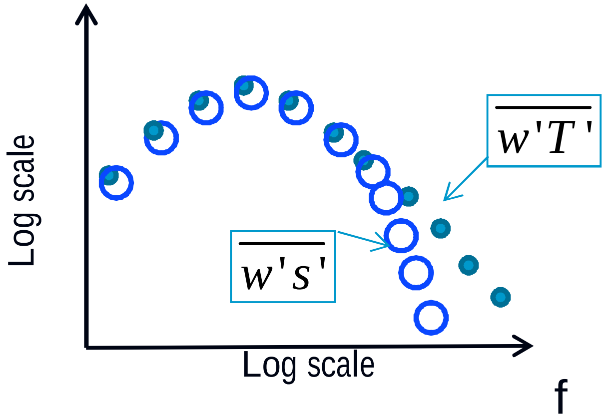
Measured cospectra for s (CO2, H2O,…)

$$TF_{HF} = \frac{C_{w's'}\Big/\overline{w's'}}{C_{w'T'}\Big/\overline{w'T'}} = \frac{1}{1+(2\pi f\tau_s)^2}$$

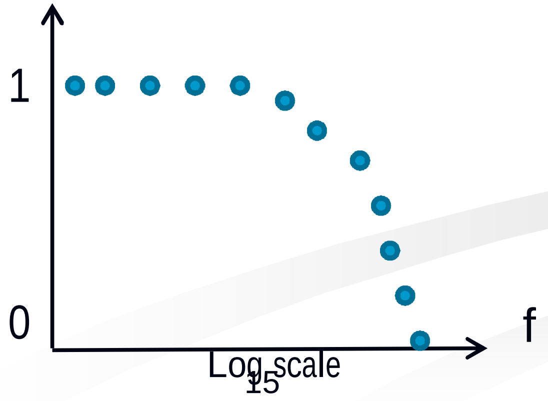
Measured cospectra for T

Response time (time constant)

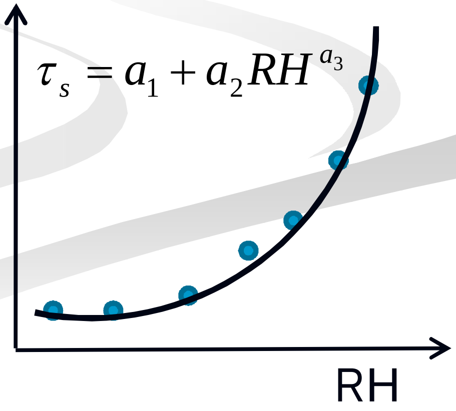
Average log-binned normalized co-spectra for T and a scalar s

