Measuring turbulent fluxes at ecosystem scale: basics of the eddy covariance technique

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Outlines

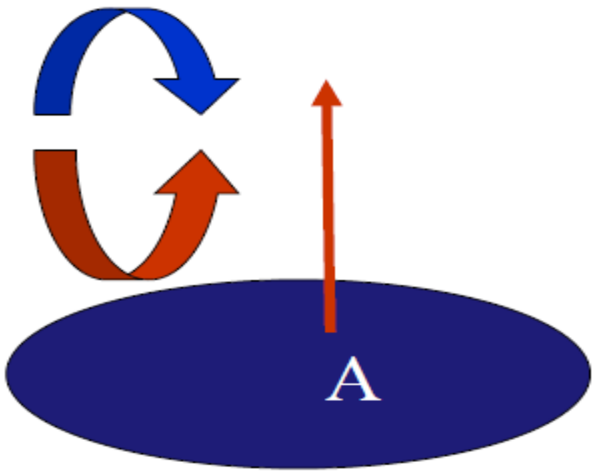
- Turbulent flux
- Linking turbulent flux and surface exchange
- Eddy covariance: basics concepts
- Night-time problem and gap-filling
- Flux uncertainty

What is (turbulent) flux?

- In micrometeorology, flux is defined as the amount of any properties (e.g. substance s) transported per unit area per unit time (flux density).

$$F = \overline{w' \chi_s '}$$

- Vertical turbulent flux: the mean value of the product between instant fluctuations of vertical velocity (w') and the concentration of substance s (χ_s'), e.g. covariance.
- typically 30min average.
- sign of the covariance indicates the direction of turbulent transport: "+" upwards, "-" downwards .

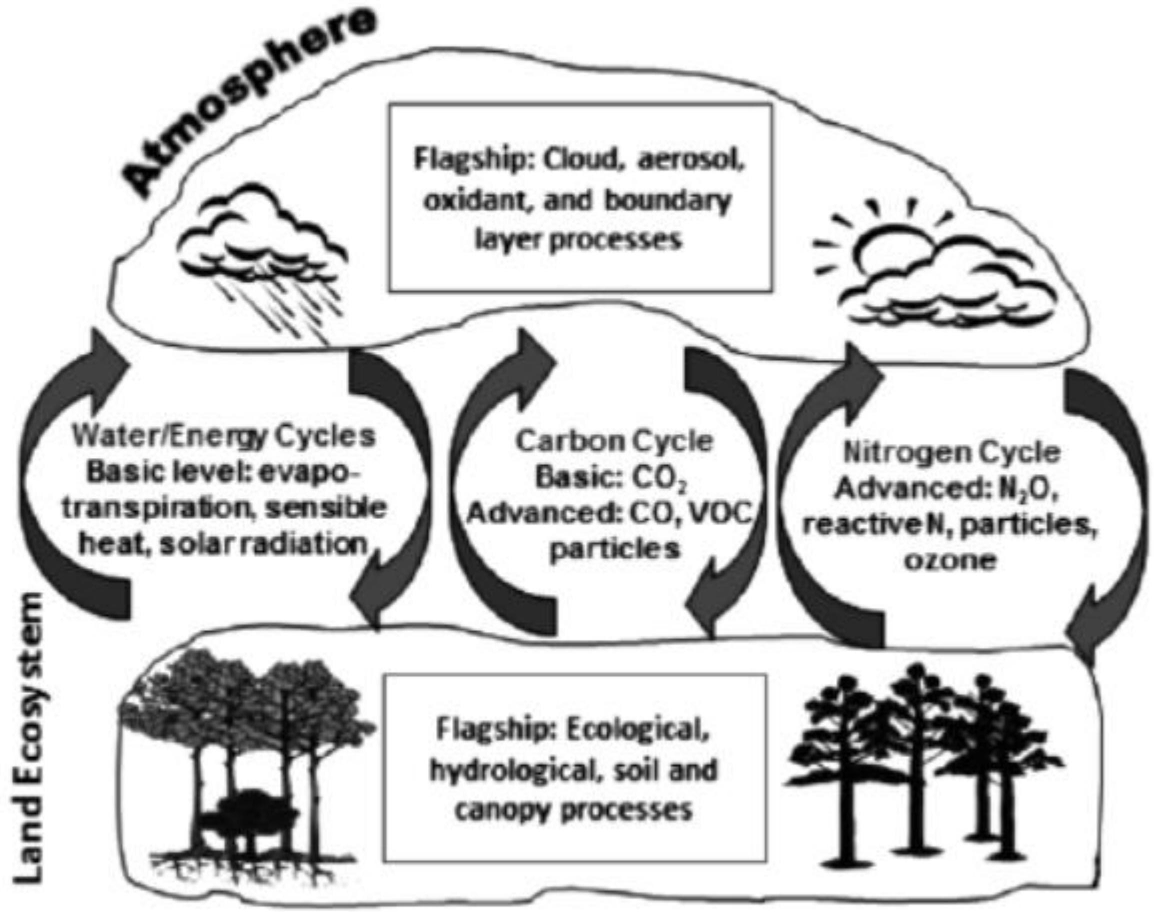


Micrometerological techniques

- Eddy covariance
- Disjunct eddy covariance
- Relaxed eddy accumulation
- Flux-gradient technique
  - M-O similarity approach
  - Modified Bowen ratio
- Bowen ratio method (for H2O)
- Dissipation
- Bulk transfer relationships

Why we want to measure fluxes in the ASL?

We want to know the surface exchange (material, energy, momentum).

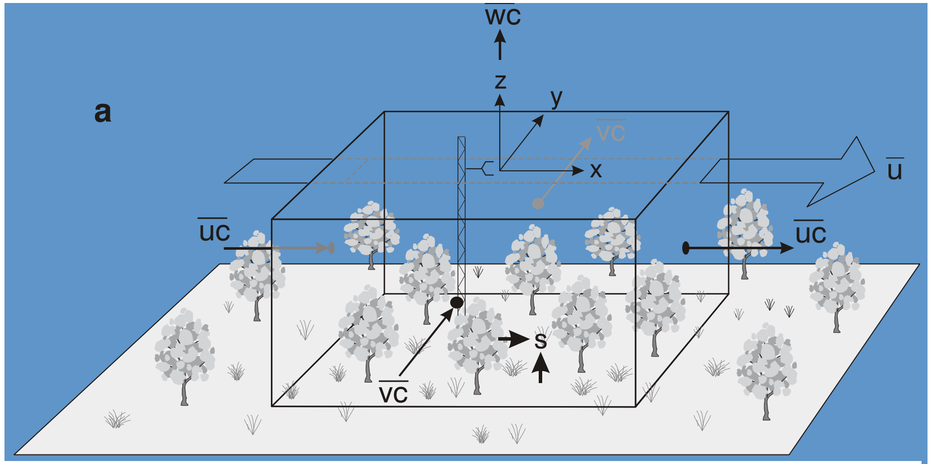


Guenther et al., 2011

Assumption: flux at measurement height h_m equals the surface flux.

