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 postprocessing steps

- Read EC rawdata and meteo files
- Units conversions
- Calibration
- Dilution correction (if needed)
- Despiking
- Coordinate rotation
- Applying 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

\[ \zeta = \frac{z - d}{L} \]

Obukhov length (units: m)

\[ u_* = \left( \frac{u'^2}{w'^2} + \frac{v'^2}{w'^2} \right)^{\frac{1}{4}} \]

\[ L = -\frac{T_0 u_*^3}{\kappa g w'T'} \]

<table>
<thead>
<tr>
<th>TABLE 16.2 Interpretation of the Monin–Obukhov Length ( L ) with Respect to Atmospheric Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L )</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Small negative</td>
</tr>
<tr>
<td>Large negative</td>
</tr>
<tr>
<td>Very large (positive or negative)</td>
</tr>
<tr>
<td>Large positive</td>
</tr>
<tr>
<td>Small positive</td>
</tr>
</tbody>
</table>
Concentration definitions

- **Mass density** \( (\rho_s, \text{kg m}^{-3}) \) and **Molar density** \( (c_s, \text{mole m}^{-3}) \) represent the mass and the number of moles of \( s \) per volume of air, respectively.

- **Mole fraction** \( (\text{mole mole}^{-1}) \) 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** \( (\chi_{s,m}, \text{mole mole}^{-1}) \) is the ratio of the constituent mole number to those of dry air.

- **Mass mixing ratio** \( (\chi_s, \text{kg kg}^{-1}) \) 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 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.

\[
\frac{1}{4L^2} \int_{-L}^{L} \int_{-L}^{L} \int_{0}^{h_m} \left[ \frac{\partial \overline{X_s}}{\partial t} + \rho \frac{\partial \overline{u}}{\partial x} + \rho \frac{\partial \overline{v}}{\partial y} + \rho w \frac{\partial \overline{X_s}}{\partial z} + \frac{\partial \rho w}{\partial z} \right] \ dx \ dy \ dz
\]

\[
= \frac{1}{4 \rho L^2} \int_{-L}^{L} \int_{-L}^{L} \int_{0}^{h_m} \overline{S_b} \ dz \ dx \ dy
\]
In homogeneous surface layer

\[ \int_0^{h_m} \frac{\rho_d}{l} \frac{\partial \chi_s}{\partial t} \, dz + \left. \frac{\rho_d}{IV} w \chi_s \right|_{h_m} = \frac{\text{NEE}}{V} \]

Net Ecosystem Exchange \((V) = \text{EC flux at } h_m (IV) + \text{Storage change flux}(I)\)

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 one path
    \[
    w' T'_{SCH} = w' T' + \frac{2}{403} uu' w'
    \]

  - Liu et al. 2001 give coefficients for different types of sonics
    \[
    w' T'_{LIU} = w' T' + \frac{2}{403} (A uu' w' + B vv' w')
    \]
<table>
<thead>
<tr>
<th>Applied online</th>
<th>Correction needed during post-processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campbell CSAT3</td>
<td>Gill Solent R2</td>
</tr>
<tr>
<td>Gill Solent HS and R3</td>
<td>ATI K-Probe</td>
</tr>
<tr>
<td>METEK USA-1 if use of the flux “hf”</td>
<td>METEK USA-1 if covariance calculated from high frequency raw data or use of the covariance “zTcov”</td>
</tr>
<tr>
<td>Young 81000</td>
<td></td>
</tr>
</tbody>
</table>
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 $u'w', w'T', w's'$ (also different for open- and closed-path)

Example of low and high frequency loss

\[
\frac{fS_s}{\sigma_s} = \begin{cases} 
\frac{f(z-d)}{U} & n = \frac{f(z-d)}{U} \\
-8/3 & \quad -2/3 \\
-8/3 & 
\end{cases}
\]

\[
\frac{fC_{w's'}}{w's'} = \begin{cases} 
\frac{f(z-d)}{U} & n = \frac{f(z-d)}{U} \\
-10/3 & \quad -4/3 \\
-10/3 & 
\end{cases}
\]
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 ($TF$).