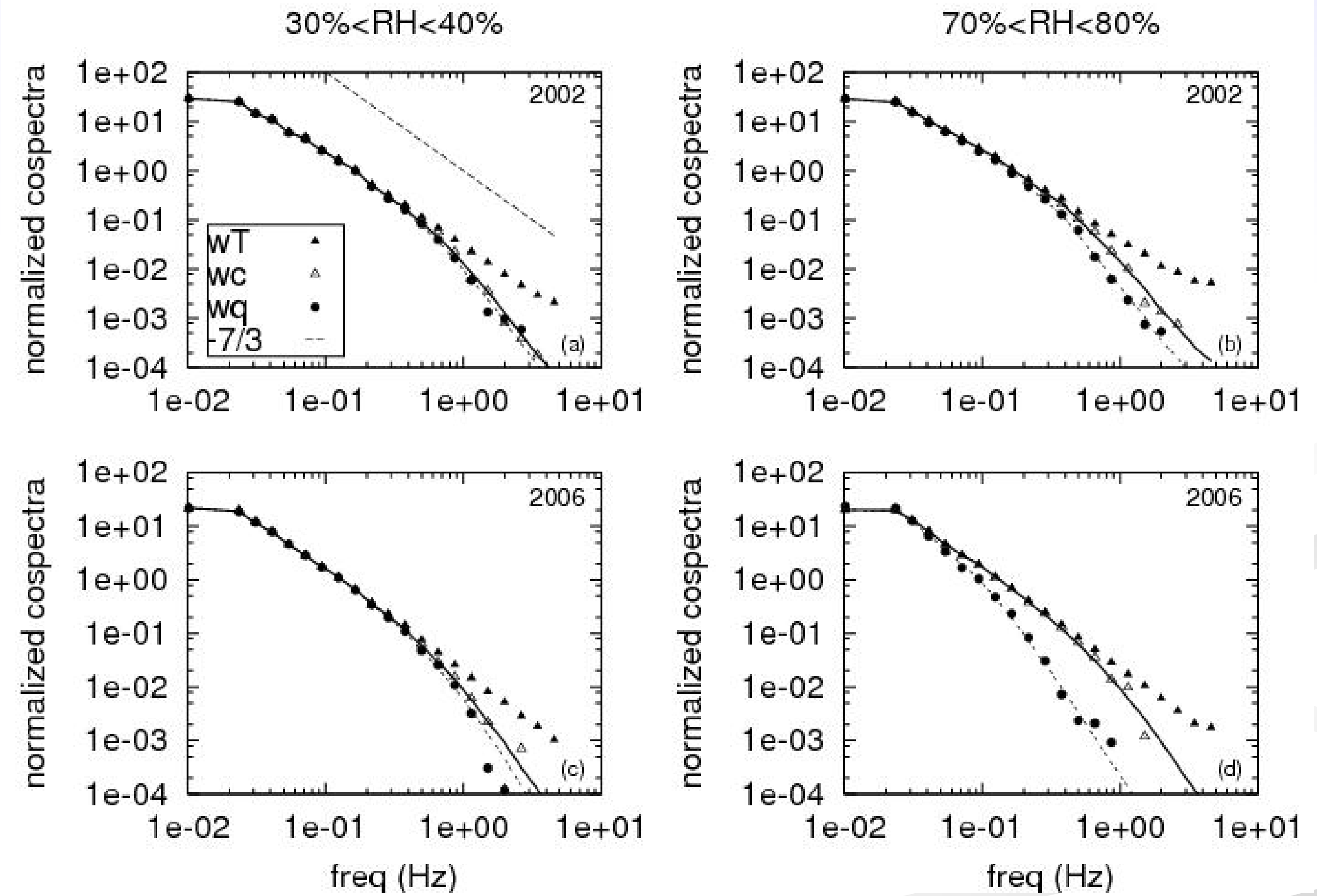


Transfer function

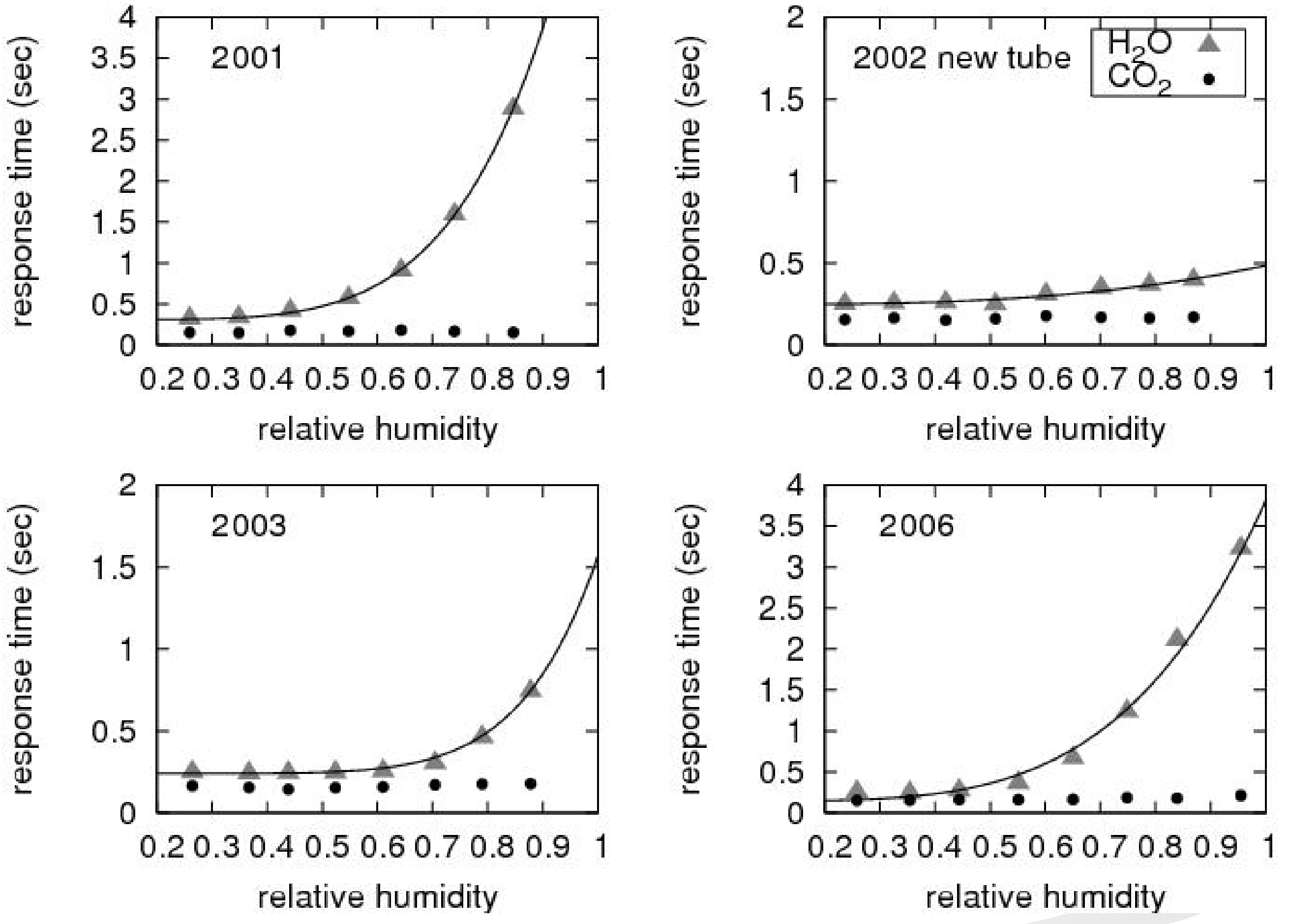


Response time as a function of RH





Mammarella et al., 2009



Mammarella et al., 2009

How to correct the flux?

- Flux attenuation is the integral of TF times model co-spectrum. Values [0,1]

$$\boxed{F_a = \frac{\overline{w's'}_{meas}}{\overline{w's'}_{real}} = \int TF(f)C_{model}(f)df} \qquad \text{EQ.1}$$

- The correction

$$\boxed{\overline{w's'}_{real} = \frac{\overline{w's'}_{meas}}{F_a}}$$

In practical how we calculate F_a ?

Standard approach: We numerically solve the integral in EQ.1 in the frequency range 1e-5 – 100 Hz.

$TF = TF_{HF} \cdot TF_{LF}$ Total transfer function.

C_{model} is your own cospectral model for w’T’, derived by fitting your measured cospectra, or the surface layer cospectral model, for example in the form proposed by Horst, 1997.

unstable condition ((z-d)/L<0)

$n_m = 0.085;$

$$\frac{fC_{wT}(f)}{\overline{w'T'}} = \begin{cases} \dfrac{1.05n/n_m}{(1+1.33n/n_m)^{7/4}} & \text{for } n \le 1.0 \\ \dfrac{0.387n/n_m}{(1+0.38n/n_m)^{7/3}} & \text{for } n \ge 1.0 \end{cases}$$

stable condition ((z-d)/L>0)