The integral scalar budget equation

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



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

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

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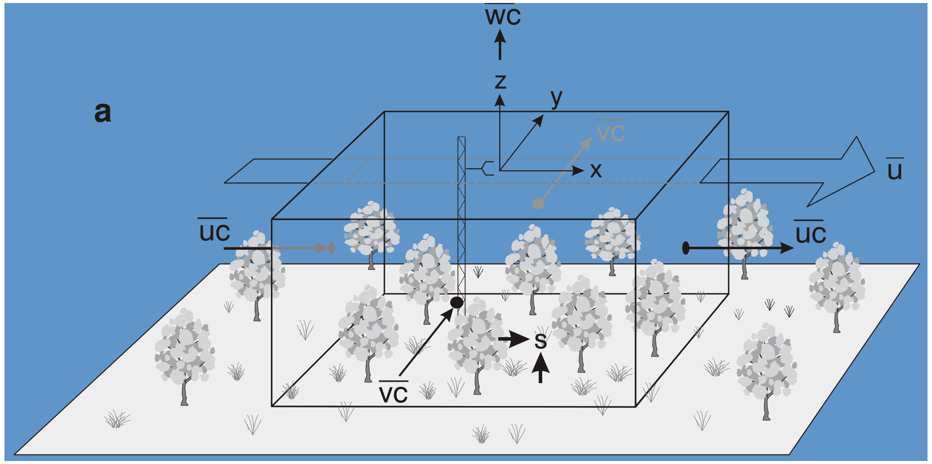
In homogeneous surface layer, terms II and III are assumed negligible.



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

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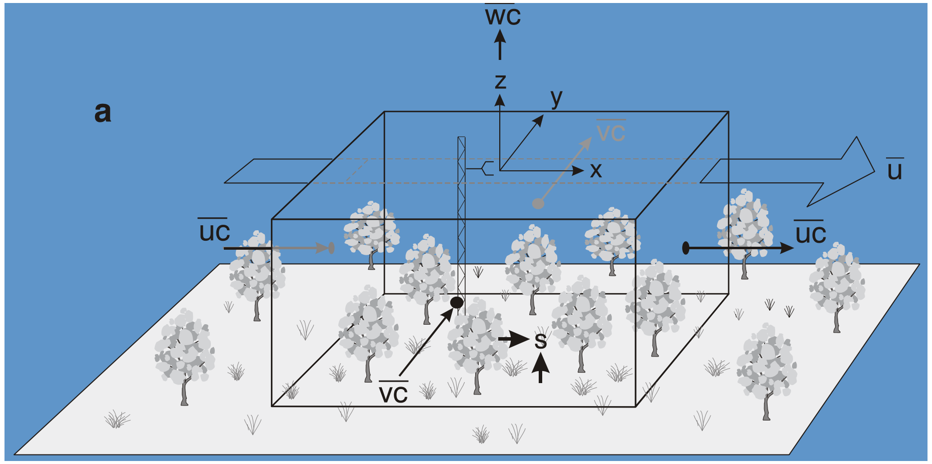
The integral scalar budget equation

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

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



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In homogeneous surface layer

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

Net Ecosystem Exchange = Turbulent flux at $\mathrm{h}_m (IV)$ + Storage change flux(I)

In homogeneous surface layer

$$\underbrace{\int \frac{\partial \overline{\chi_s}}{\partial t} dz}_{I} + \underbrace{\overline{w'\chi_s'}\Big|_{h_m}}_{IV} = NEE$$

$$\text{Net Ecosystem Exchange} = \text{Turbulent flux at } h_m(IV) + \text{Storage flux}(I)$$

And in stationarity conditions

This equation is at the basis of micrometeorological methods for measuring surface exchange!

Eddy covariance

- Direct and continuous measurements of net surface exchanges of energy and gases at ecosystem scale.
- Time scale half-hour to interannual.
- Non destructive, non invasive.
- Ecosystem function.

- Only net fluxes.
- Random errors.
- Systematic errors.
- Gaps.
- Flat terrain

Turbulent fluxes typically measured by EC

$H = \rho_a c_p \overline{w'T'}$	Sensible heat flux [W/m^2]
$LE = \rho_a L_v \overline{w'\chi_v'}$	Latent heat flux [W/m^2]
$\tau = -\rho_a \overline{w'u'}$	Momentum flux [kg/ms^2]
$F_c = \frac{\rho_a}{M_a} \overline{w'\chi_s'} \approx \overline{w'c_s'}$	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))
$L_v = 3147.5 - 2.37T_K$	Latent heat of vaporization of air (2260kJ/kg at 100C=373K)
$w', u', T', \chi_v', \chi_s', c_s'$	Deviation from average of vertical and horizontal wind speed, temperature, water vapor mixing ratio, mixing ratio of substance s, density of substance s

How do we measure EC flux

3D sonic anemometer + fast gas analyzer

High frequency (≥10 Hz) measurements of u, v, w, T, CO_2, H_2O, CH_4, N_2O…

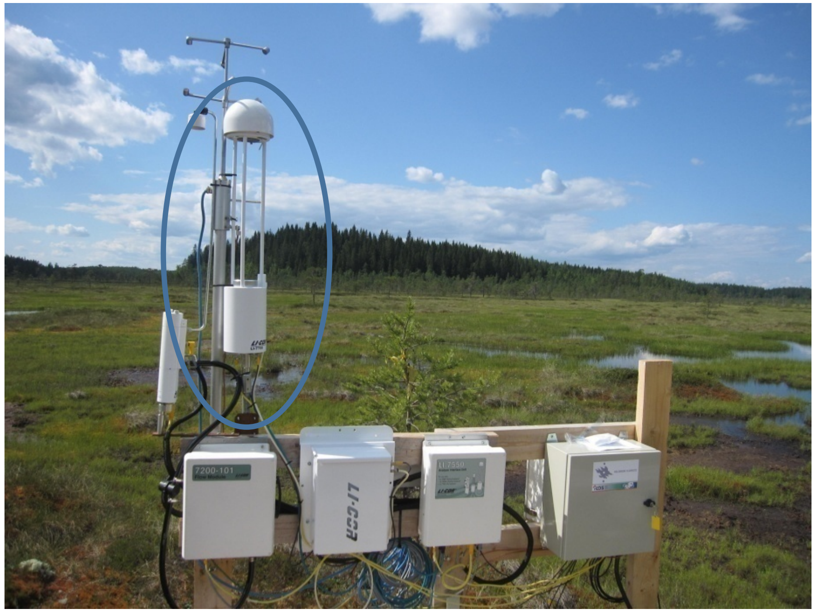
Open-path IRGA Licor 7500 (CO_2 and H_2O)

