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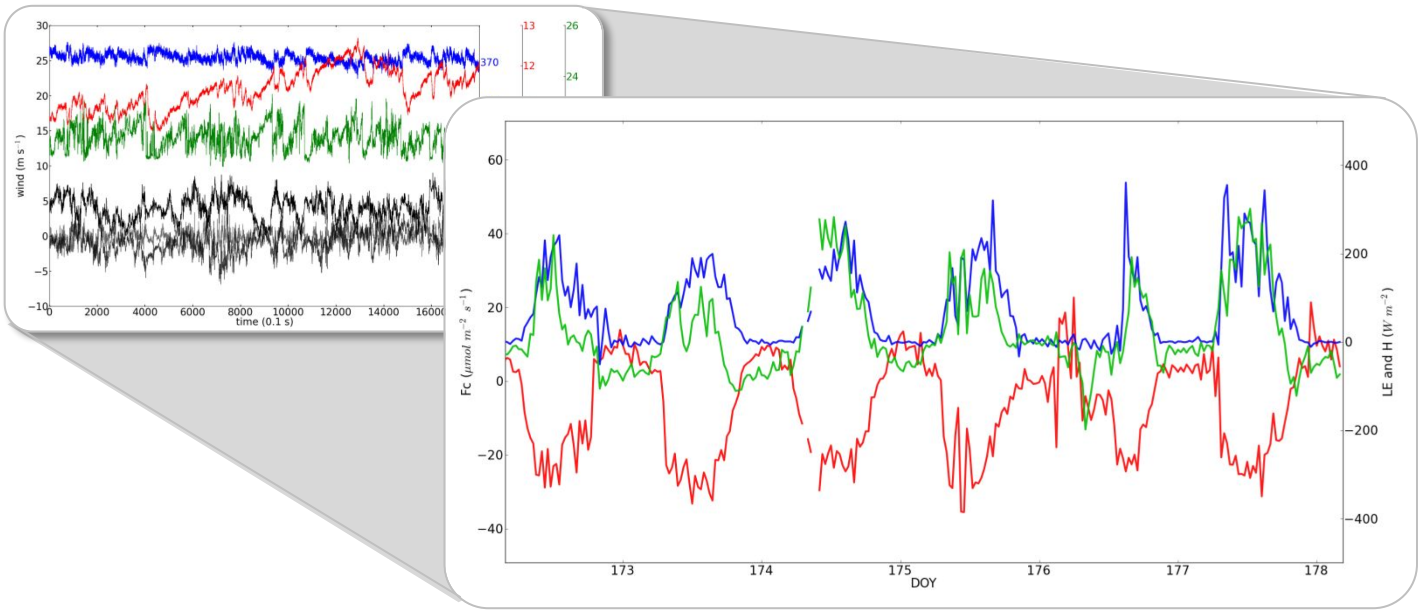
EDDY COVARIANCE METHOD

DATA PROCESSING PRINCIPLES AND PROCEDURES



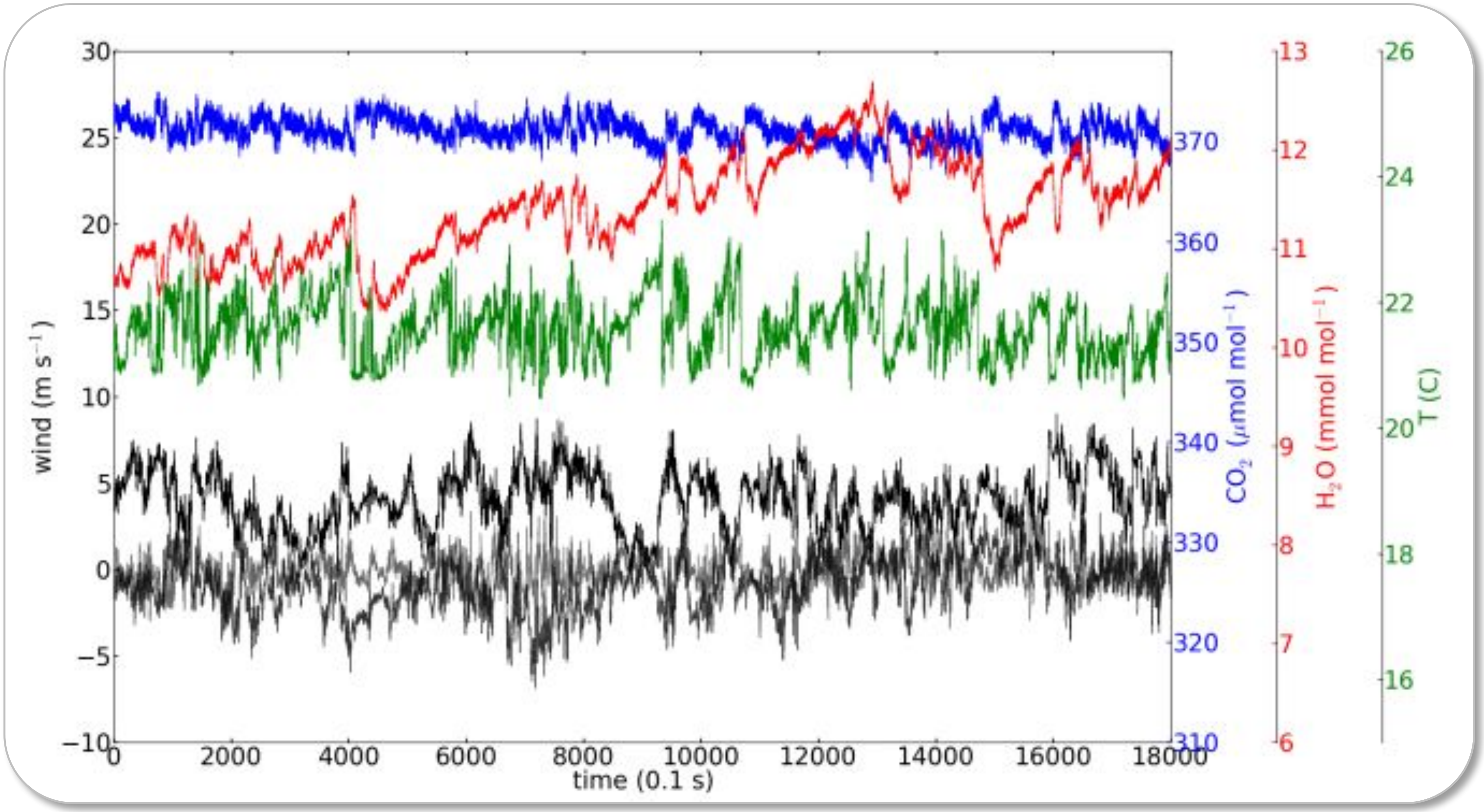
Gerardo Fratini

Principal Scientist, R&D
LI-COR Environmental

July 2022

LI-COR Biosciences

FROM THIS



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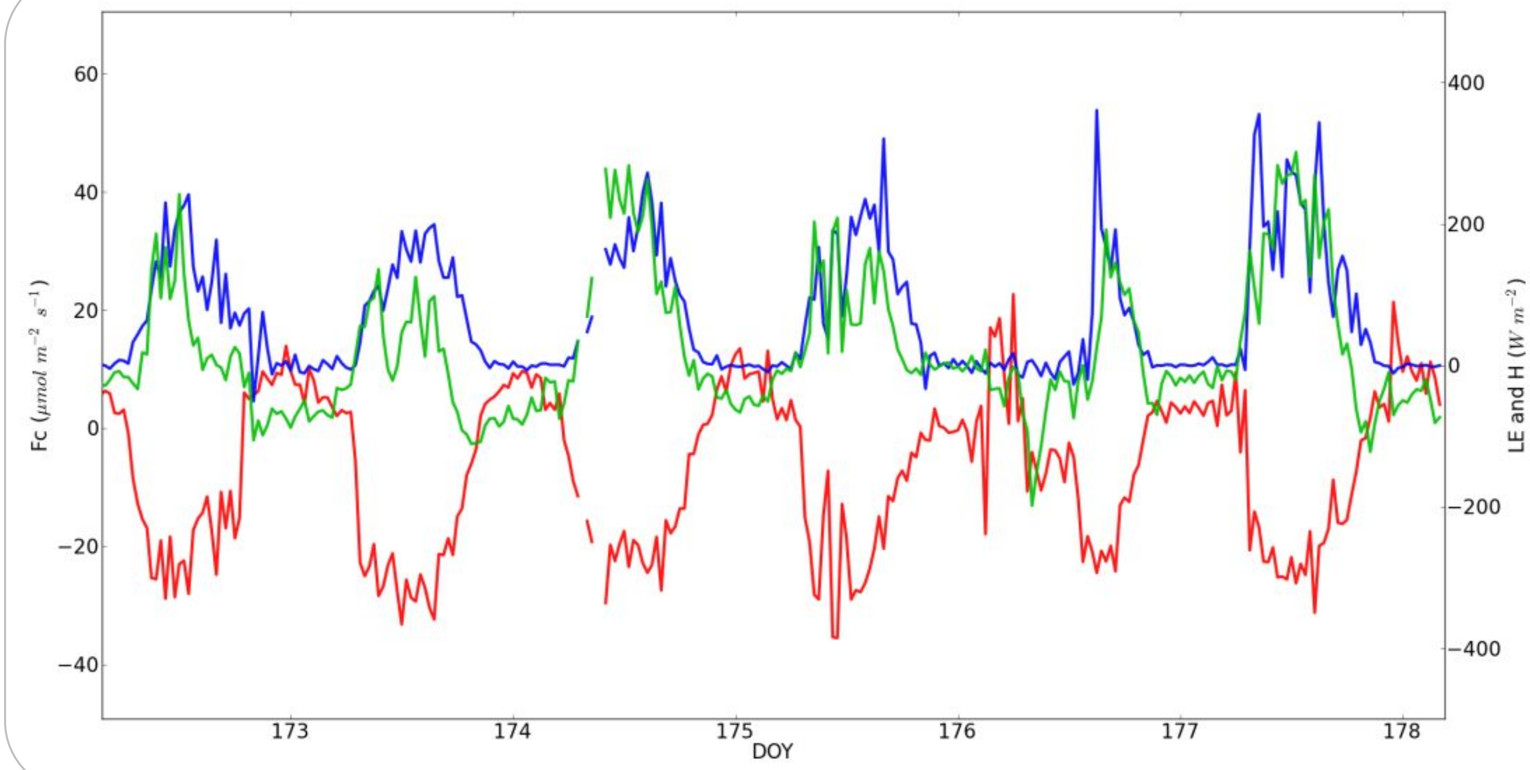
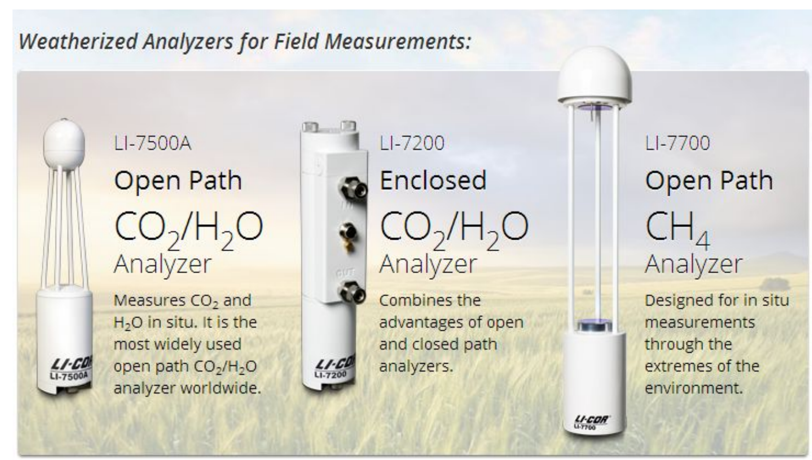
TO THIS



60
40
20
0
−20
−40
Fc ($\mu mol\ m^{-2}\ s^{-1}$)
400
200
0
−200
−400
LE and H ($W\ m^{-2}$)
173
174
175
176
177
178
DOY

- Introduction to the Eddy Covariance data processing
- Eddy Covariance raw datasets
- Description of main processing steps

Several instruments from different manufacturers



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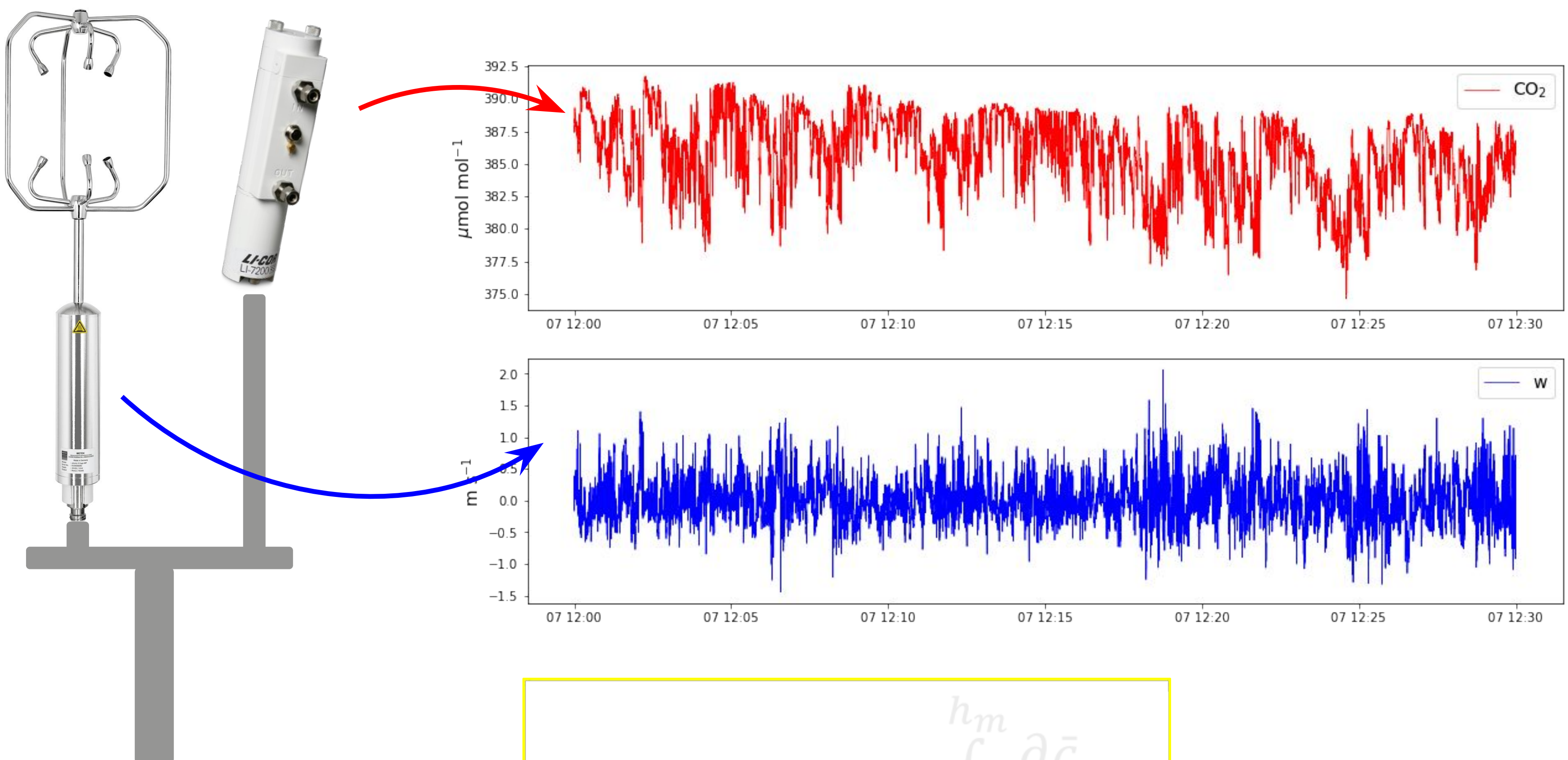
In theory flux computation is simple



$$F_c = \rho \cdot \overline{w'c'} + \int_{z=0}^{h_m} \frac{\partial \bar{c}}{\partial t} dz$$

Fluxes are not measured, they are estimated!