$n_m = 2\text{-}1.915/(1+0.5(z\text{-}d)/L);$

$$\frac{fC_{wT}(f)}{\overline{w'T'}} = 0.637(n/n_m)./(1+0.91(n/n_m)^{2.1});$$

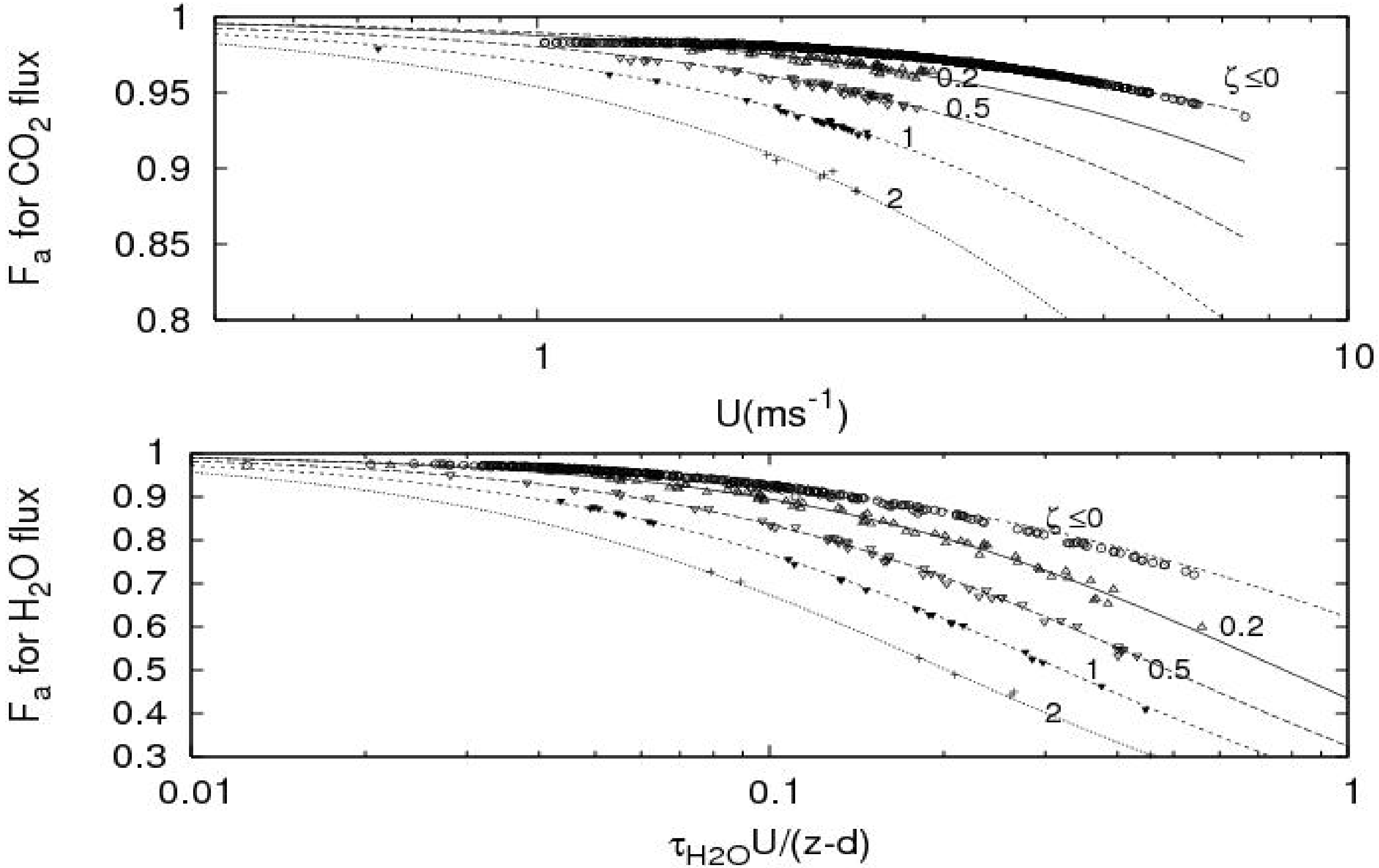
Horst(1997) analytical approach: the integral in EQ.1 is analytically solved and only the TF_{HF} is included.

Then the flux attenuation F_a can be simply calculated as

$$F_a = \frac{\overline{w's'}_{meas}}{\overline{w's'}_{real}} = \frac{1}{\left[1+2\pi n_m \tau_s \frac{U}{(z-d)}\right]^{\alpha}}$$

$$\text{where } \begin{cases} \alpha = 1 \text{ in stable condition (z-d/L>0)} \\ \alpha = 7/8 \text{ in unstable condition (z-d/L<0)} \end{cases}$$