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

$C_{ws}$ is here the normalized model co-spectrum. The denominator $= 1$ according to its definition.

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

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

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)

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

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

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

- 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

\[ TF_{HF} = \frac{C_{w's'}}{C_{w'T'}} = \frac{1}{1 + (2\pi f \tau_s)^2} \]

- Measured cospectra for s (CO2, H2O, ...)
- Measured cospectra for T
- Average log-binned normalized cospectra for T and a scalar s
- Response time (time constant)
- Response time as a function of RH

\[ \tau_s = a_1 + a_2 RH^{a_3} \]

Transfer function

Log scale

Log scale

Log scale

f

f

RH
Mammarella et al., 2009
How to correct the flux?

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

\[ F_a = \frac{\hat{w}'s'_{meas}}{\hat{w}'s'_{real}} = \int TF(f)C_{model}(f)df \]  

EQ.1

- The correction

\[ \frac{\hat{w}'s'_{real}}{F_a} = \frac{\hat{w}'s'_{meas}}{F_a} \]
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.

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

$C_{model}$ 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.

\[
\begin{align*}
\text{unstable condition } ((z-d)/L < 0) \\
& n_m = 0.085; \\
& \frac{fC_{wT}(f)}{w'T'} = \begin{cases} \\
& 1.05n/n_m \\
& (1+1.33n/n_m)^{7/4} \quad \text{for } n \leq 1.0 \\
& 0.387n/n_m \\
& (1+0.38n/n_m)^{7/3} \quad \text{for } n \geq 1.0 \\
\end{cases} \\
\end{align*}
\]

\[
\begin{align*}
\text{stable condition } ((z-d)/L > 0) \\
& n_m = 2-1.915/(1+0.5(z-d)/L); \\
& \frac{fC_{wT}(f)}{w'T'} = 0.637(n/n_m)/(1+0.91(n/n_m)^{2.1}); \\
\end{align*}
\]
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

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

where

\[
\begin{align*}
\alpha &= 1 \text{ in stable condition } (z-d/L>0) \\
\alpha &= 7/8 \text{ in unstable condition } (z-d/L<0)
\end{align*}
\]
SMEAR II CP system

Lines: analytical approach
Symbols: numerical integration EQ.1

Mammarella et al., 2009
SMEAR III Aerosol particle averaged cospectrum

Unstable-summer 2007

Normalized Frequency

Logarithmic scale on the y-axis.
SMEAR III Aerosol particle transfer function

![Graph showing the co-spectral transfer function with a frequency range from 10^-2 to 10^0 Hz and a characteristic time \( \tau_c = 0.5 \) s.](image)
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)

\[ H = \rho C_p (w'T_s' - 3.210 \cdot 10^{-4} Tw' \chi_{H2O}) \]

- \( c^2 = 403T(1+0.32e/p) \),
- \( T_s = \frac{m_d \left(c_1^2 + c_2^2 + c_3^2\right)}{\gamma R} = \frac{1}{403} \left(c_1^2 + c_2^2 + c_3^2\right) \),
- \( T_v = T(1+0.38e/p) \), Virtual temperature
- \( T_s = T(1+0.32e/p) \), Sonic temperature

\( c = \) Speed of sound in air [ms-1]
\( T = \) Temperature [K]
\( e = \) Water vapor pressure
\( p = \) Atmospheric pressure
\( m_d = 28.96 \cdot 10^{-3} \) kg mol-1 molecular mass of dry air
\( \gamma = 1.4 \), 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$_2$O (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$_2$O flux, warming air of constant gas concentration

$\rightarrow$ instrument measures a flux due to volume expansion
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
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$_2$O flux

$$F_{q,WPL} = w' \bar{\rho}_q' + \left( \frac{M_a}{M_w} \frac{\bar{\rho}_q}{\bar{\rho}_{a,dry}} \right) w' \bar{\rho}_q' + \left( 1 + \frac{M_a}{M_w} \frac{\bar{\rho}_q}{\bar{\rho}_{a,dry}} \right) \frac{\bar{\rho}_q}{T} w'T'$$