- Fast, precise instruments measure high-frequency data of wind, gas concentration, temperature, ...
- Slow, accurate instruments measure low-frequency data of biomet variables
- Raw measurements and initial flux estimates need to be corrected for instrumental limitations, setup imperfections and less-than-ideal turbulence conditions
- Fluxes must be accompanied by quality flags and other means of quality evaluation

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Sources of bad data that cannot be corrected

Preventable

- Measurements are not done inside the boundary layer of interest
- Terrain is not horizontal and uniform: advection
- Distortion of the air flow field

Not preventable

- Air flow is not fully turbulent (advection fluxes, storage)
- Turbulence is not stationary

EC ≈ Endless Correction

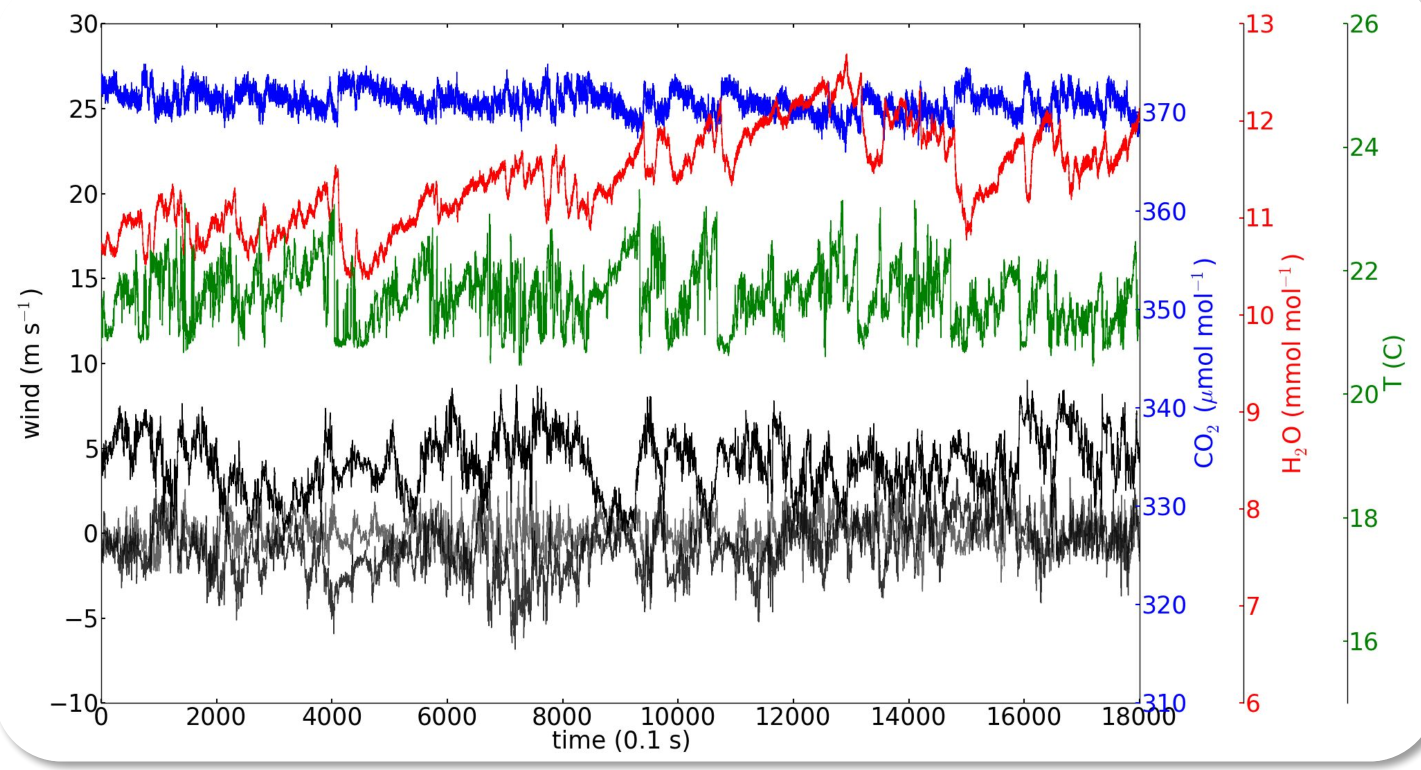
We “correct” for:

- Instrumental limitations:
  - Native gas measurement is density (not concentration)
  - Finite time response
  - Finite measuring volume and presence of sampling line
  - Instrumental drifts
  - Transducers’ shadowing
  - Technology-specific quirks (LASER, NDIR…)
  - Short-term malfunctions, power-downs

- Deployment limitation:
  - Measurement height
  - Leveling of the instruments
  - Lack of instruments’ co-location

Raw Eddy Covariance datasets – Fast EC data

- High frequency (1-20 Hz) data of 3D wind speed, gas concentrations, temperature, pressure, diagnostics...



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Raw Eddy Covariance datasets – Fast EC data

Timestamp, often not used but worth storing

Diag	Time	CO2(mmol/m^3)	H2O(mmol/m^3)	Total_P(kPa)	U(m/s)	V(m/s)	W(m/s)	Ts(C)	CO2_dry(umol/mol)	H2O_dry(mmol/mol)	Cell_T(C)	AGC	Flow_Rate(lpm)
8188	10:30:00:000	12.0264	618.902	95.8138	2.90473	6.58468	2.71233	19.4736	312.396	16.0739	21.4713	81.25	16.6569
8188	10:30:00:100	12.0261	620.54	95.8055	1.74097	7.19178	1.77273	18.9618	312.422	16.1208	[illegible]	81.25	16.6569
8188	10:30:00:200	12.0235	623.696	95.8174	0.77521	4.53362	3.64819	19.085	312.383	16.2043	21.5187	81.25	16.6569
8188	10:30:00:300	12.0355	623.392	95.826	-0.0523	6.11955	3.59215	19.481	312.695	16.1964	21.5387	81.25	16.6569
8188	10:30:00:400	12.036	623.114	95.8369	0.81071	5.66003	2.94022	19.4399	312.716	16.1896	21.5845	81.25	16.6569
8188	10:30:00:500	12.0321	625.332	95.8301	0.78082	5.42279	3.16065	19.6566	312.608	16.2469	21.612	81.25	16.6569
8188	10:30:00:600	12.0314	627.345	95.8406	0.61850	6.86488	2.95143	19.2009	312.507	16.2949	21.5211	81.25	16.6569

Gas molar densities are "native" gas measurements that one should always store

3D wind components, sonic temperature, diagnostics

Gas concentrations only meaningful in closed/enclosed path instruments

Cell T and P are essential for calculating concentrations from molar densities, or for applying WPL correction

Diagnostic information (AGC, RSSI) can be used to filter out individual measurements flagged for poor quality

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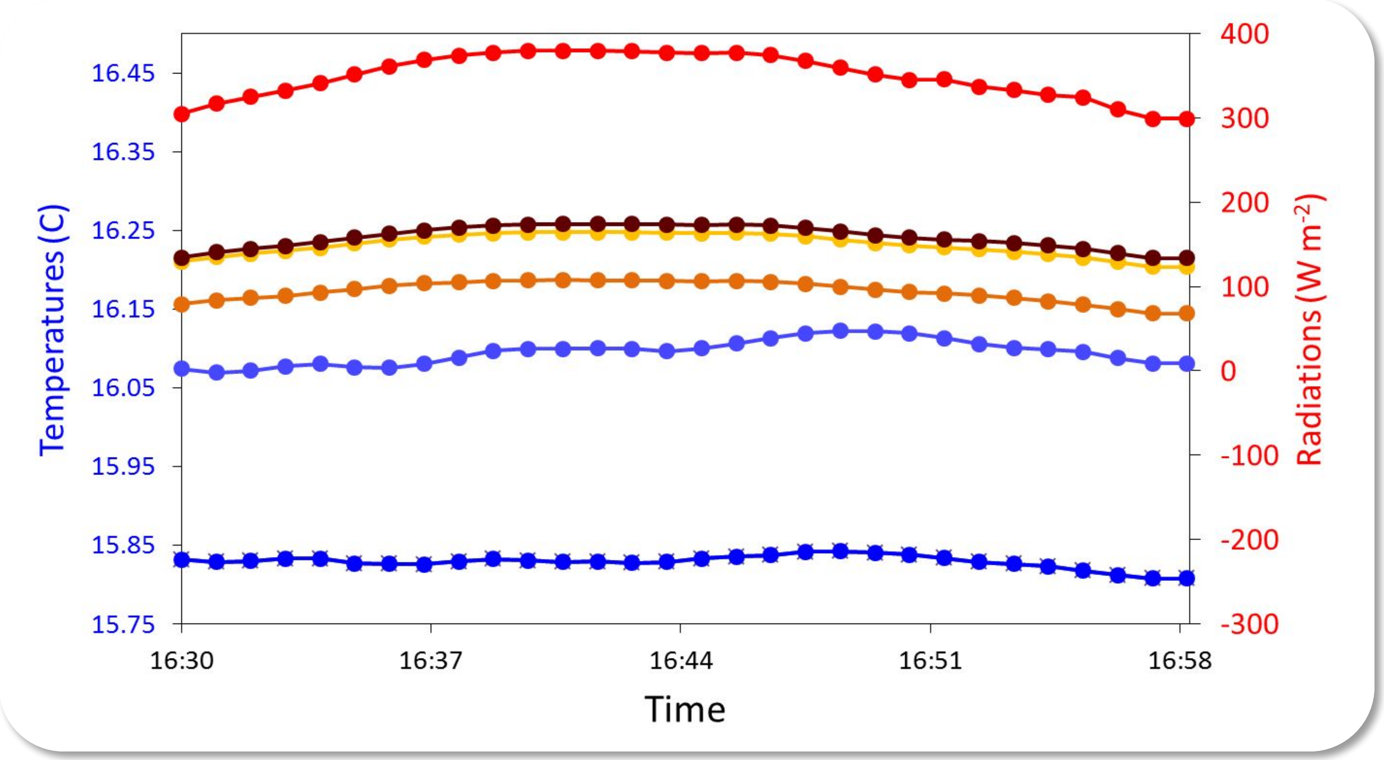
Raw Eddy Covariance datasets – Slow biomet data

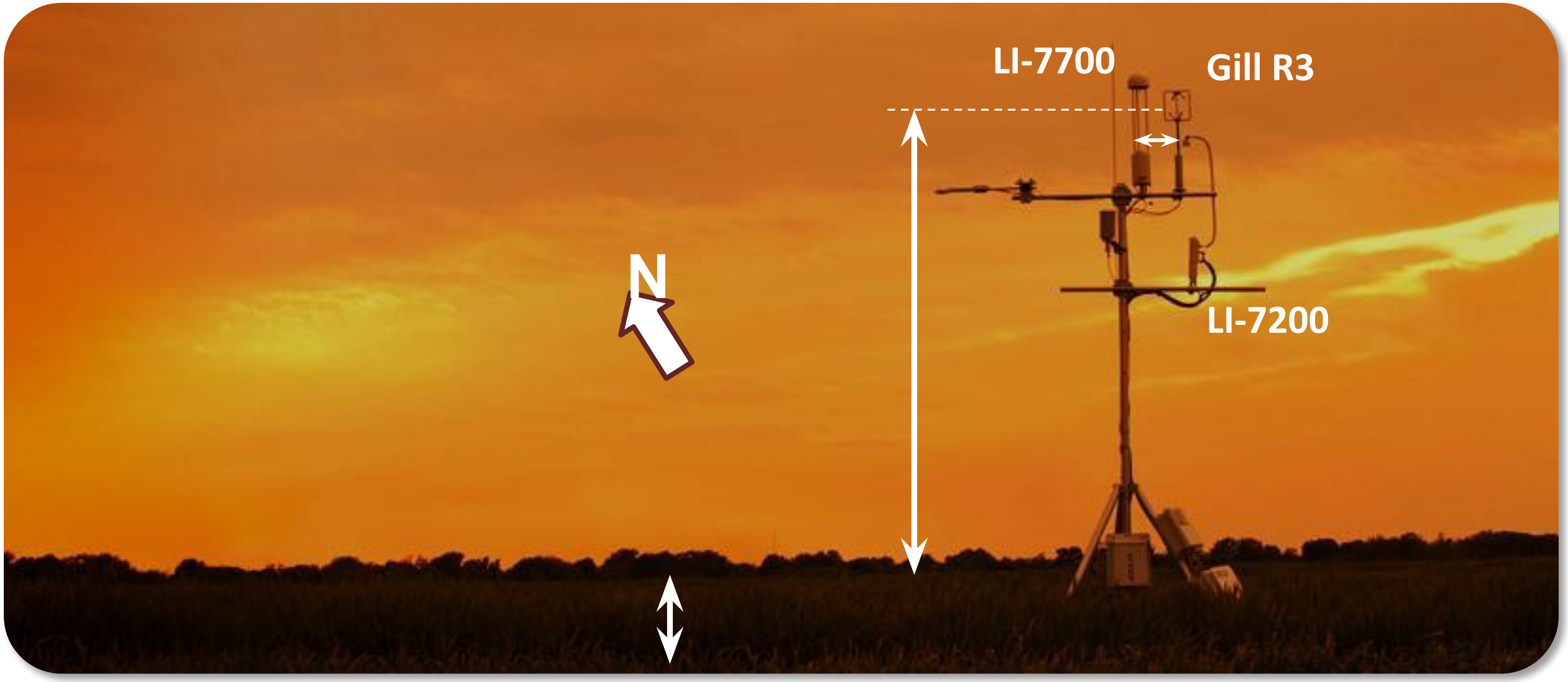
- Low frequency (<1 Hz) data of ambient T, P, RH, radiations, precipitation, ...