SMEAR II CP system

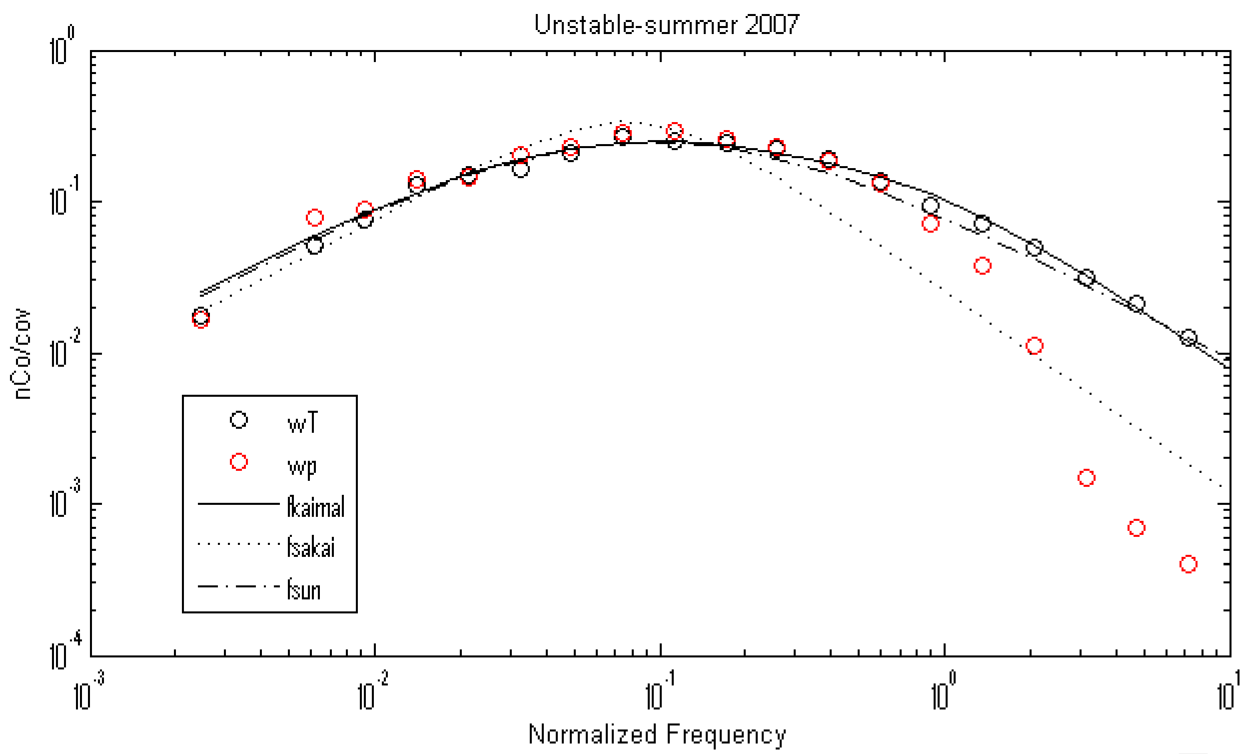


Lines: analytical approach

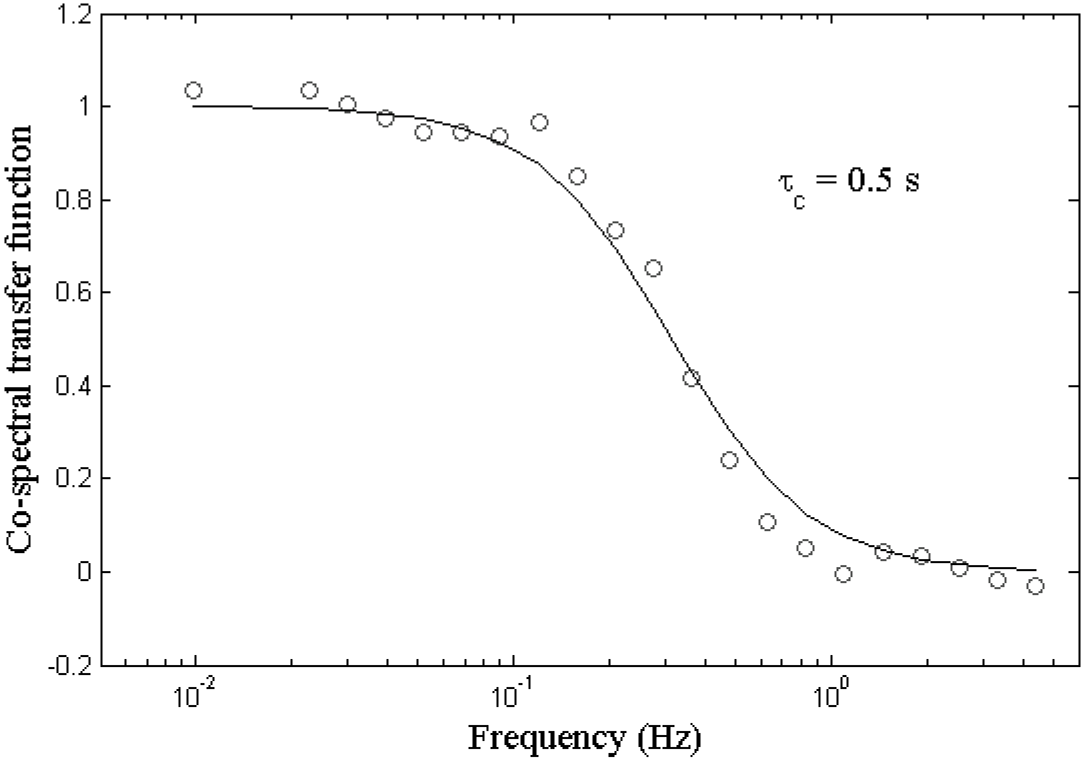
Symbols : numerical integration EQ.1

Mammarella et al., 2009

SMEAR III Aerosol particle averaged cospectrum



SMEAR III Aerosol particle transfer function



Conversion of sonic temperature buoyancy flux into the sensible heat flux (Sonic heat correction)

- Schotanus et al. 1983
- Problem
  - If the sonic gives out the sonic temperature instead of the real temperature, the flux must be corrected

- The definition of virtual and sonic temperatures (e.g. Kaimal and Gaynor, 1991)

$$H = \rho C_p \left(\overline{w'T_s'} - 3.210 \cdot 10^{-4} \, \overline{T} \, \overline{w'\chi_{H2O}'} \right)$$

$$c^2 = 403T(1 + 0.32e/p),$$

$$T_s = \frac{m_d}{\gamma R} \frac{\left(c_1^2 + c_2^2 + c_3^2\right)}{3} = \frac{1}{403} \frac{\left(c_1^2 + c_2^2 + c_3^2\right)}{3}$$

$$T_v = T\left(1 + 0.38e/p\right),$$ Virtual temperature

$$T_s = T\left(1 + 0.32e/p\right),$$ Sonic temperature

c = Speed of sound in air [ms-1]
T = Temperature [K]
e = Water vapor pressure
p = Atmospheric pressure
m_d = 28.96 10-3 kg mol-1 molecular mass of dry air
γ = 1.4, the ratio of constant pressure and constant volume heat capacities

T_v is the temperature at which dry air has the same density as moist air at the same pressure.

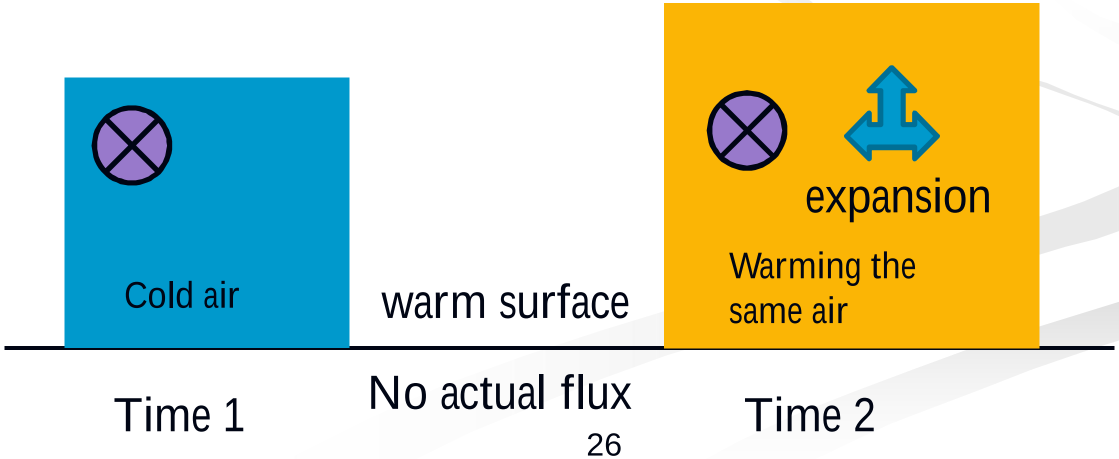
WPL-correction

- Webb et al. (1980)
- Problem:
  - Compensates for the effect of density fluctuation (temperature and water vapor fluctuations) on measured CO_2 and H_2O ($CH_{4...}$) fluctuations
  - Gas analysers DO NOT MEASURE mixing ratios, but either mass or molar density.

- Example 1 (temperature fluctuation)

a surface with zero CO_2 or H_2O flux, warming air of constant gas concentration

→ instrument measures a flux due to volume expansion



Cold air

warm surface

expansion

Warming the same air

Time 1

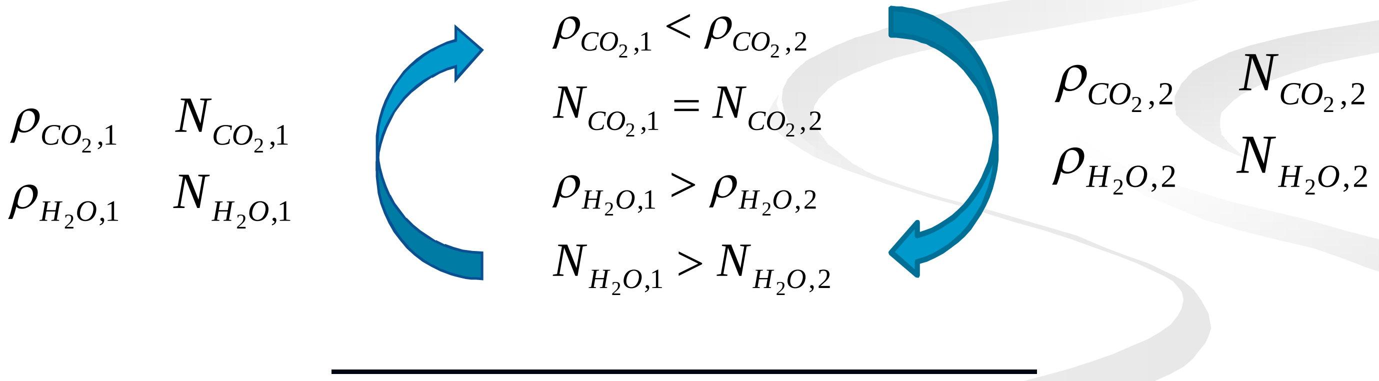
No actual flux

Time 2

- Example 2: expansion and dilution

a wet and warm CO2 inert surface, updrafts are a little warmer and wetter than downdrafts