Sampling tube inlet of closed-path IRGA

Photos by Sami Haapanala, UH

Open-path gas analyzers

Licor 7500 (CO_2 and H_2O), Licor 7700 (CH_4)



Licor 7700 (CH_4)

Advantages:

- Low power consumption (~ 8-10 W)
- Small high frequency flux loss

Disadvantages:

- Flux correction for H_2O and T fluctuations (Webb et al., 1980)
- Sensor self heating (Burba et al., 2008)
- Separation distance from the sonic anemometer
- Not working with adverse weather (rain, fog, snow)

Photos by Sami Haapanala, UH

Open-path gas analyzers

Licor 7500 (CO_2 and H_2O), Licor 7700 (CH_4)

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Closed-path gas analyzers

Licor 6262, 7000, 7200 (CO_2 and H_2O)

Photos by LICOR Inc.

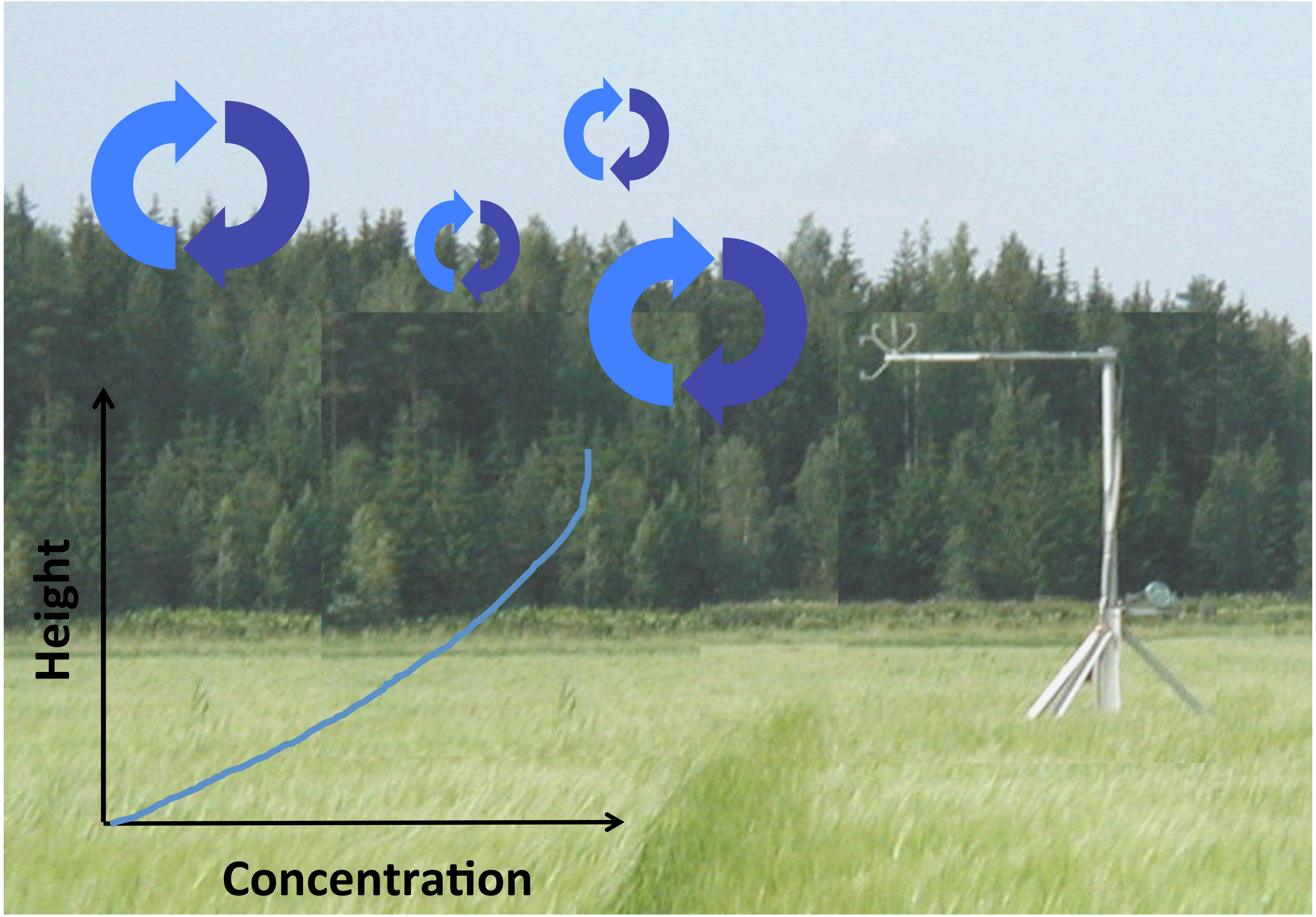
Advantages:

- Working with adverse weather (rain, fog, snow)
- Temperature fluctuations are damped.
- On-line calculation of mixing ratio (no need for WPL)

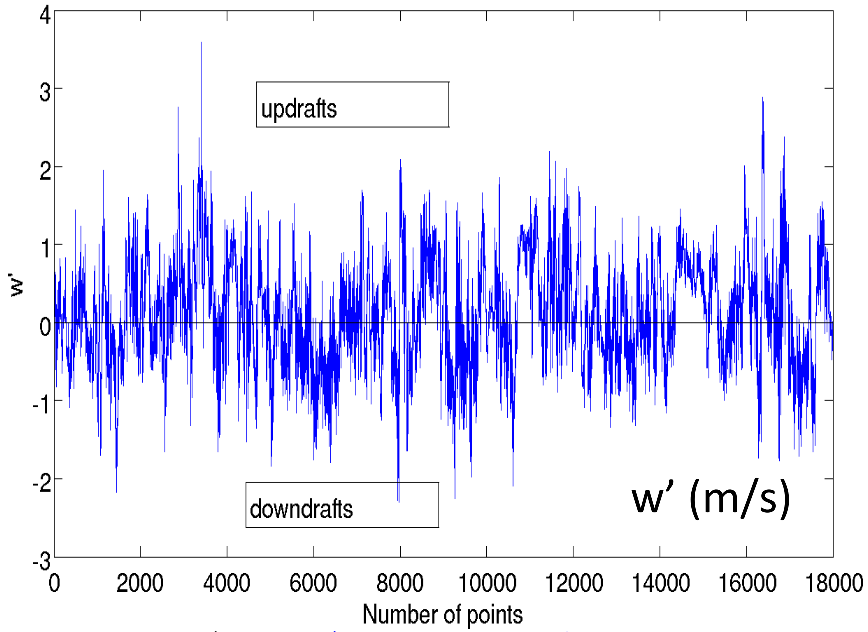
Disadvantages:

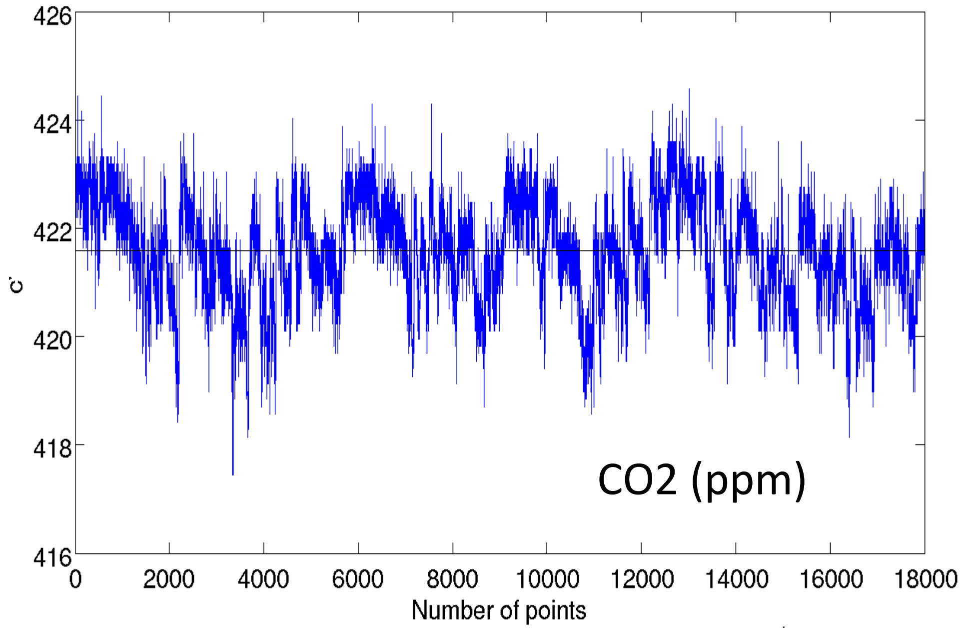
- Need high power (~10 + 40 W for the pump)
- Except for Licor 7200, potentially large flux attenuation at high frequency (depending on EC system set-up)
- Time lag and flux attenuation of H_2O due to the sampling line and filters affected also by ambient condition (relative humidity)