Biosciences

Raw Eddy Covariance datasets – Metadata

- Site location, instrument models and their actual deployment (height above aground, separations, acquisition frequency..)



Eddy Covariance Software

- EddyPro®
- TK3
- eddy4R
- EdiRe
- EddyUH
- EasyFlux® DL/PC

EDDYPRO™

- Released and maintained by LI-COR®
- 7000+ users
- 1000+ peer-reviewed citations
- Used by and developed with ICOS, AmeriFlux

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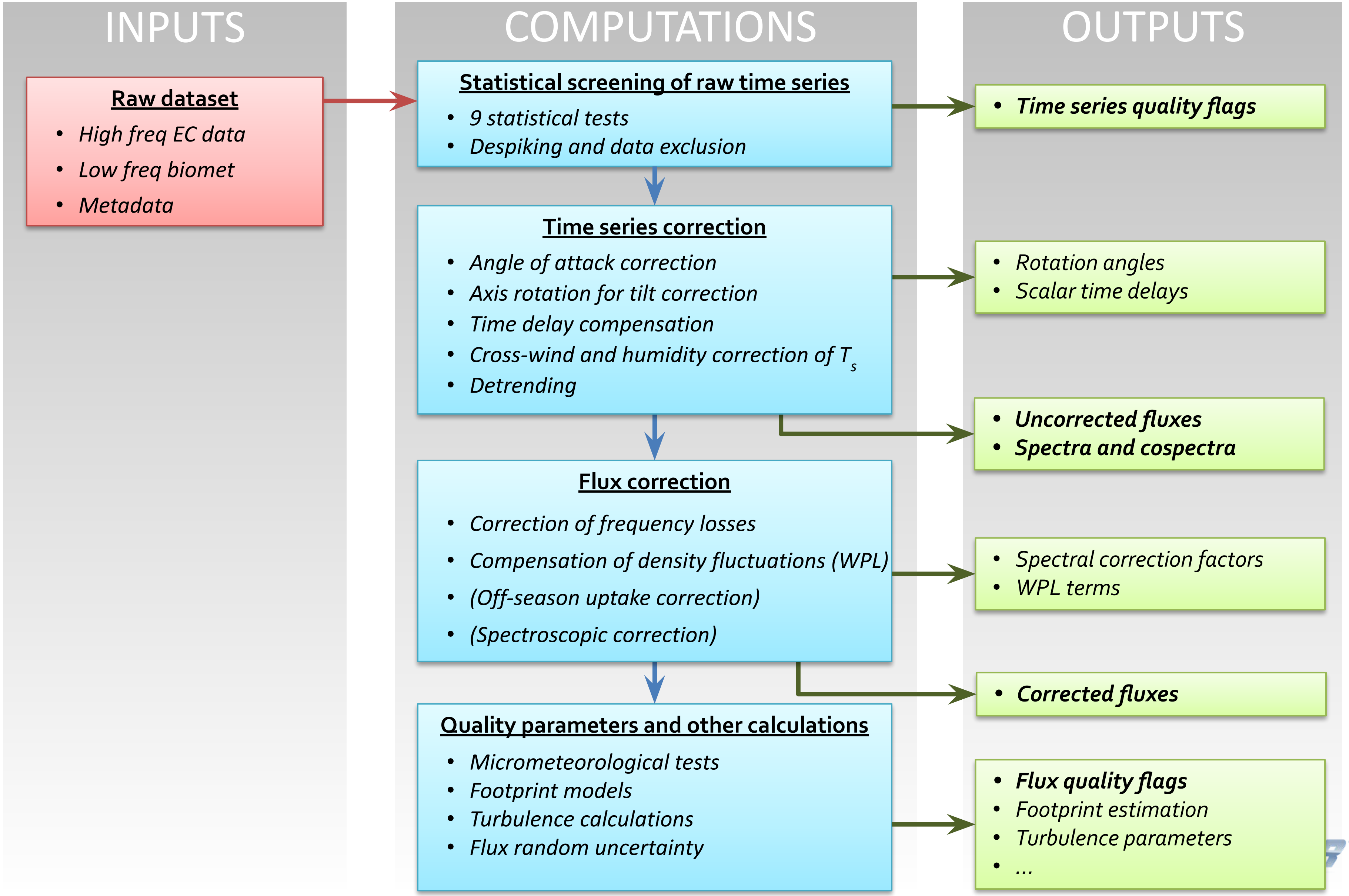
Data processing workflow



A parenthesis on fluxes on-the-fly

- Sometimes the EC logging system allows for on-the-fly flux computation, on a 30-min basis
- Good for checking status of acquisition
- Without a complete use of metadata, on-the-fly fluxes are likely to be not accurate
- In some conditions, on-the-fly fluxes cannot be accurate (e.g. closed path systems with long sampling lines, complex topographies)
- In any case, storing raw data is essential for future reprocessing or re-evaluation of calculated fluxes

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First step

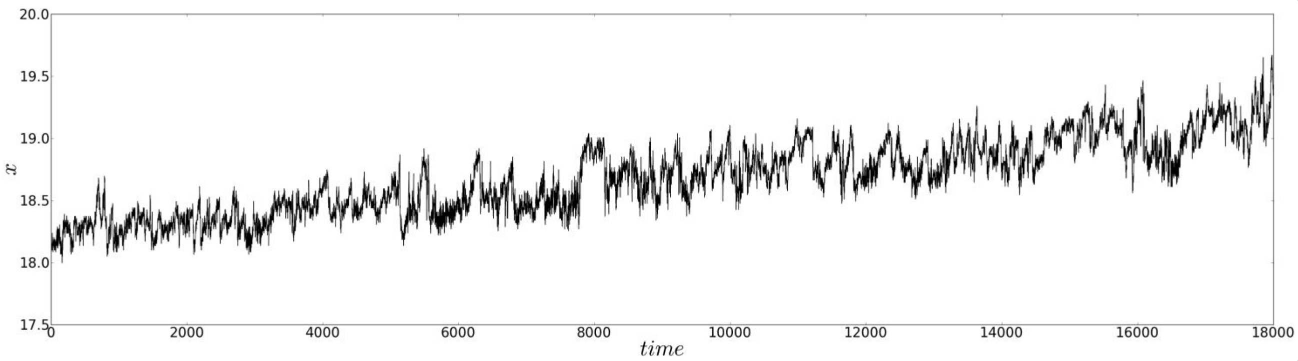
Quality screening of high frequency time series and removal of implausible values

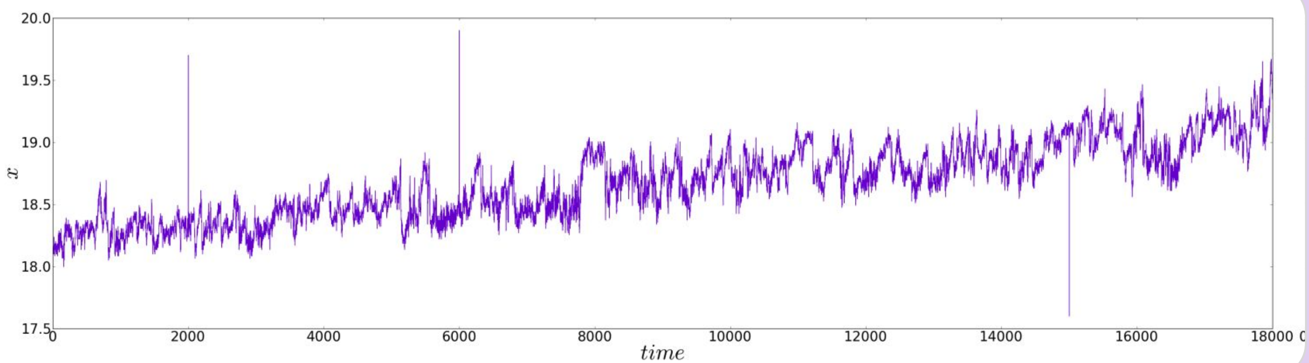
Detecting anomalies in raw time series (e.g., Vickers and Mahrt, 1997)

- Attempt to detect different problems in the time series
- Provide good/bad flags for each test, for each time series, for each raw file
- Can be used to clean up raw time series
- Complement micrometeorological flags for QA/QC of fluxes