→ updrafts have a slightly lower CO2 density than downdrafts though the average number would stay the same



$\rho_{CO_2,1}$ $N_{CO_2,1}$

$\rho_{H_2O,1}$ $N_{H_2O,1}$

$\rho_{CO_2,1} < \rho_{CO_2,2}$

$N_{CO_2,1} = N_{CO_2,2}$

$\rho_{H_2O,1} > \rho_{H_2O,2}$

$N_{H_2O,1} > N_{H_2O,2}$

$\rho_{CO_2,2}$ $N_{CO_2,2}$

$\rho_{H_2O,2}$ $N_{H_2O,2}$

A Definitive Test of WPL Theory over Parking Lot (Ham and Heilman, 2003)

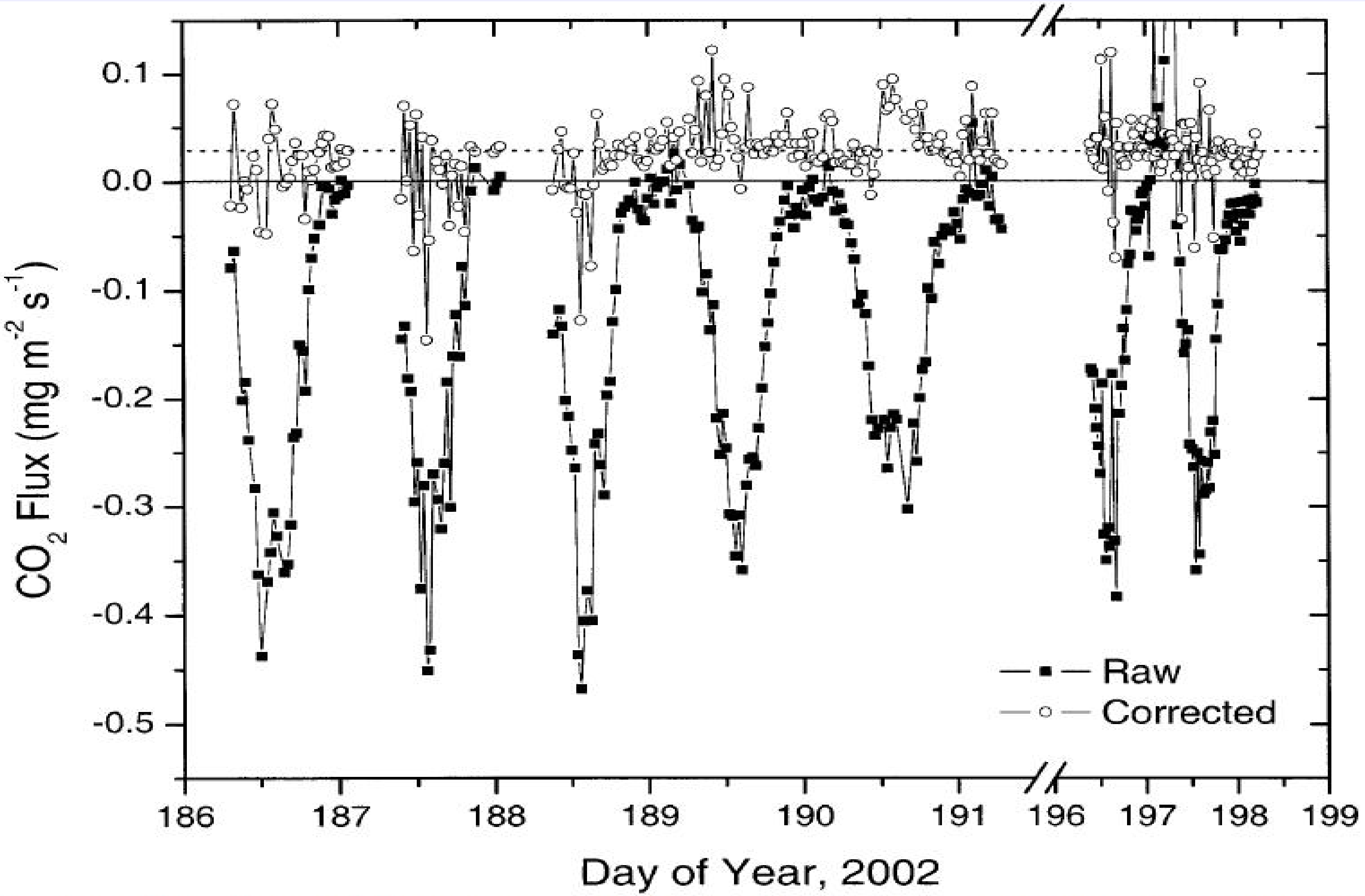


Fig. 4. Eddy covariance measurements of CO_2 flux above a parking lot for 7 d in July 2002. Shown are uncorrected *raw* measurements and the same data after density corrections have been applied. Actual fluxes of CO_2 from the surface were approximately 0.04 mg m^{-2} s^{-1} (dashed line). Downward fluxes are negative; upward fluxes are positive.

- For open-path H_2O flux

NOTE: density (kg/m^3) instead of mixing ratio (mmol/mol)

$$F_{q,WPL} = \overline{w'\rho_q'} + \left(\frac{M_a}{M_w}\frac{\overline{\rho_q}}{\rho_{a,dry}}\right)\overline{w'\rho_q'} + \left(1+\frac{M_a}{M_w}\frac{\overline{\rho_q}}{\rho_{a,dry}}\right)\frac{\overline{\rho_q}}{\overline{T}}\overline{w'T'}$$

- For open-path CO2 flux

$$F_{c,WPL} = \underbrace{\overline{w'\rho_c'}}_{\text{CO2 flux}} + \underbrace{\left(\frac{M_a}{M_w}\frac{\overline{\rho_c}}{\rho_{a,dry}}\right)\overline{w'\rho_q'}}_{\substack{\text{Water vapor flux term}\\ \text{(water dilution)}}} + \underbrace{\left(1+\frac{M_a}{M_w}\frac{\overline{\rho_q}}{\rho_{a,dry}}\right)\frac{\overline{\rho_c}}{\overline{T}}\overline{w'T'}}_{\substack{\text{Heat flux term}\\ \text{(thermal expansion)}}}$$