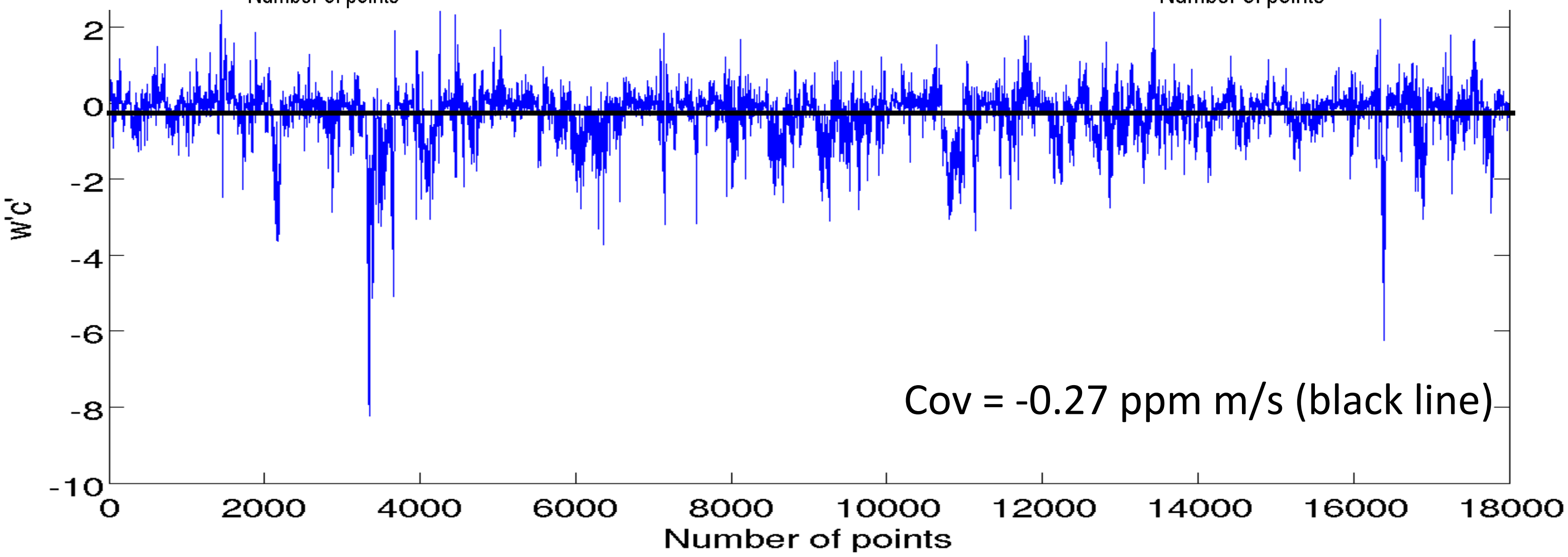
Transport of CO_2 by eddies

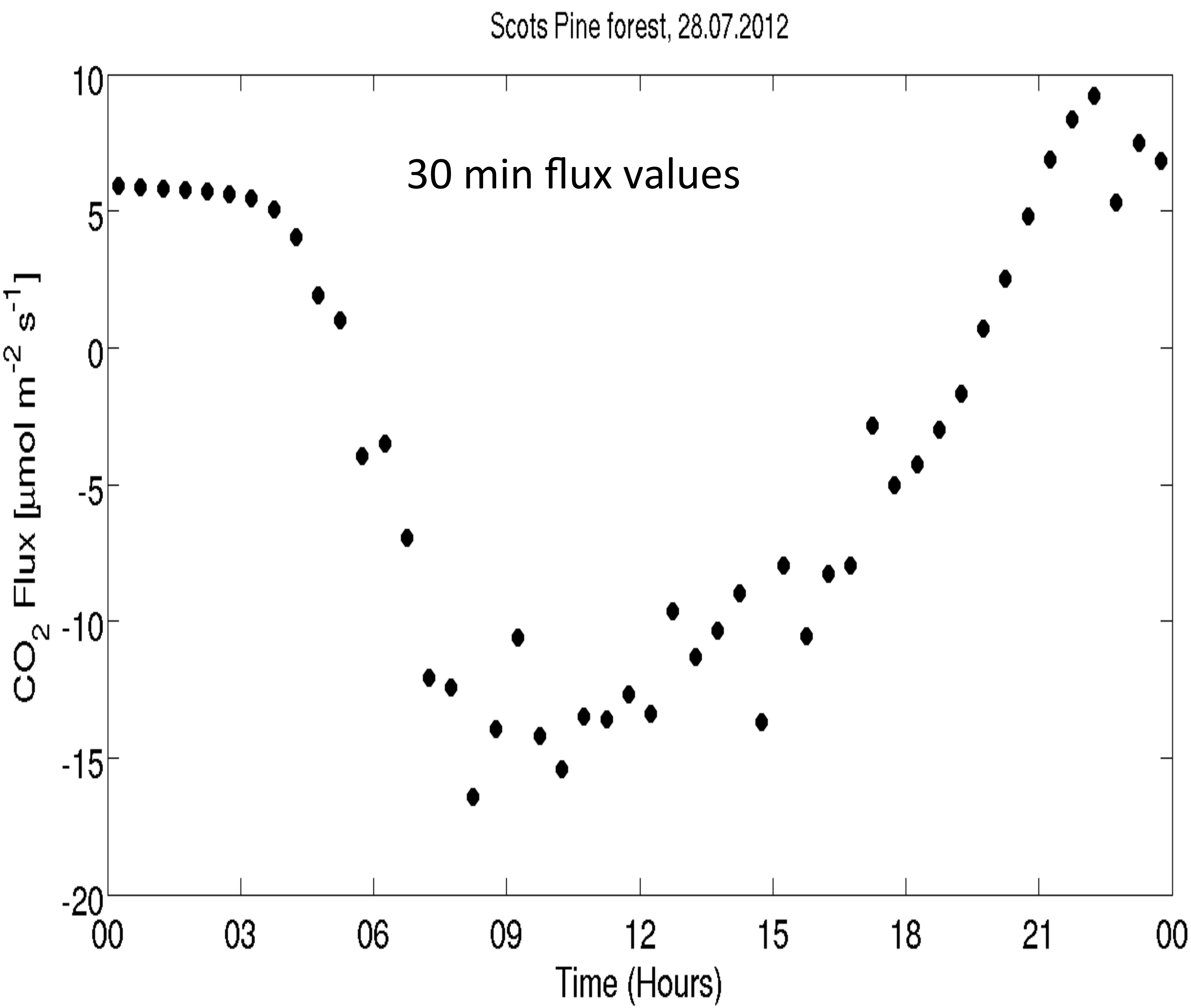


Example of 10 Hz measurements above a forest canopy (28.07 11-11.30 am)








Scots Pine forest, 28.07.2012
30 min flux values
CO2 Flux [µmol m-2 s-1]
10
5
0
-5
-10
-15
-20
00
03
06
09
12
15
18
21
00
Time (Hours)

Design and implementation

Minimal Eddy Station

- Product: flux of 1 gas and/or H_2O
- u, v, w, T_s (*fast 3D sonic anemometer*)
- \+ **concentration of 1 gas** (*fast gas analyzer*)
- \+ **concentration of H_2O** (*fast H_2O analyzer*)

Typical Eddy Station

- Product: flux of 1 gas and H_2O, + supporting weather data
- u, v, w, T_s (*fast 3D sonic anemometer*)
- \+ **concentration of 1 gas** (*fast gas analyzer*)
- \+ **concentration of H_2O** (*fast H_2O analyzer*)
- \+ **mean** T_{air}, RH, U, P, W_{dir}, **precipitation,** *etc.* (*slow weather sensors*)