Spike test

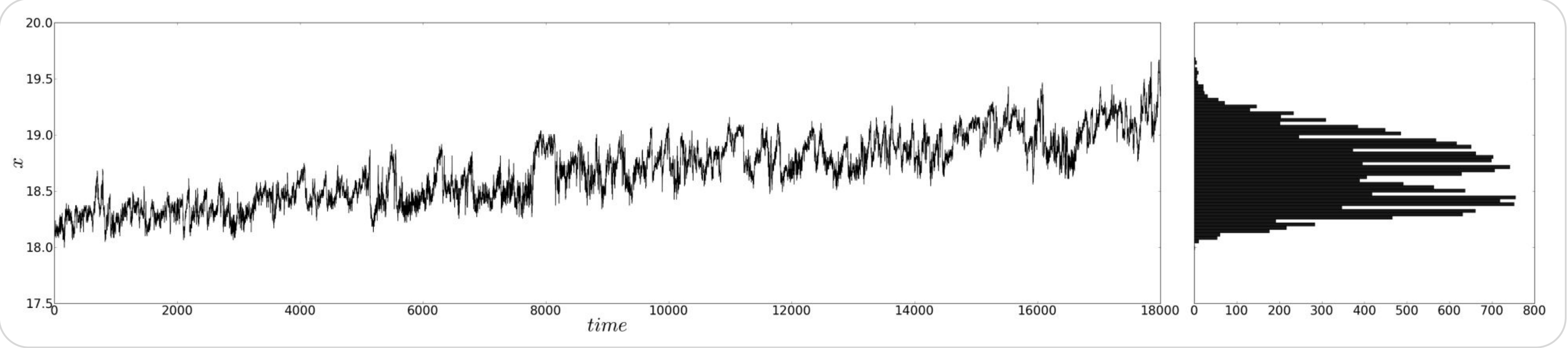
Good time series

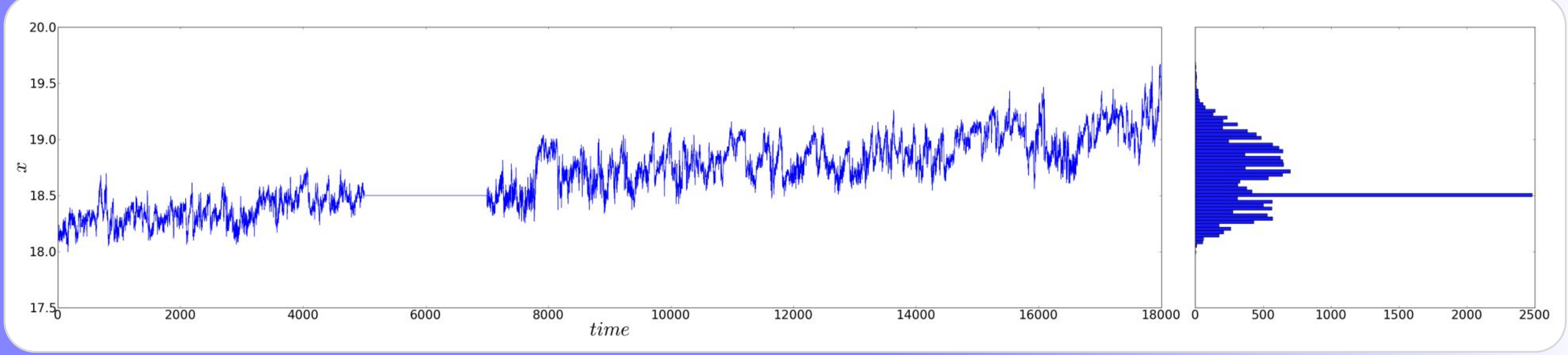




Drop-outs

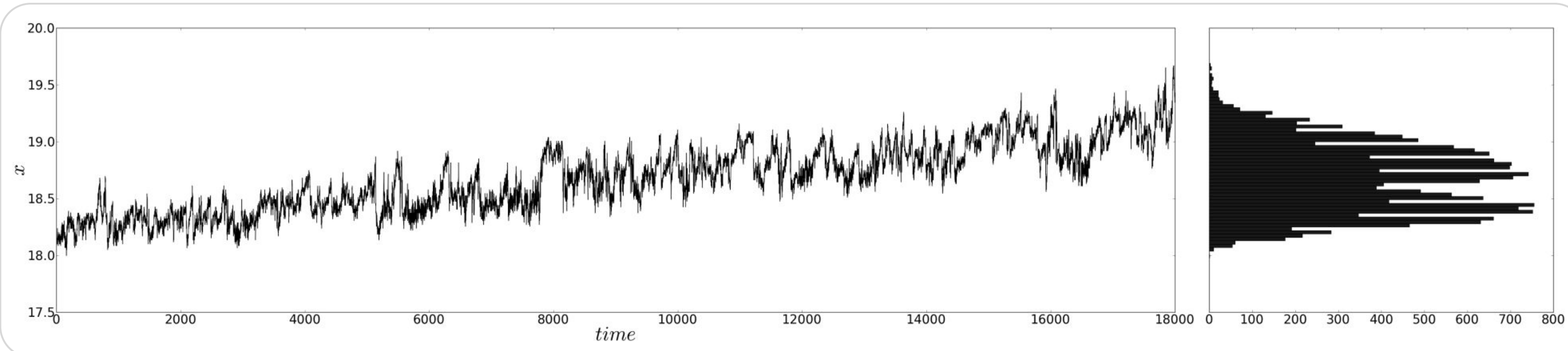
Good time series

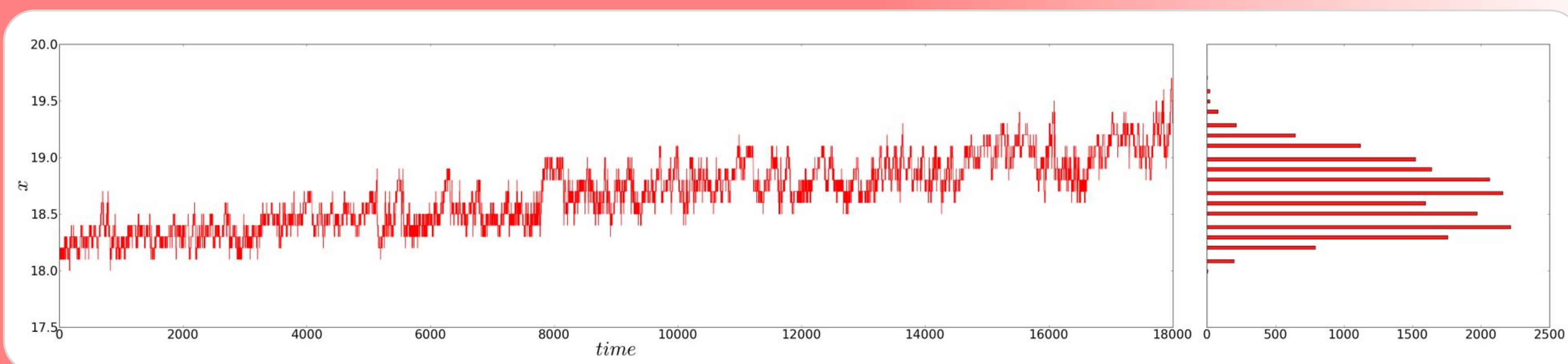




Amplitude resolution

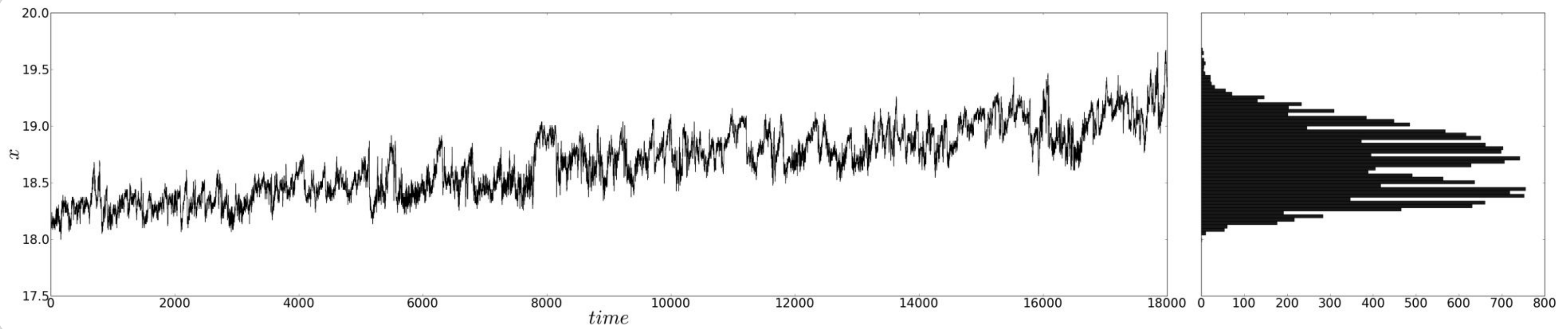
Good time series

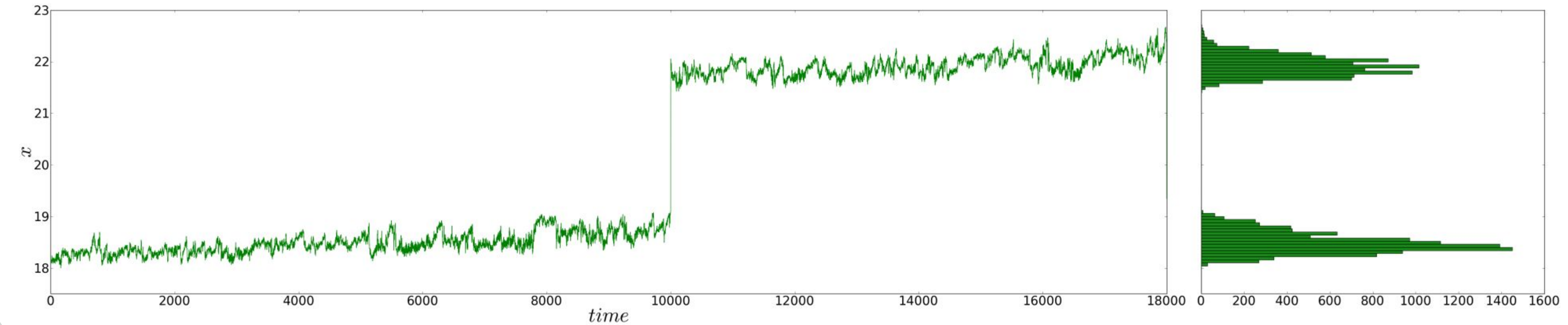




Discontinuities

Good time series





Other 5 statistical tests

- Variables shall not get physically implausible values
- Skewness and Kurtosis shall not deviate too much from normal distribution
- Angle of attack shall not be very large for too many samples
- Time delays shall be close enough to expectations
- Time series shall not be instationary

Second step

Correction of time series for instrumental and setup limitations

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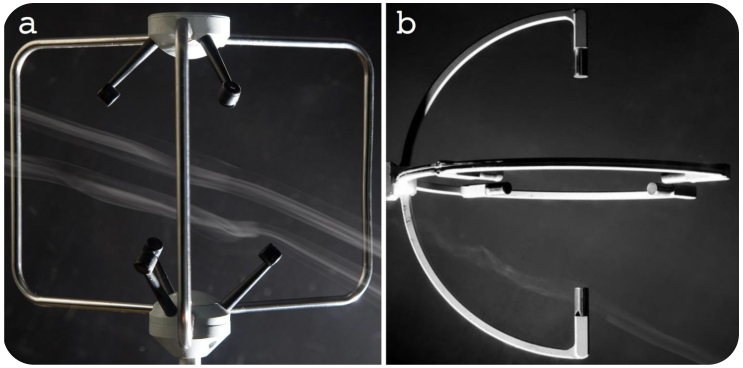
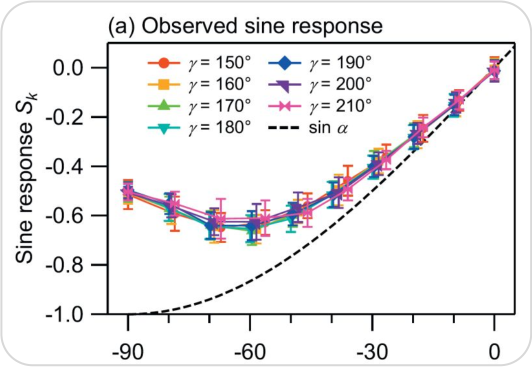
Angle-of-attack correction

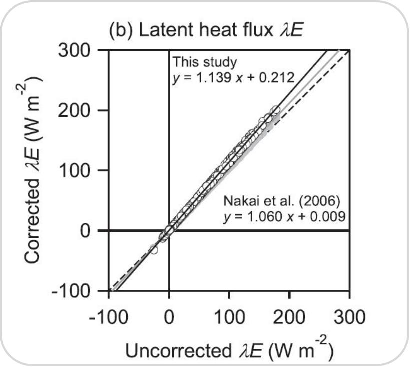
- Corrects for the flow distortion induced by the anemometer (shadowing)
- Available only for vertical-mounting Gill anemometers (R3, WindMaster)
- If not applied, <u>all</u> fluxes are underestimated by some 10-15%!



Kochendorfer et al., 2011



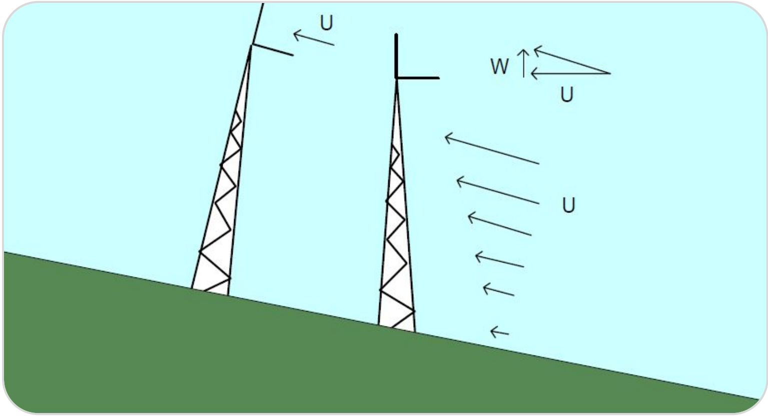
Nakai and Shimoyama, 2012

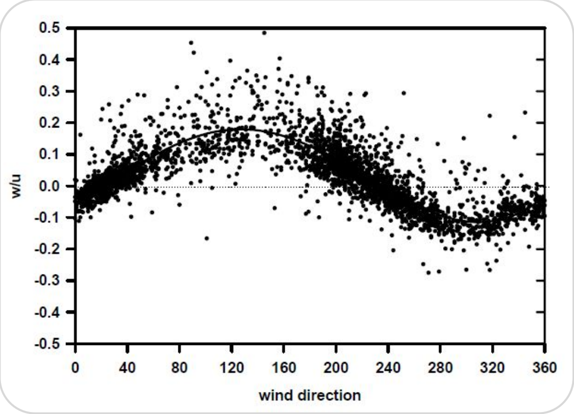


Nakai and Shimoyama, 2012

Axis rotations for tilt correction

- Correct anemometer misalignment with respect to local flow streamlines
- If not applied, all fluxes are likely to be strongly overestimated
- Different correction approaches:
  - Double rotations, triple rotations



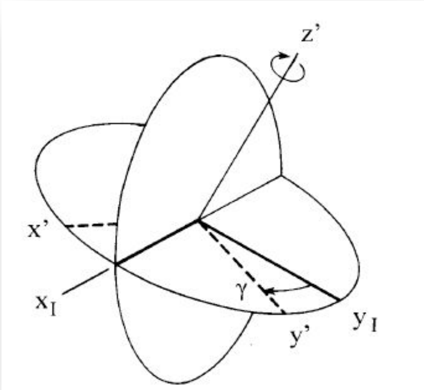


Axis rotations for tilt correction – Double rotation

- Assumes that average vertical wind component is zero on a 30-min basis (no vertical advection fluxes)

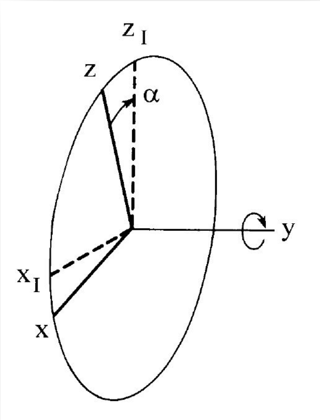
Step 1: Nullify v component of average wind vector

$$\begin{cases} u_1 = u_m \cos\gamma + v_m \sin\gamma \\ v_1 = -u_m \sin\gamma + v_m \cos\gamma \\ w_1 = w_m \end{cases} \qquad \gamma = \tan^{-1}\left(\frac{v_m}{u_m}\right)$$



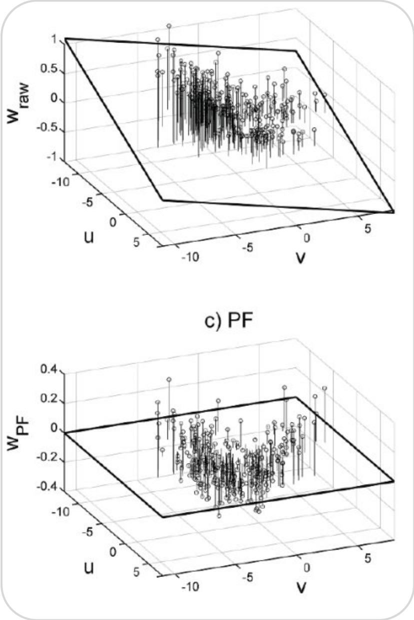
Step 2: Nullify w component of average wind vector

$$\begin{cases} u_2 = u_1 \cos\alpha + w_1 \sin\alpha \\ v_2 = v_1 (= 0) \\ w_2 = -u_1 \sin\alpha + w_1 \cos\alpha \end{cases} \qquad \alpha = \tan^{-1}\left(\frac{w_1}{u_1}\right)$$

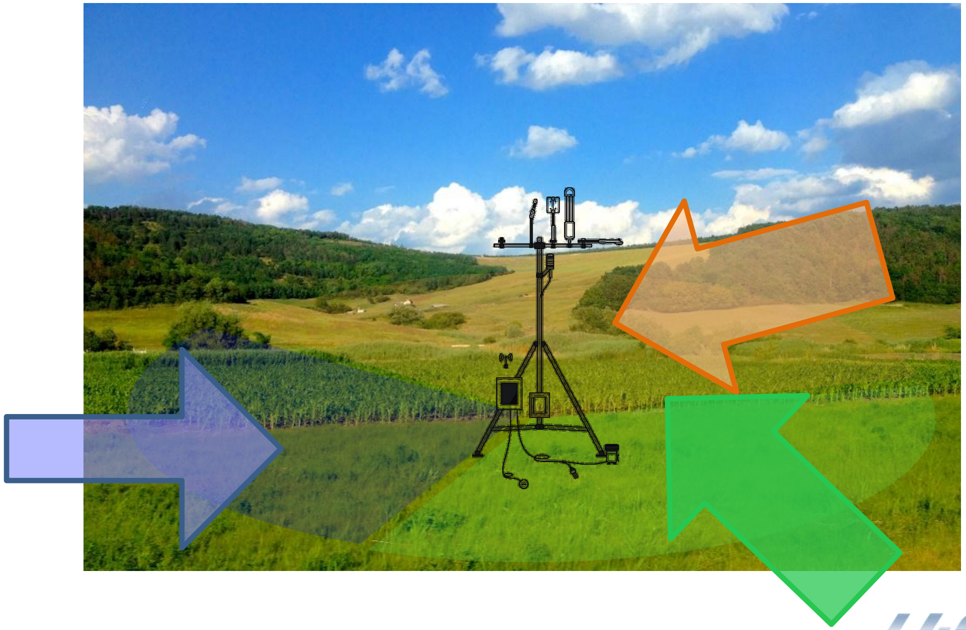


Axis rotations for tilt correction – Sector-wise planar fit

- Assumes that average vertical wind component is zero on the long term (weeks), not on a 30-min basis
- Requires pre-processing raw data to assess rotation matrices



Griessbaum and Schmidt, 2009



Time delay compensation

- Time delays (lags) arise due to the air sampling systems, signal phase-shift, instruments separation
- If not compensated, lead to systematic flux underestimation
- The covariance maximization procedure is used to calculate time lags automatically.