M_a = 28.965e-3 kg/mol = Molecular mass of air

M_w = 18.0153e-3 kg/mol = Molecular mass of water

$\rho_{a,dry} = p \cdot M_a / R \cdot \overline{T}$ p = pressure, $R = 8.314 JK^{-1}mol^{-1}$

$\overline{T}, \overline{\rho_q}, \overline{\rho_c}$ = average temperature, H_2O and CO_2 density

$\overline{w'T'}, \overline{w'\rho_q'}, \overline{w'\rho_c'}$ = temperature, H_2O and CO_2 covariances

- In closed-path analyzers, the effect of water vapor is either accounted for internally (Licor 6262, Licor 7200) or then not (Licor 7000, Licor 7200) and the effect of temperature fluctuations is negligible (reduced to 1% of their initial value) if tube length=1000 x diameter (for turbulent flow) and tube length=600 x diameter (for laminar flow) (Leuning and Judd 1996, Rannik et al., 1997)

- Leaving the correction out may cause e.g. an apparent uptake of CO_2

- For closed-path CO_2 flux (must be done for LI-7000 in post-processing, can be done on-line for 6262 and 7200) >> dilution correction
  - The concentration of carbon dioxide should be changed into units relative to dry air and then a correction to the covariance is not needed
  - Note that the CO_2 and H_2O concentrations should be in phase meaning that the lag correction should have been done!

$$\chi_c = \frac{c_c}{1 - c_q}$$

χ_c = mixing ratio of H_2O and CO_2

c_c, c_q = mole fraction of CO_2 (µmol/mol) and H_2O (mol/mol)

Otherwise apply the WPL correction to the covariance accounting only for H2O fluctuation term.

- For closed-path H_2O flux

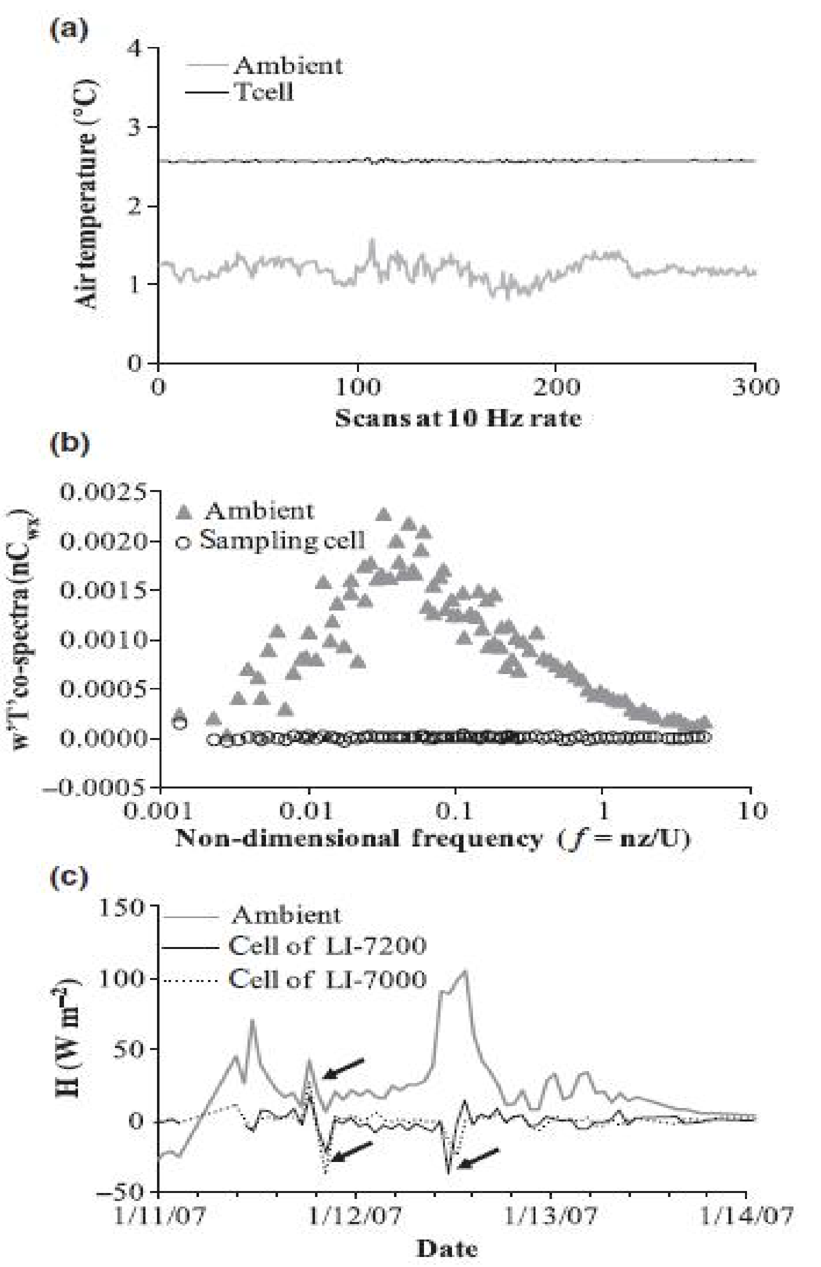
$$\overline{w'\chi_q'} = \overline{w'c_q'} + \left(\frac{\overline{c_q}}{1-\overline{c_q}}\right)\overline{w'c_q'}$$