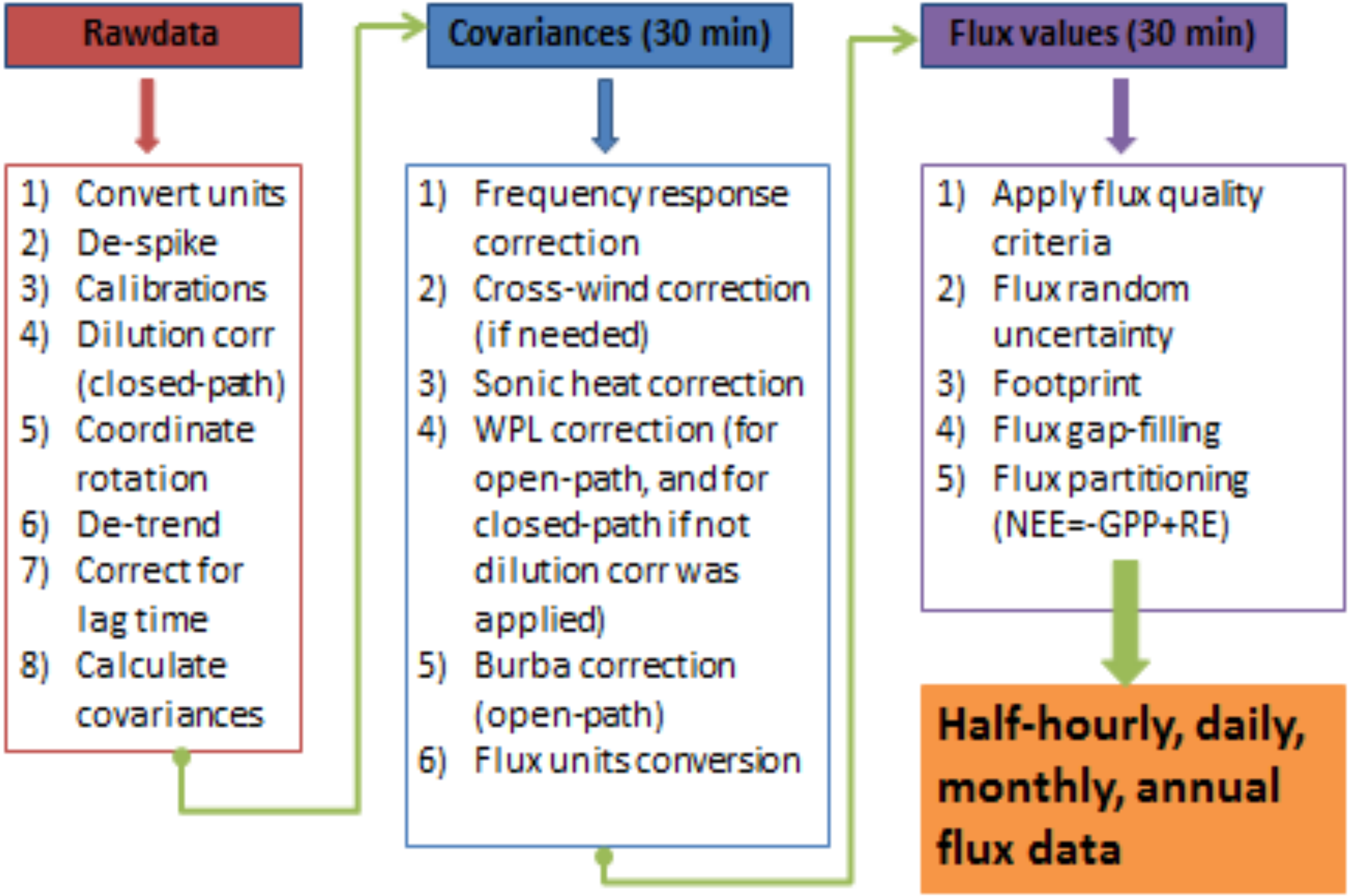
Full Eddy Station

- Product: flux of 1 gas and H_2O, + supporting weather, radiation, and soil data
- u, v, w, T_s (*fast 3D sonic anemometer*)
- \+ **concentration of 1 gas** (*fast gas analyzer*)
- \+ **concentration of H_2O** (*fast H_2O analyzer*)
- \+ **mean** T_{air}, RH, U, P, W_{dir}, **precipitation,** *etc.* (*slow weather sensors*)
- \+ **gas concentration profile** (*slow gas analyzer*)
- \+ Rn, Rs_{in}, Rs_{out}, PAR_{in}, PAR_{out} (*slow radiation sensors*)
- \+ **soil heat flux,** T, **moisture** (*slow soil sensors*)

- Approximate list of variables provided by commonly used eddy covariance stations
- Minimal station contains a list of essential variables needed in every application

(Burba, 2013)

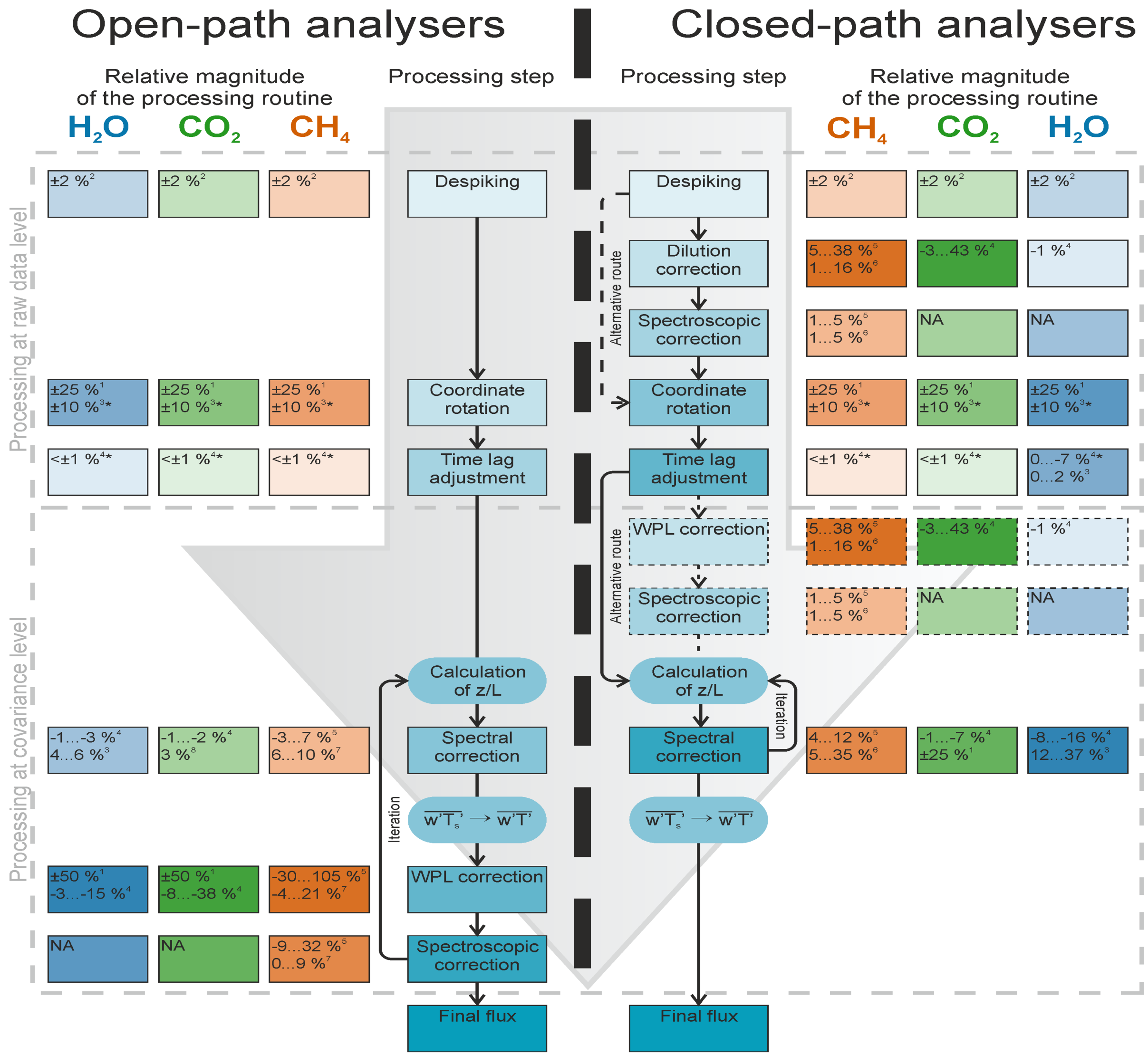
Basic flow chart of EC post-processing



EC post-processing softwares

- EDIRE (University of Edinburgh, UK)
- ALTEDDY (Alterra)
- TK3 (University of Bayreuth, Germany)
- EddySoft (Max-Planck-Institute Jena, Germany)
- Eth-flux (Technical University Zürich, Swiss)
- ECPack (University of Wageningen)
- EddyPro (www.licor.com)
- EddyUH (University of Helsinki, Finland)

Effects of processing steps/corrections in EC method



[1] Burba (2013), [2] Moncrieff et al. (2004), [3] Nordbo et al. (2012), [4] This study, [5] Peltola et al. (2013), [6] Peltola et al. (2014), [7] Iwata et al. (2014), [8] Järvi et al. (2009)

* Comparison between methods

Relative magnitude definition: [1,8] $\frac{F_{corr} - F_{raw}}{F_{raw}}$ [5,6] $\frac{F_{corr} - F_{raw}}{|F_{raw}|}$ [2,3,4,7] $\frac{F_{run} - F_{ref}}{F_{ref}}$

Mammarella et al, 2016, Atm. Meas Tech

Flux footprint

The footprint is defined as the relative contribution from each element of the surface area source/sink to the measured vertical flux.