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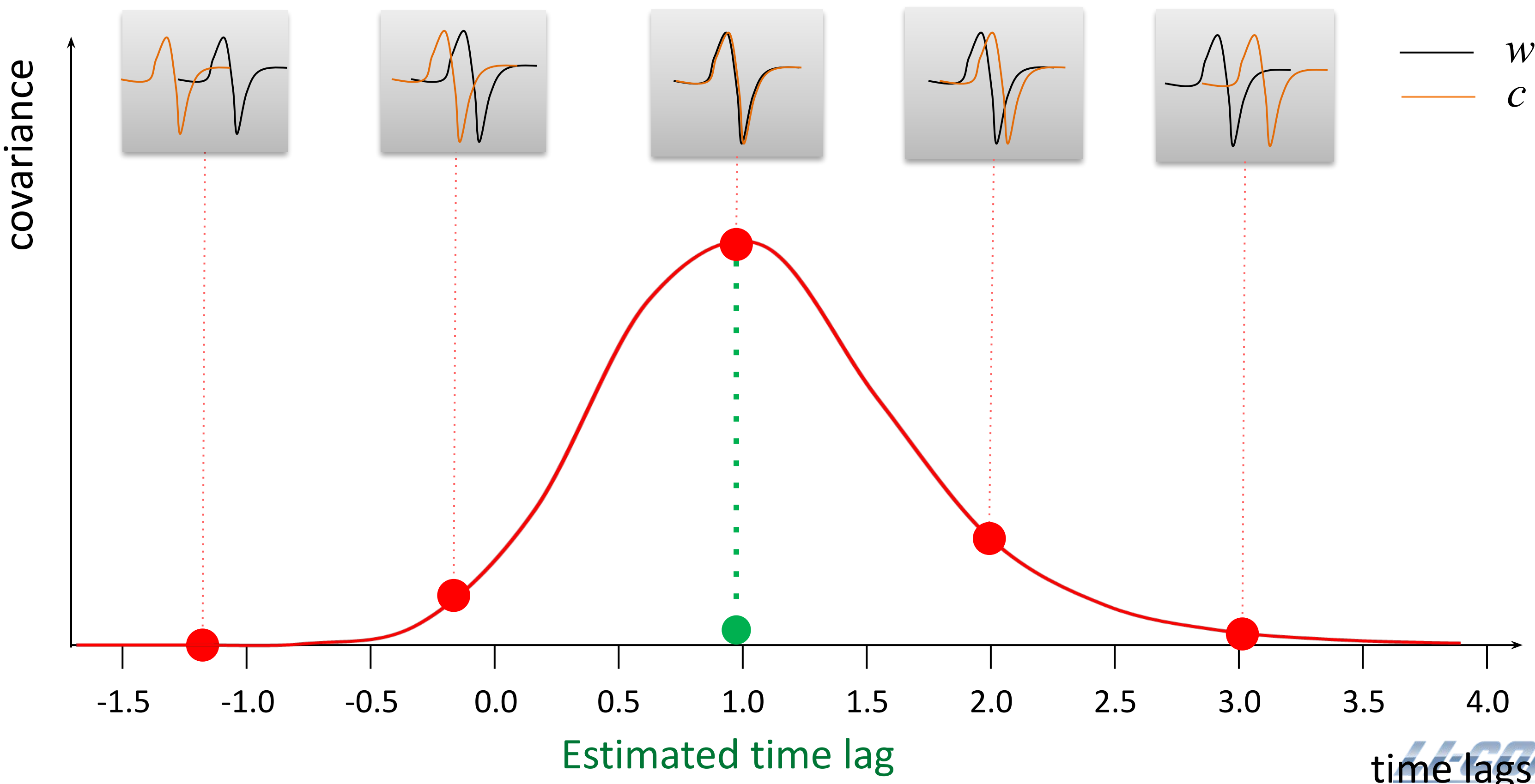
Covariance maximization

- We impose a range of (plausible) artificial lags between to the time series of w and gas concentration, and determine the time lag that maximizes the covariance



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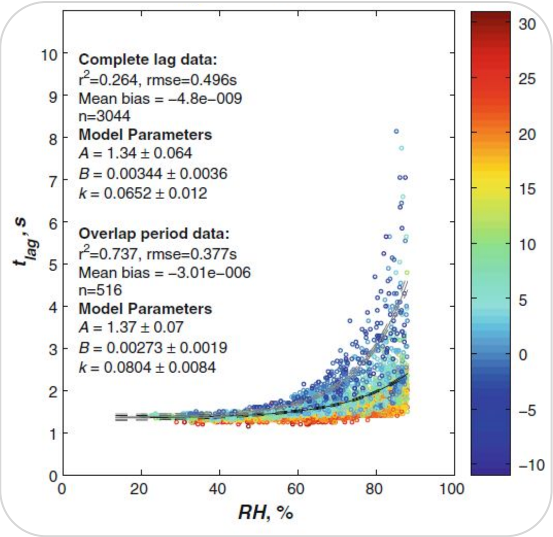
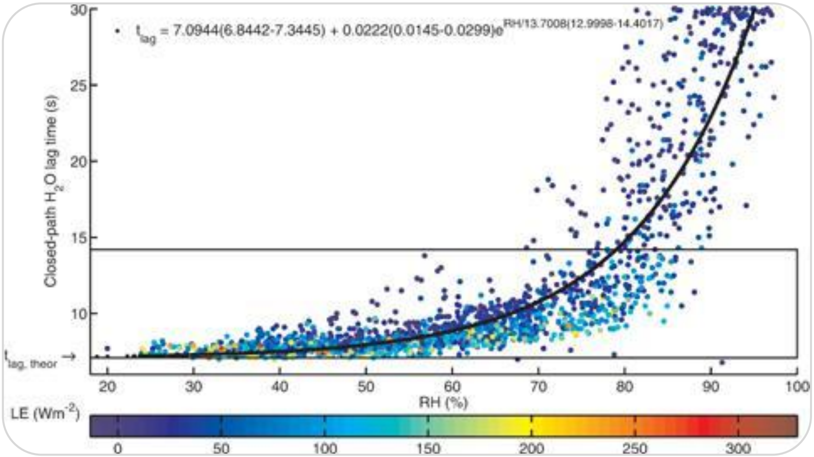
The special case of water vapor in closed-path systems

- Being a sticky gas, H2O travelling time in the sampling line depends on RH (and secondarily on T).
- Covariance maximization must be adapted to account for such dependency.



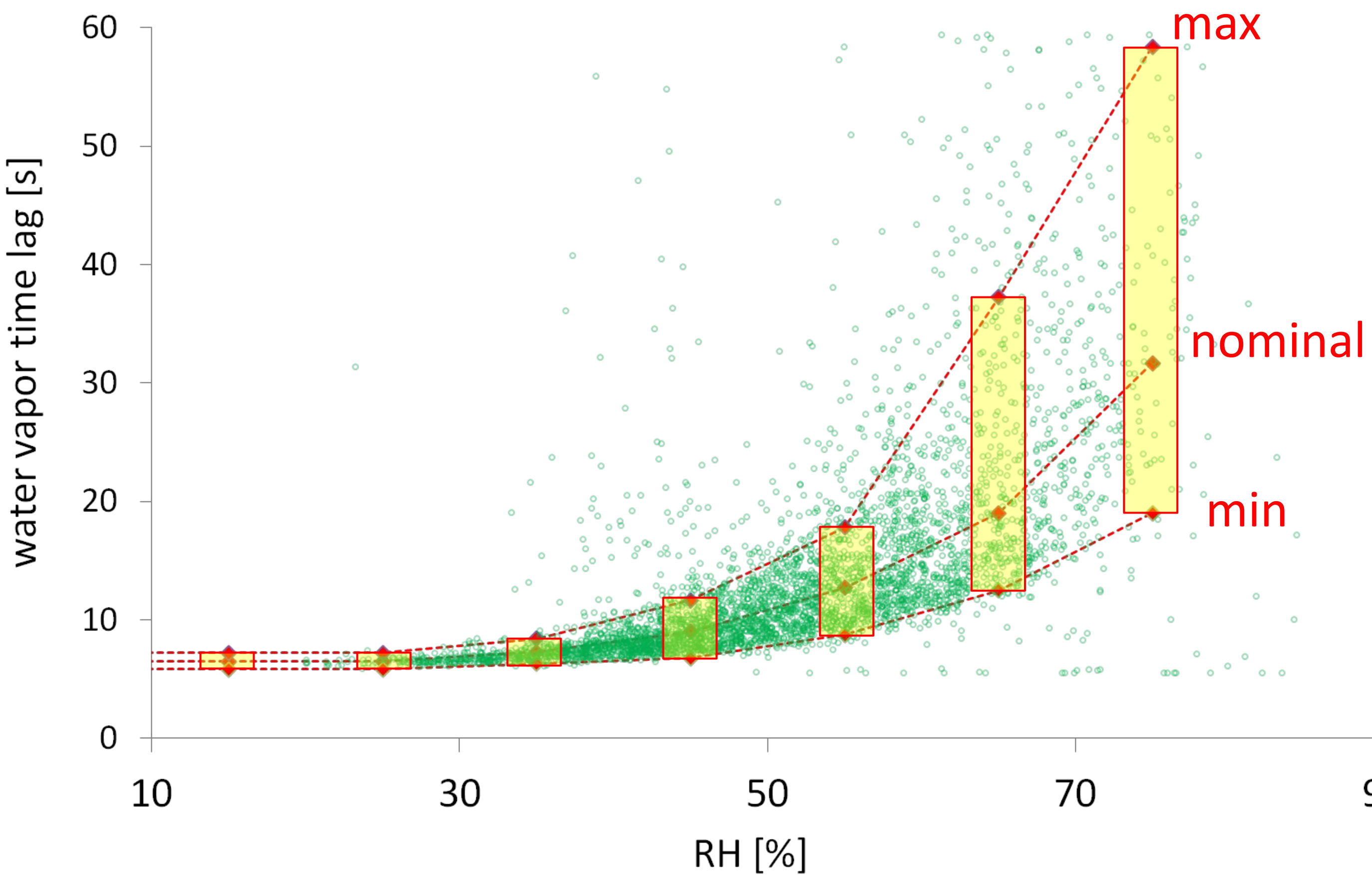
Runkle et al. (2012, BLM)



Nordbo et al. (2012, Tellus B)

Time lag optimizer

- A pre-processing step for an in-situ assessment of the dependency of H_2O time lag on RH