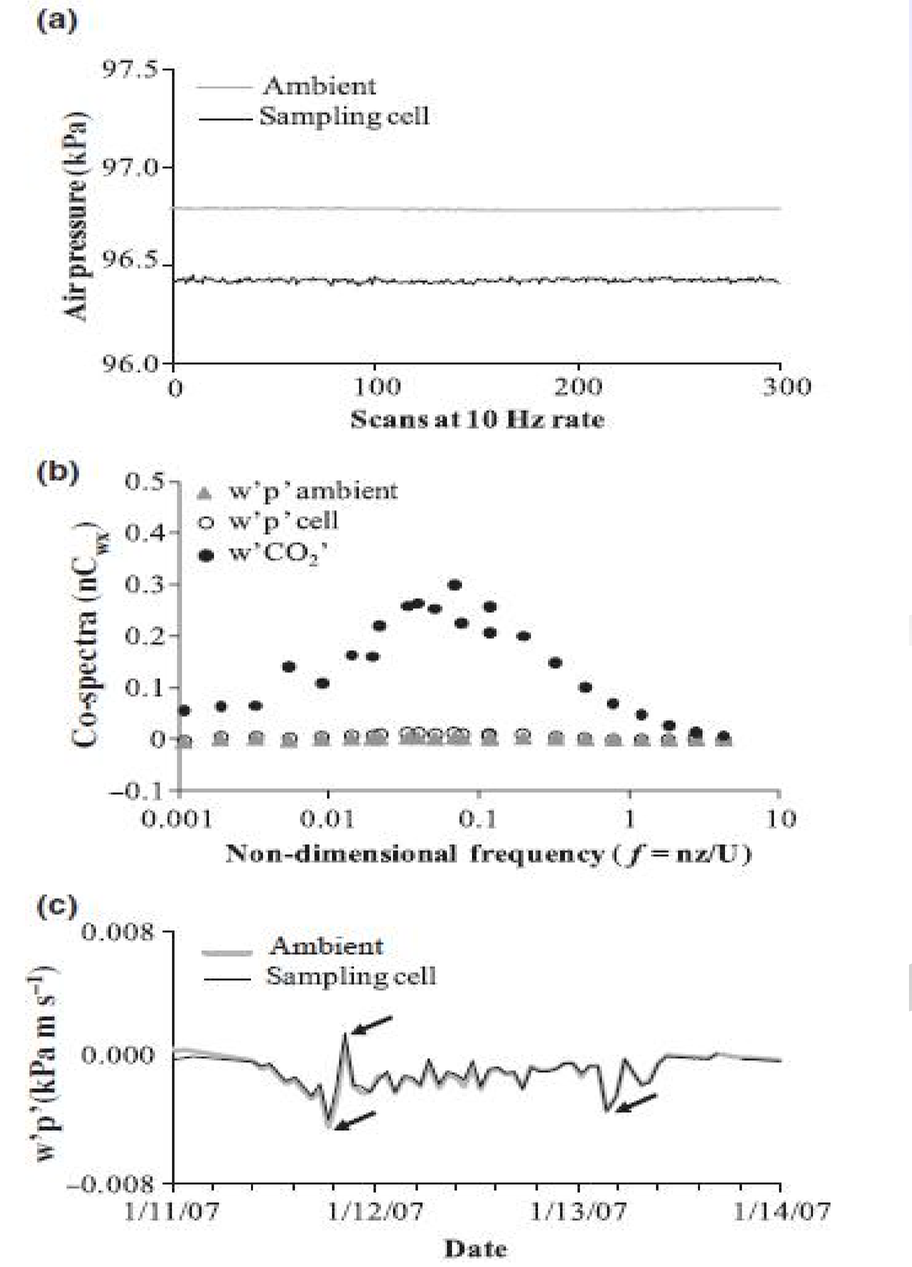
- For closed-path CO_2 flux

$$\overline{w'\chi_c'} = \overline{w'c_c'} + \left(\frac{\overline{c_c}}{1-\overline{c_q}}\right)\overline{w'c_q'}$$

NOTE: this term is the water vapor covariance not spectral corrected and calculated using the lag time of CO_2

Licor 7200 – use of online calculated mixing ratio is recommended (Burba et al., 2012)





Self-heating correction (only for open-path Licor 7500)

- Burba et al. 2008 (Burba correction)
- Problem
  - The self-heating of the open-path sensor causes density fluctuations itself

    → additional term to the WPL-correction needed
  - An apparent CO2 flux outside the growing season is observed if correction not done

- For open-path CO2 flux

µmol/m^3

$$F_{c,BUR} = F_{c,WPL} + \delta \frac{(T_s - T_a)\rho_c}{r_a(T_a + 273.15)}\left(1 + \frac{M_a}{M_w}\frac{\overline{\rho_q}}{\rho_{a,dry}}\right)$$

δ = the fraction of heat produced by the analyzer which stays in the thermal boundary layer of the analyzer

$r_a = U/u_*$ = aerodynamic transfer resistance [sm^{-1}]

T_s = the surface temperature of the instrument [^{o}C]

Not a standard correction procedure (yet)
Knowledge needed on T_a measurements

With the new Licor7500A, this effect is minimized (at least this is what Licor says!).

Corrections

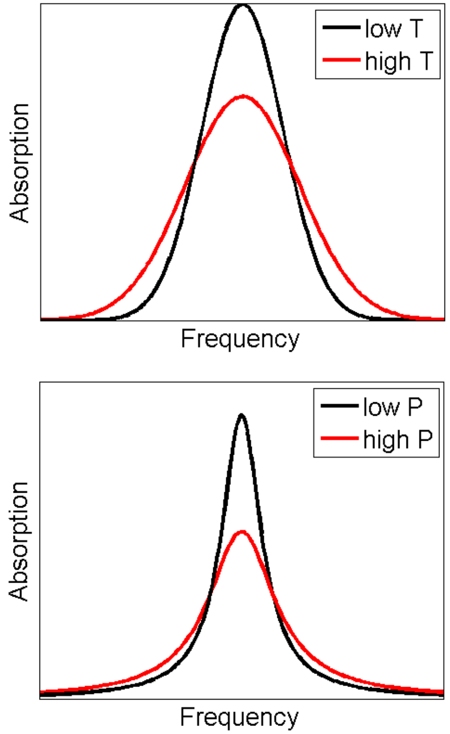
Cause of error	H2O	CO2	Heat	Range	Remedy
Spikes	X	X	X	±0-15%	De-spiking
Unleveled instruments / flow	X	X	X	± 0-25%	Coordinate rotation
Time lag	X	X		+5-15%	Lag removal
Sonic temperature			X	± 0-10%	Sonic heat correction
Density fluctuation	X	X		± 0-50%	WPL-correction
Open-path sensor heating	OP	OP		?	Burba-correction
Frequency response	X	X	X	+5-30%	Spectral corrections

From Burba and Anderson 2007, for a typical summer day over a green vegetative canopy

The magnitude of the corrections depends on the measurements setup, site, time of year…

SPECTROSCOPIC CORRECTION

- Caused by absorption line broadening
- Line broadening can be caused by several factors:
  - Temperature (Doppler broadening)
  - Pressure (pressure broadening)
- Line broadening causes error to measured concentration because absorption lines are measured with high accuracy



SPECTROSCOPIC CORRECTION

- For closed-path:

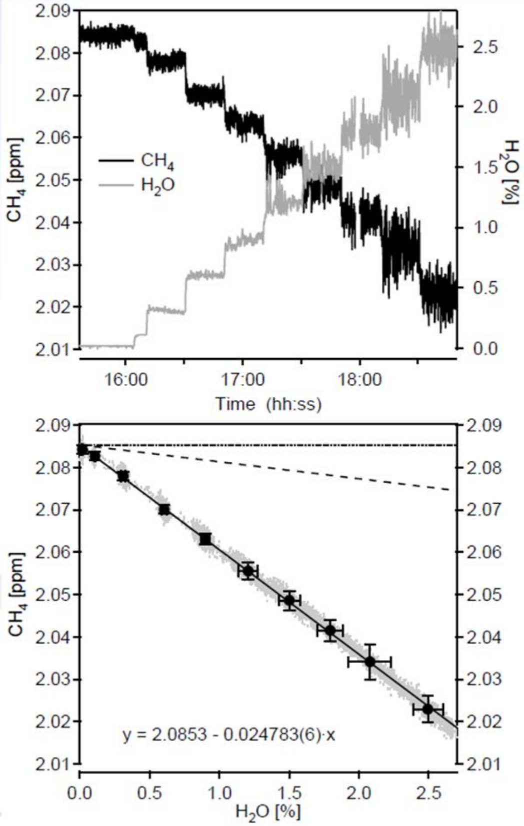
b_{ct} is a instrument specific coefficient

$$\overline{w'c'}_{corr} = \overline{w'c'}_{meas} + b_{ct}\,\overline{w'c'}_{H_2O}$$