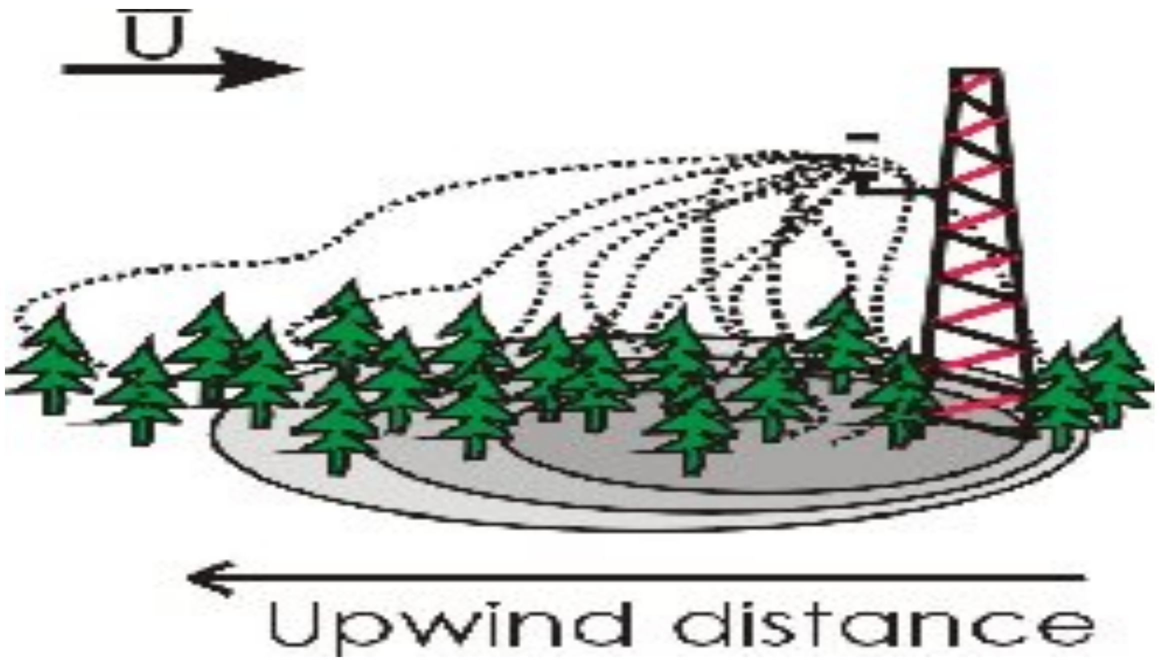
The flux measured at location x is

$$F(x) = \int \varphi(x,\hat{x}) Q(\hat{x}) d\hat{x}$$

where

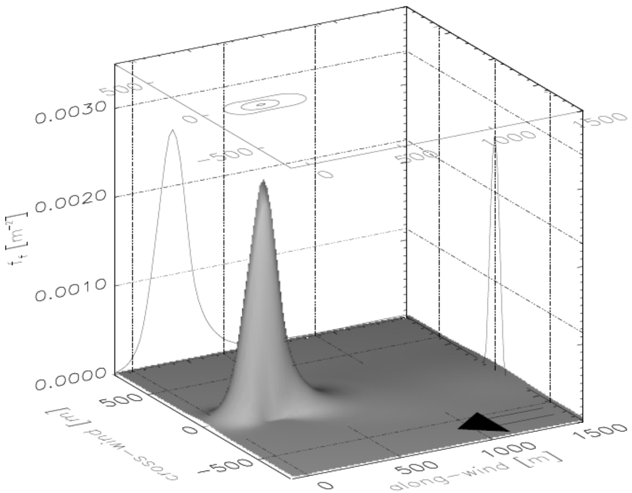
$Q(\hat{x})$ is the source/sink strength at location $\hat{x}$

$\varphi(x,\hat{x})$ is the footprint function

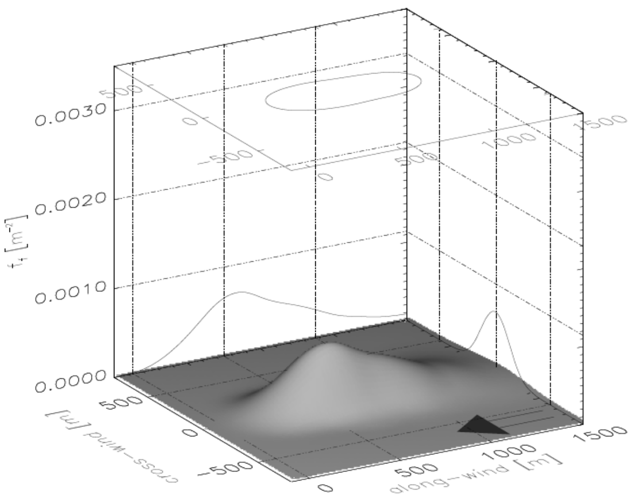


Generally footprint depends on

- measurement height : higher you measure, longer is the upwind distance contributing to the flux.
- roughness length: longer footprint for smooth surfaces than for rough surfaces.
- atmospheric stability (z/L): the footprint increases from unstable to stable conditions (longer footprint during nighttime than for daytime)