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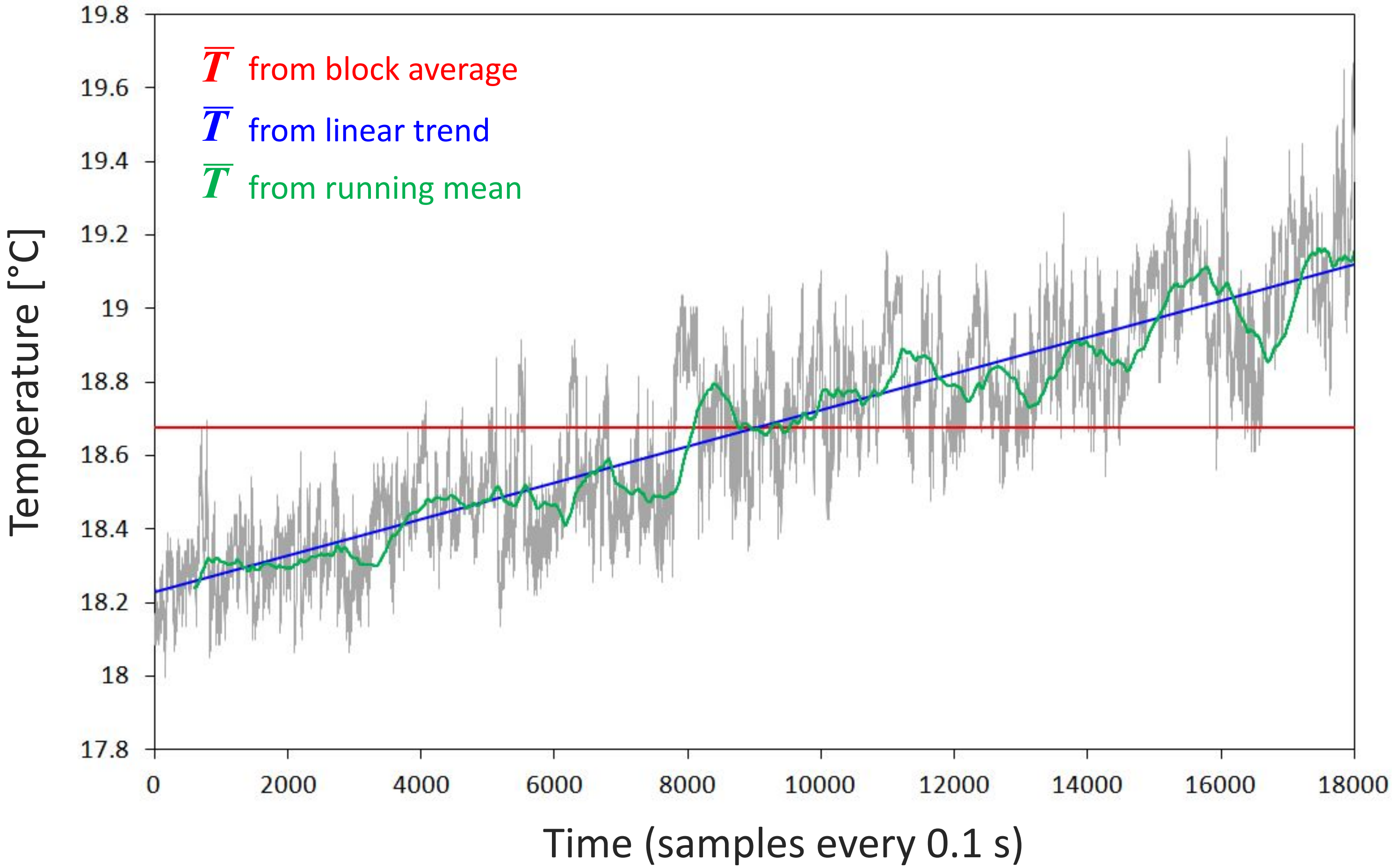
Detrending

- Calculation of turbulent fluctuations (elimination of non turbulent trends)

$$H = \rho c_p \overline{w'T'} \qquad T' = T - \overline{T}$$



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Detrending

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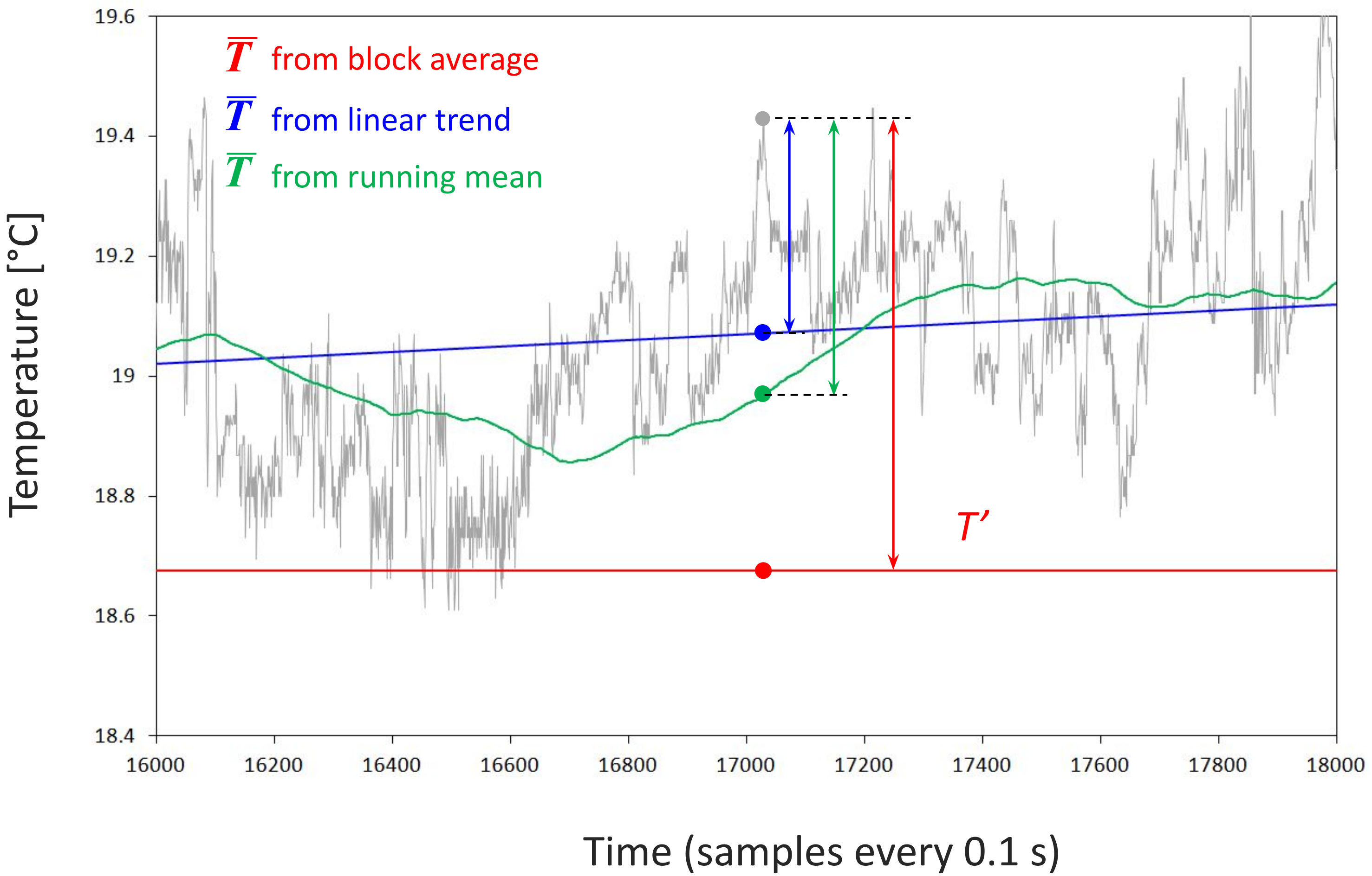
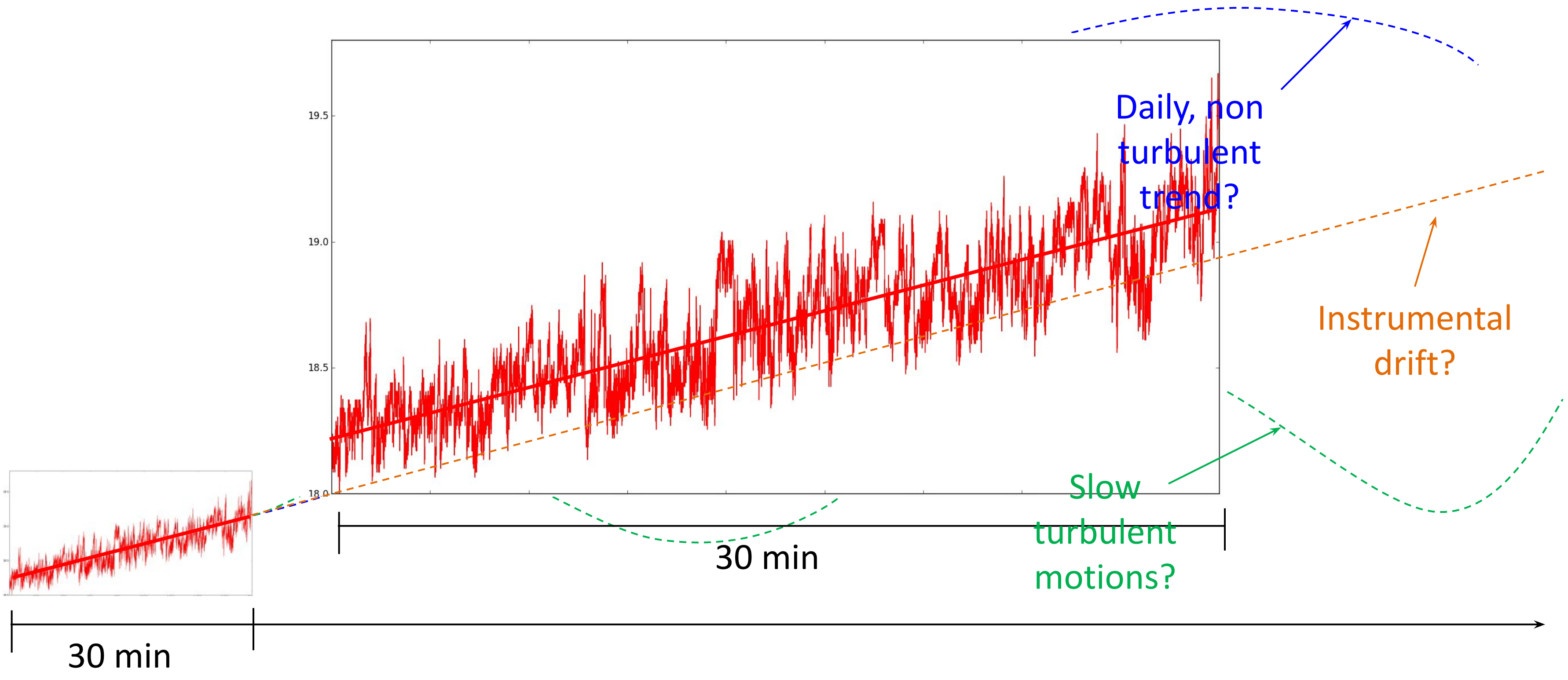


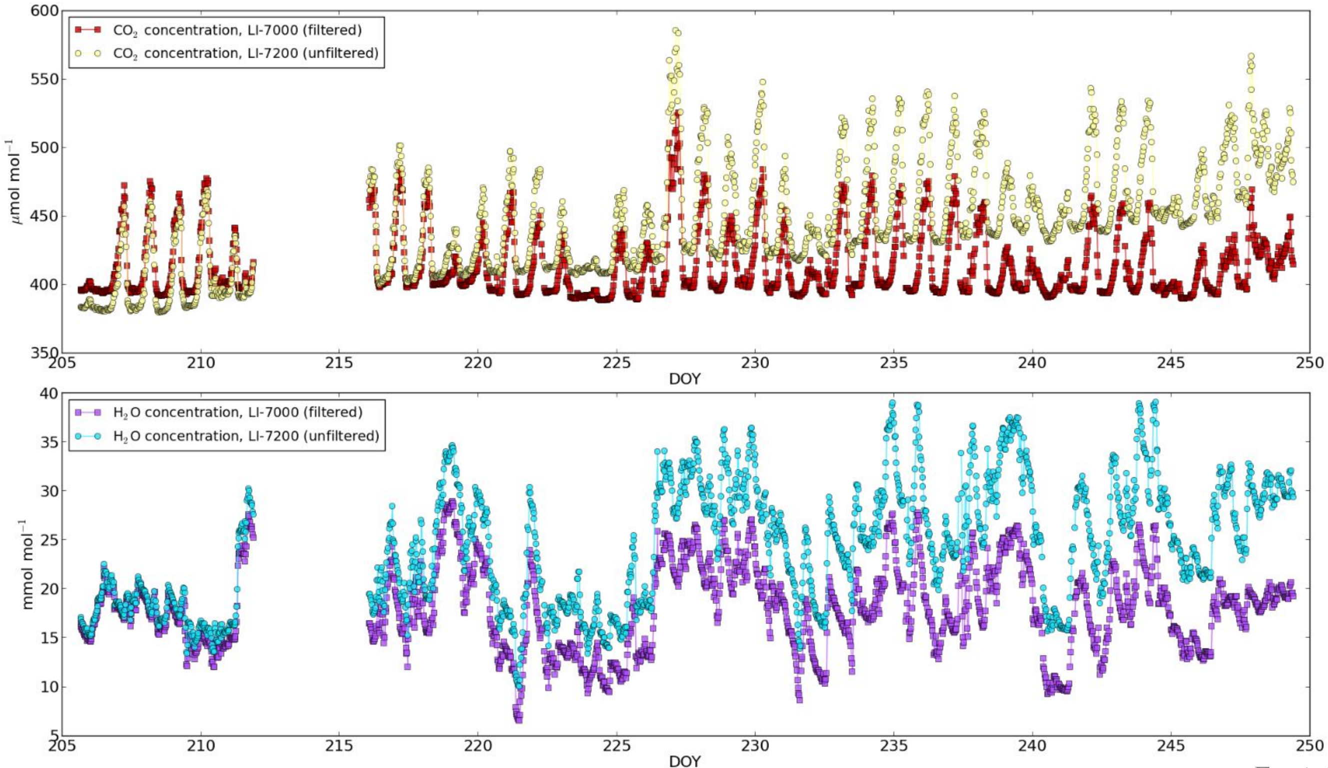
Detrending

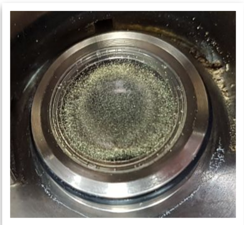
- Long-term (30-min) motions are to be expected, or should they be interpreted as non-turbulent trends?