For open-path CO$_2$ flux

$$F_{c,WPL} = w' \bar{\rho}_c' + \left( \frac{M_a}{M_w} \frac{\bar{\rho}_c}{\bar{\rho}_{a,dry}} \right) w' \bar{\rho}_c' + \left( 1 + \frac{M_a}{M_w} \frac{\bar{\rho}_q}{\bar{\rho}_{a,dry}} \right) \frac{\bar{\rho}_c}{T} w'T'$$

- CO$_2$ flux
- Water vapor flux term (water dilution)
- Heat flux term (thermal expansion)

$M_a$ = 28.965e-3 kg/mol = Molar mass of air
$M_w$ = 18.0153e-3 kg/mol = Molar mass of water
$p = \text{pressure,}$
$
\bar{T}, \bar{\rho}_q, \bar{\rho}_c, \bar{T}', \bar{\rho}_q', \bar{\rho}_c'
$ = average temperature, H$_2$O and CO$_2$ density
$
\bar{w}'T', \bar{w}'\rho_q', \bar{w}'\rho_c'
$ = temperature, H$_2$O and CO$_2$ covariances

NOTE: density (kg/m$^3$) instead of mixing ratio (mmol/mol)
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$_2$O concentrations should be in phase meaning that the lag correction should have been done!

\[
\chi_c = \frac{c_c}{1-c_q}
\]

\(\chi_c\) = mixing ratio of H$_2$O and CO$_2$
\(c_c, c_q\) = mole fraction of CO$_2$ (µmol/mol) and H$_2$O (mol/mol)
Otherwise apply the WPL correction to the covariance accounting only for H2O fluctuation term.

- For closed-path H$_2$O flux

\[
\bar{w}'\chi_q = \bar{w}'c_q' + \left( \frac{c_q}{1 - c_q} \right) \bar{w}'c_q'
\]

- For closed-path CO$_2$ flux

\[
\bar{w}'\chi_c = \bar{w}'c_c' + \left( \frac{c_c}{1 - c_q} \right) \bar{w}'c_q'
\]

**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

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

\[
\delta = \text{the fraction of heat produced by the analyzer which stays in the thermal boundary layer of the analyzer}
\]

\[
r_a = \frac{U}{u_*} = \text{aerodynamic transfer resistance [sm}^{-1}]\]

\[
T_s = \text{the surface temperature of the instrument [°C]}
\]
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

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

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

  \[ w' c'_{\text{corr}} = w' c'_{\text{meas}} + b_{ct} w' c'_{H_2O} \]

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

  \[ A = A(T,P,q_v), \quad B = B(T,P,q_v) \quad \text{and} \quad C = C(T,P,q_v) \]

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

Tuzson et al. (2010)
Effects of different corrections on the flux

From Olli Peltola
Turbulent fluxes: units

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

\[
H = \rho_a c_p w'T'
\]

\[
LE = \frac{\rho_a}{M_a} M_w L_v w' \chi_v'
\]

\[
\tau = -\rho_a w'u'
\]

\[
F_c = \frac{\rho_a}{M_a} w' \chi_s' \approx w' \rho_s'
\]

- Sensible heat flux \([W/\text{m}^2]\)
- Latent heat flux \([W/\text{m}^2]\)
- Momentum flux \([\text{kg/\text{m}}^2\text{\text{s}}]\)
- Flux density of substance \(s\) \([\text{µmol/}\text{m}^2\text{s}]\)

\(\rho_a\)  
Mass air density \([\text{Kg/\text{m}^3}]\)

\(c_p\)  
Specific heat of air \((1003.5 \text{ J/(Kg K)})\)

\(L_v = 3147.5 - 2.37T_k\)  
Latent heat of vaporization of air \((2260\text{ kJ/kg at 100C = 373K})\)
References