- For open-path (meaning LI-7700):

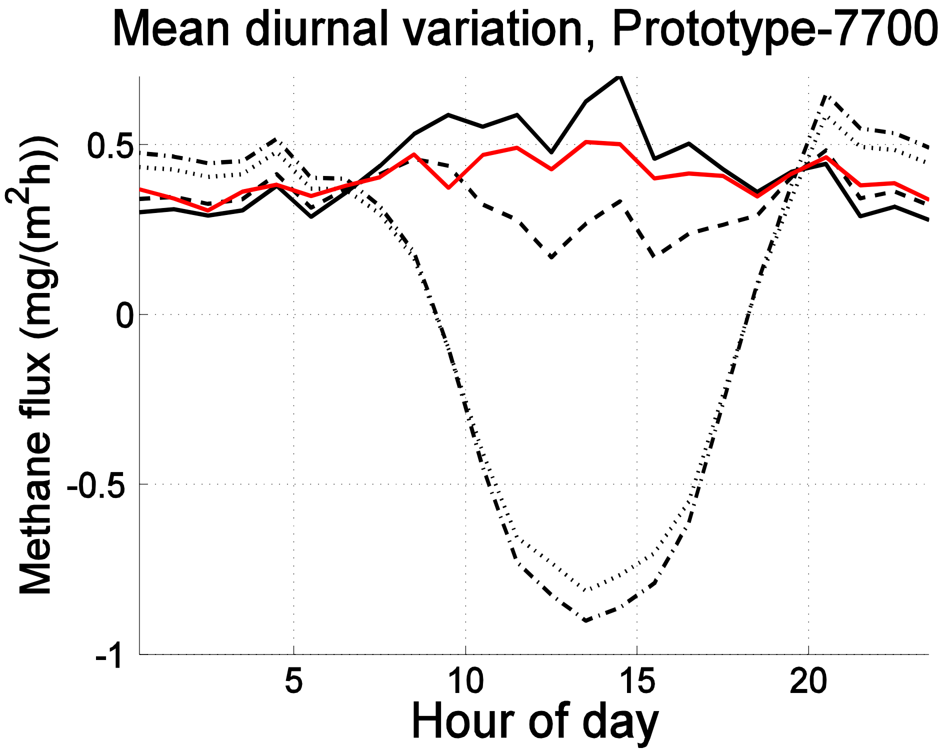
A = A(T,P,q_v), B = B(T,P,q_v) and C = C(T,P,q_v)

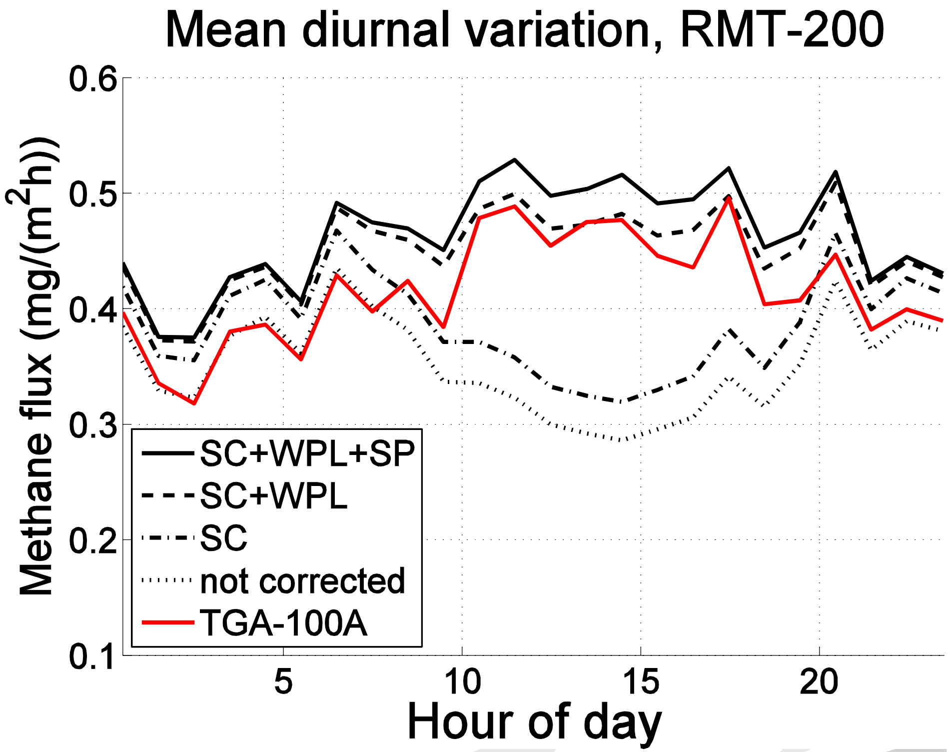
$$\overline{w'c'} = A\left(\left(\overline{w'c'}\right)_{meas} + B\mu\frac{\overline{q_c}}{\overline{q_d}}\overline{w'q_v'} + C\left(1+\mu\sigma\right)\frac{\overline{q_c}}{\overline{T}}\overline{w'T'}\right)$$



Tuzson et al. (2010)

Effects of different corrections on the flux


Mean diurnal variation, Prototype-7700


Mean diurnal variation, RMT-200

From Olli Peltola

Turbulent fluxes: units

- Vertical flux defined as the amount of material transported vertically per unit areas per unit time

$H = \rho_a c_p \overline{w'T'}$	Sensible heat flux [W/m^2]
$LE = \frac{\rho_a}{M_a} M_w L_v \overline{w'\chi_v'}$	Latent heat flux [W/m^2]
$\tau = -\rho_a \overline{w'u'}$	Momentum flux [kg/ms^2]
$F_c = \frac{\rho_a}{M_a} \overline{w'\chi_s'} \approx \overline{w'\rho_s'}$	Flux density of substance s [µmol/m^{2}s]

ρ_a	Mass air density [Kg/m^3]
c_p	Specific heat of air (1003.5 J/(Kg K))
$L_v = 3147.5 - 2.37\mathrm{T_K}$	Latent heat of vaporization of air (2260kJ/kg at 100C=373K)

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