Instrumental drift

- Open-path and closed-path instruments without adequate protection against pollutants are subject to contamination
- If the optical path is obstructed by pollutants, concentration measurement can be affected (usually shows up as a drift in time)





Fratini, internal LI-COR report

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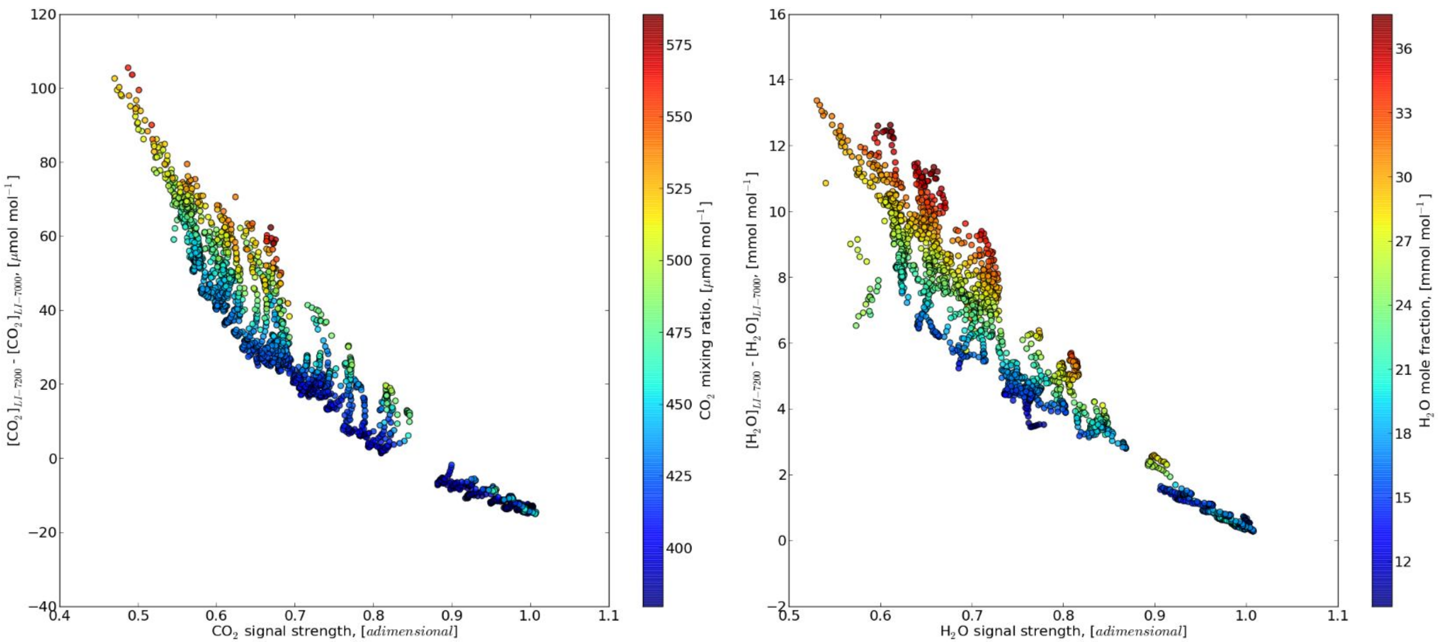
Instrumental drift

- For dynamics with clear patterns and “reference values” (e.g. atmospheric CO_2), drifts can easily be recognized. For H2O it’s much less obvious.
- Effects of contamination depends on pollutants size, effective refractive index, etc.
- RSSI (Signal Strength) is a proxy, but not always a reliable one.



Fratini, internal LI-COR report

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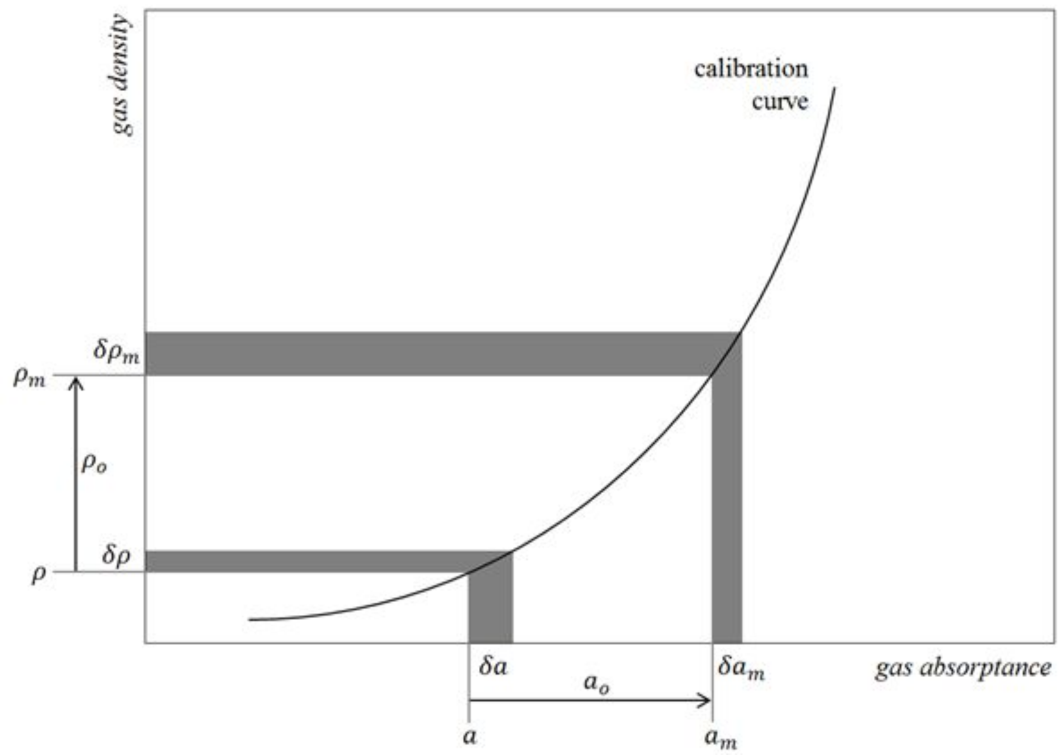
Instrumental drift

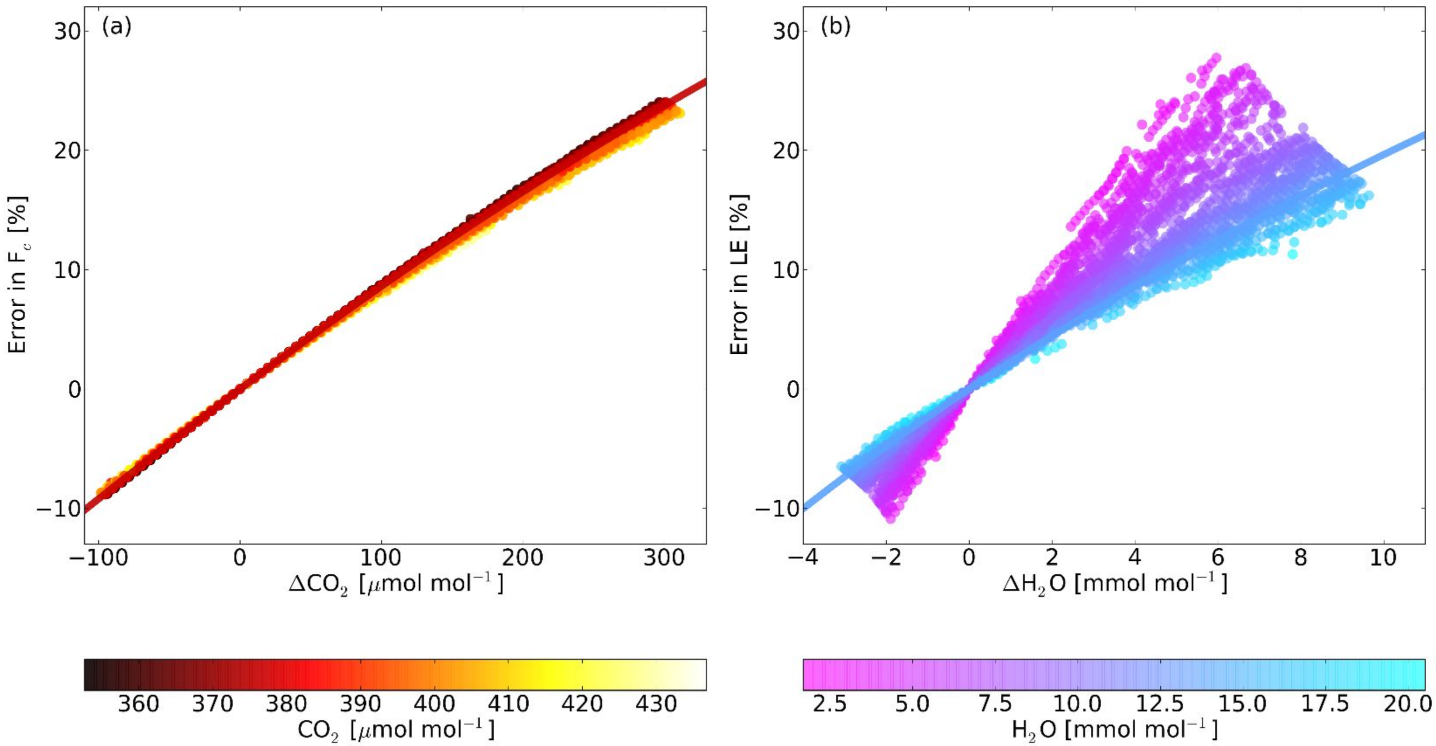
- It is commonly believed that errors in mean concentrations do not bias resulting fluxes.
  - After all: $F = \overline{\rho_a} \cdot \overline{w'c'}$
- In reality, on account of the non-linearity of calibration curves, this is not true:



Fratini et al. 2014, Biogeosciences

Instrumental drift

- Flux error depends directly on concentration bias
- For water vapor, flux error depends strongly also on the concentration at which the bias occurs



Fratini et al. 2014, Biogeosciences

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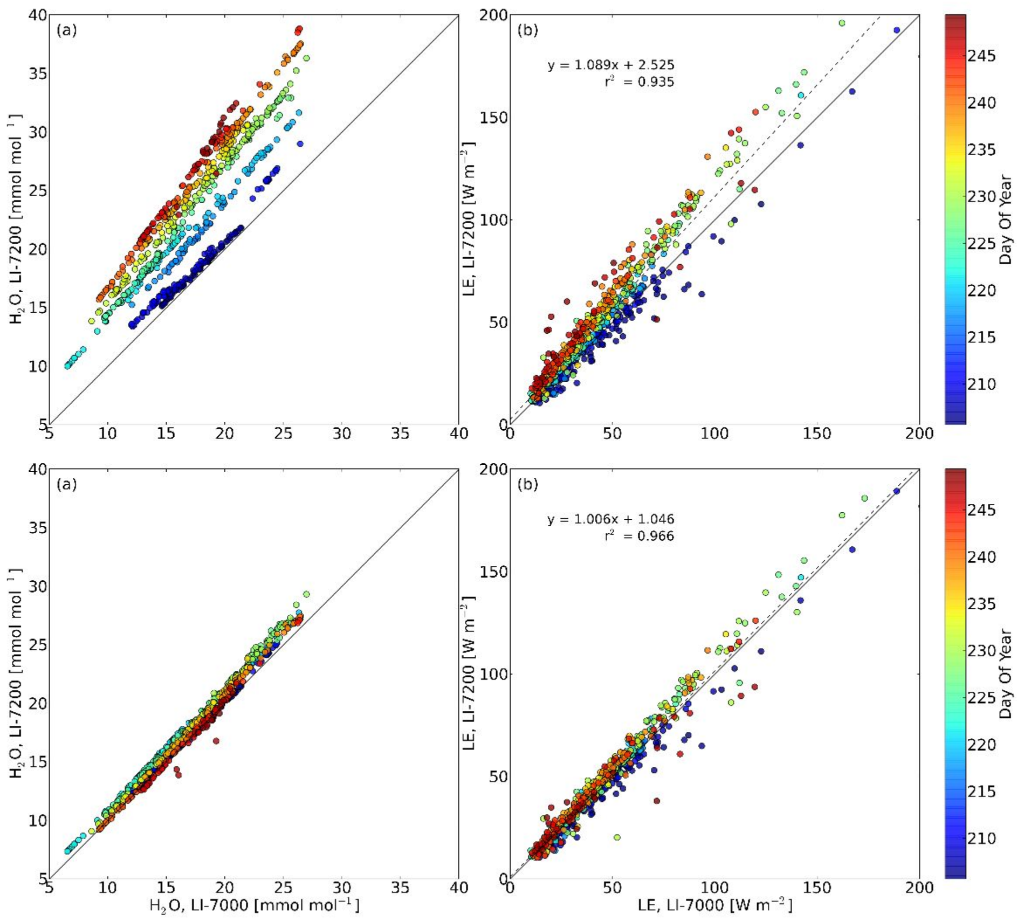
Instrumental drift

- A procedure is available in EddyPro® to correct concentration biases
- LE fluxes can improve as much as 8%



Fratini et al. 2014, Biogeosciences

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Third step

Correction of preliminary flux estimates

Compensation of air density fluctuations (WPL term)

$$c = d\frac{RT}{P(1-\chi_w)} = \frac{d}{d_a}$$

- Compensate for the dependency of gas molar density measurements on fluctuations of air temperature, pressure and humidity
- This is not a correction: it is an actual term in the mass balance equation

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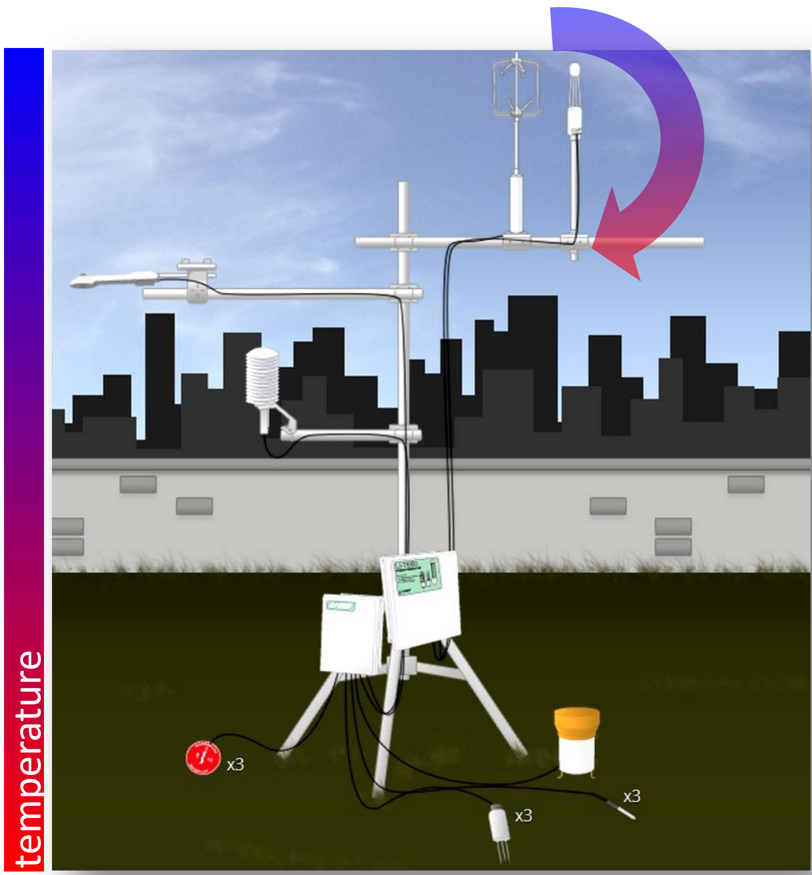
Compensation of air density fluctuations (WPL term)



$$d = c\frac{P(1-\chi_w)}{RT}$$

w' ↓

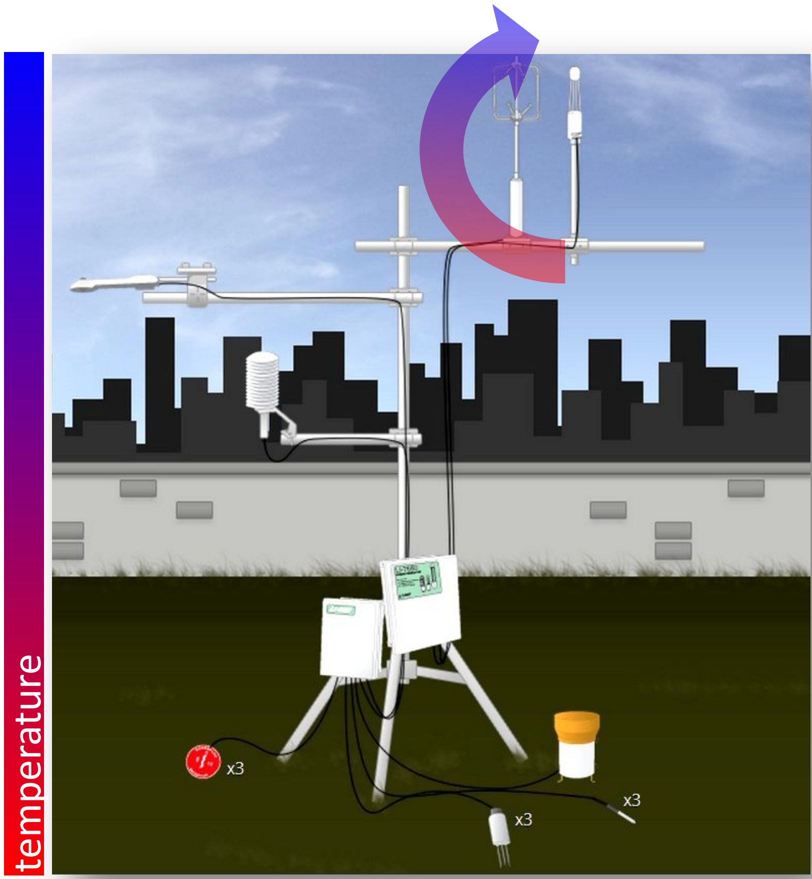
T' ↓

d' ↑

$$w' \cdot d' < 0$$

Apparent CO_2 uptake!

Compensation of air density fluctuations (WPL term)



$$d = c\frac{P(1-\chi_w)}{RT}$$

w' ↑

T' ↑

d' ↓

$$w' \cdot d' < 0$$

Apparent CO_2 uptake!

Compensation of air density fluctuations (WPL term)

- Must be applied for all gas analyzers that measure gas molar densities
- Several approaches available:
  - Transform densities to mixing ratios at high frequency
    - enclosed-path analyzers with fast T and P measurements
  - Neglect T and P fluctuations, compensate for humidity
    - Closed-path analyzers with long sampling lines
  - WPL approach to add T, P and humidity terms to preliminary fluxes
    - Open-path analyzers

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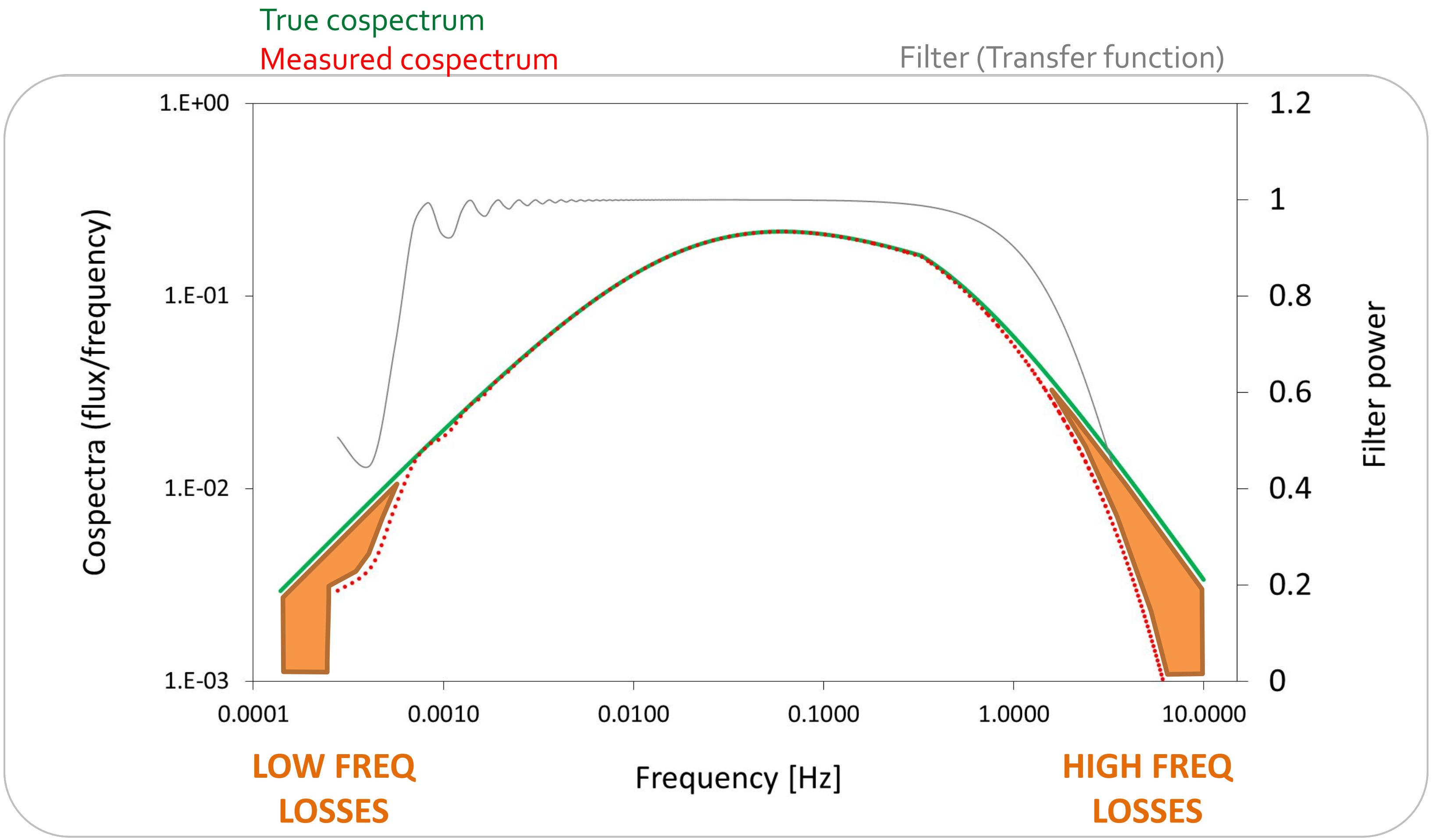
Compensation of spectral attenuations

- Spectra attenuations arise due to:
  - Instrumental limitations (response time, volume averaging)
  - Instruments deployment (sampling lines, instrument separations, height above the ground)
  - Site characteristics (surface roughness)
  - Processing choices (finite flux averaging interval)

Compensation of spectral attenuations



Strategies for spectral attenuations

- **Analytic** (Moncrieff et al. (1997); Massman (2000)):
  - PROS: Simple, robust, physically based
  - CONS: some important sources of attenuation are not described (filters, water vapor interactions with surfaces..)
- **In-situ** (Ibrom et al. (2007); Runkle et al. (2012), Fratini et al. (2012)):
  - PROS: don't make (too many) assumptions on attenuation sources, assess attenuations based on collected data

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Other corrections (instrument-specific)

- Correction of sensible heat fluxes for effects of humidity on air temperature estimated with sonic temperature
- Cross-wind correction of sonic temperature (often included in anemometer firmware)
- «Self-heating correction» for some open-path CO_2/H_2O analyzer models in cold environments
- Spectroscopic correction for LASER-based analyzers (e.g. LI-7700)
- Band-broadening correction for NDIR-based analyzers

Micrometeorological QC tests: stationarity

- *Foken et al. 2004, Handbook of Micrometeorology*

$$(\overline{x'w'})_i = \frac{1}{N-1}\left[\sum_j x_j w_j - \frac{1}{N}\sum_j x_j \sum_j w_j\right]$$

Covariance calculated on single sub-period i

$$\overline{x'w'} = \frac{1}{M}\sum_i (\overline{x'w'})_i$$

Average covariance calculated usign the M sub-periods

$$(\overline{x'w'})_o = \frac{1}{M(N-1)}\left[\sum_i (\sum_j x_j w_j)_i - \frac{1}{MN}\sum_i (\sum_j x_j \sum_j w_j)_i\right]$$

Covariance calculated on the full averaging period

$$\mathrm{RN_{COV}} = \left|\frac{(\overline{x'w'}) - (\overline{x'w'})_o}{(\overline{x'w'})_o}\right|$$

Relative difference between the two covariance estimates, should not exceed a threshold (30% or 100%)

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Micromet. QC tests : developed turbulence

- *Foken et al. 2004, Handbook of Micrometeorology*

$$\frac{\sigma_{u,v,w}}{u_*} = c_1(\frac{z}{L})^{c_2}$$

$$\frac{\sigma_x}{X_*} = c_1(\frac{z}{L})^{c_2}$$

In atmospheric turbulence the ratio between variance of a quantity and its turbulent flux is constant or function of the stability parameter

Parameter	z/L	c_1	c_2
σ_w/u_*	$0 > z/L >$ -0.032	1.3	0
	$-0.032 > z/L$	2.0	1/8
σ_u/u_*	$0 > z/L >$-0.032	2.7	0
	$-0.032 > z/L$	4.15	1/8
σ_T/T_*	$0.02 < z/L < 1$	1.4	-1/4
	$0.02 > z/L >$-0.062	0.5	-1/2
	$-0.062> z/L >$-1	1.0	-1/4
	$-1 > z/L$	1.0	-1/3

$$ITC_\sigma = \left|\frac{(\sigma_x/X_*)_{model} - (\sigma_x/X_*)_{measurement}}{(\sigma_x/X_*)_{model}}\right|$$

Relative difference between the two estimates of turbulence parameters must be below a given thrensold

Micrometeorological QC tests combination

- ✔ Stationarity and developed turbulence tests provide an individual "flag" (one per test)
- ✔ The two flags are combined in a single general flag that can be used to filter the data

a		b	
class	range	class	range
1	0-15%	1	0-15%
2	16-30%	2	16-30%
3	31-50%	3	31-50%
4	51-75%	4	51-75%
5	76-100%	5	76-100%
6	101-250%	6	101-250%
7	251-500%	7	251-500%
8	501-1000%	8	501-1000%
9	>1000%	9	>1000%

a: State-state test according to Equation 9.6.

b: Integral turbulence characteristics according to Equation 9.9.

Foken et al. 2004, Handbook of Micromet

How does EddyPro use biomet data?

- Fluxes (e.g. over 30 min intervals) are calculated and corrected based on:
  - Covariances calculated from fast measurement, acquired at f > 5Hz
  - Mean quantities, averaged over the 30 min interval

For example, CO_2 flux:

$$F = \overline{\rho_a} \cdot \overline{w'c'}$$

Mean value over 30 mins, calculated starting either from fast or slow measurements

Covariance over 30 mins, calculated starting from fast measurements

How does EddyPro use biomet data?

- Average **air temperature** and **RH** are involved in various flux equations, for example:

air density: $$\rho_d = \frac{P}{R_d T_a} - \rho_w \frac{m_d}{m_w}$$

WPL term: $$F = F_o + \mu \frac{E}{\rho_d} \frac{\rho_c}{1 + \mu \frac{\rho_w}{\rho_d}} + \frac{H}{\rho_a C_p} \frac{\rho_c}{T_a} + P_{term}$$

H correction: $$H = \rho C_p \overline{w' T_a'} + \rho C_p \frac{-0.51 T_a E}{\rho_a}$$

How does EddyPro use biomet data?

- Global (R_g) and longwave incoming (R_l) radiations and PAR are needed in the off-season uptake correction of the LI-7500(A), Burba et al. 2008:

	Parameters for multiple regression* between T_s–T_a and T_a, R_g, R_l, U				
	Offset	Parameter 1 (for T_a)	Parameter 2 (for R_g)	Parameter 3 (for R_l)	Parameter 4 (for U)
Daytime					
$T_s^{bot}-T_a$	2.8	−0.0681	0.0021	–	−0.334
$T_s^{top}-T_a$	−0.1	−0.0044	0.0011	–	−0.022
$T_s^{spar}-T_a$	0.3	−0.0007	0.0006	–	−0.044
Night-time					
$T_s^{bot}-T_a$	0.5	−0.1160	–	0.0087	−0.206
$T_s^{top}-T_a$	−1.7	−0.0160	–	0.0051	−0.029
$T_s^{spar}-T_a$	−2.1	−0.0200	–	0.0070	0.026

*Multiple regression: daytime T_s-T_a = offset + parameter 1 × T_a + parameter 2 × R_g + parameter 4 × U; night-time T_s-T_a = offset + parameter 1 × T_a + parameter 3 × R_l + parameter 4 × U. All temperatures are in °C.

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