strongly convective



stable

Footprint functions

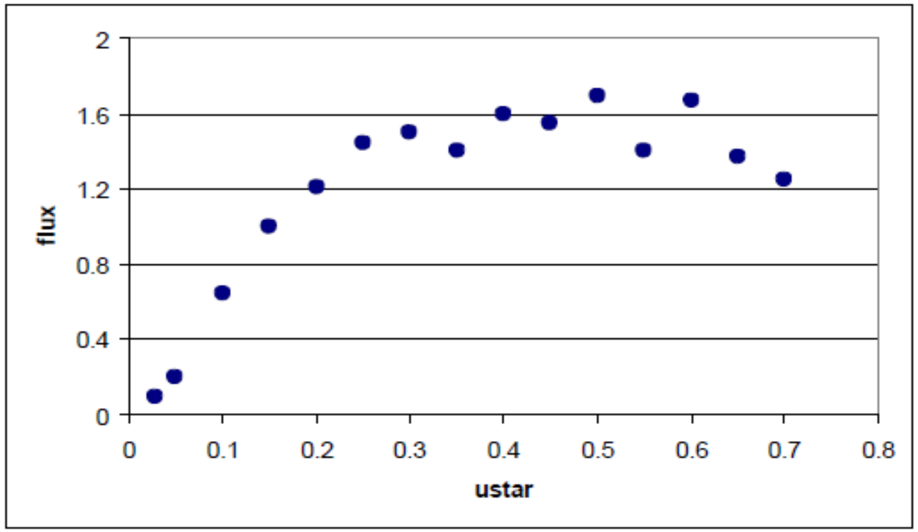
Eddy covariance and night-time problem

- The eddy covariance method underestimates the flux in stable conditions (low turbulence mixing).
- In these cases, the measured EC flux does not equal the surface flux (NEE), which is typically underestimated.
- The mismatch is caused by a variety of complex and poorly quantified processes, such as storage, advection, drainage flows and other non-turbulent air motions.
- For forest canopies, most often decoupling between within and above canopy layers is observed.
- In case of complex terrain, the night-time problem may be very important.
- For CO_2 flux, this underestimation acts as a systematic error, and could lead to a strong overestimation of annual NEE budget.

Night-time CO2 fluxes and friction velocity (ustar)

Justification:

1. During night there is only ecosystem respiration (no photosynthesis) so NEE=Reco;
2. Ecosystem respiration is measured by the EC system;
3. Ecosystem respiration is controlled mainly by temperature and season (but also water);
4. Turbulence (ustar) should not affect respiration, so measurement acquired in the same period (season, month) and with similar temperature should be ustar-independent
5. This is not what happen when there is advection since with low turbulence (low ustar) part of the CO2 produced by respiration is not measured by the EC system.

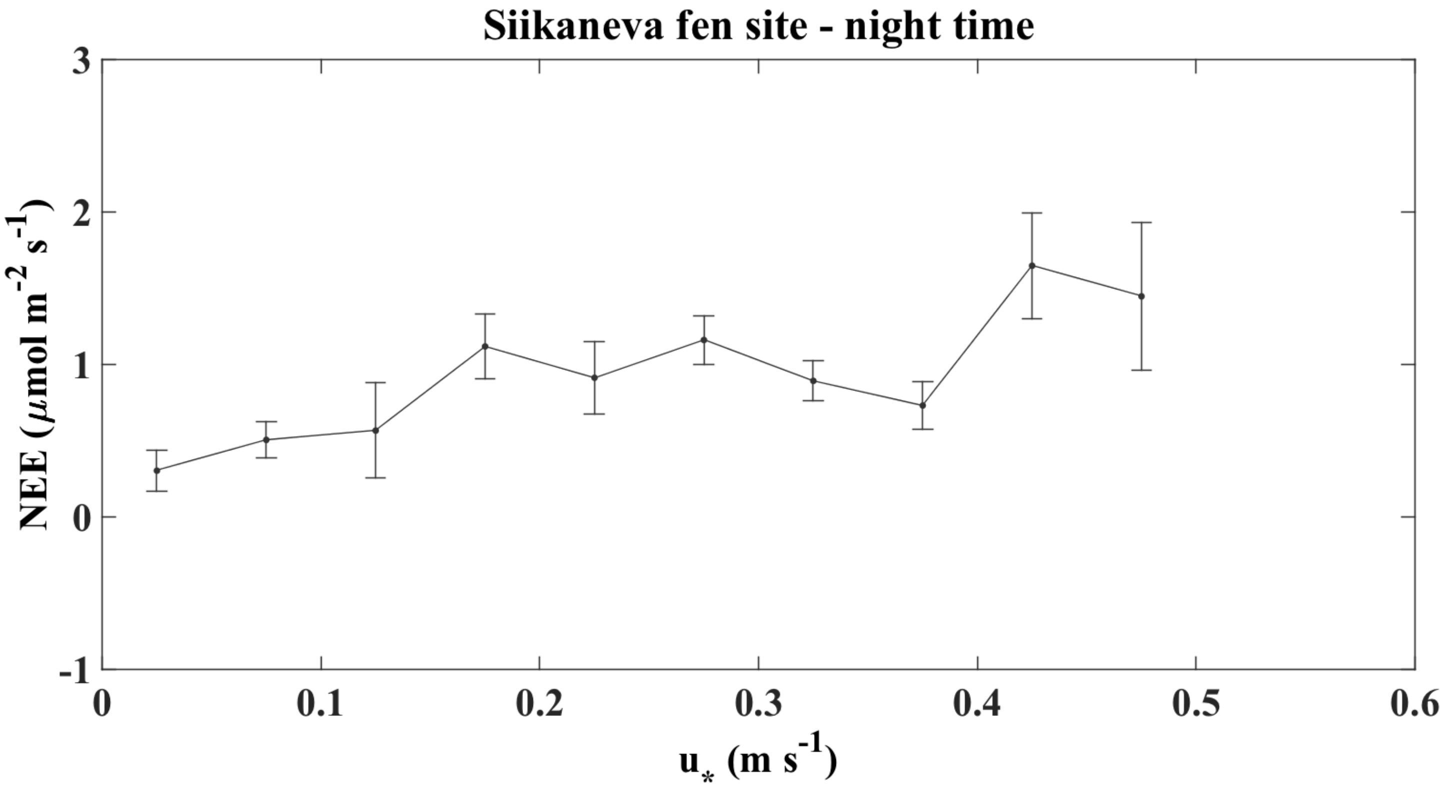


When turbulence reach a certain level (the ustar threshold) advection become limited while below this threshold the fluxes are underestimated and data acquired under these conditions must be filtered out.

- Particular important for forest canopy and complex terrain

  See ADVEX experiment (Feigenwinter et al.(2008), AFM).

- But relevant also on homogeneous flat terrain during very stable and calm nights.



Summary of recommended steps for ustar filtering

1) Compute NEE as the sum of EC flux and storage change.
2) Sort night flux data by increasing u_*.
3) Evaluate if there is co-variation between u_* and other respiration driving variables (most often the temperature). If yes, normalize the data in order to get rid of co-variation of respiration with this variable.
4) Set a number of u_* classes and calculate the mean NEE for each class.
5) Determine the threshold by comparison between NEE in each u_* class and the average of the mean NEE values measured at higher u_*. The new threshold is reached when the NEE of a given u_* class become significantly different from the mean NEE at higher u_*.
6) Remove 30 min flux data situated below the ustar threshold.

Flux Gap-filling

- The purpose of gap-filling is the replacement of missing or bad flux records to allow for determining matter or energy budgets over prolonged periods.

- The replacement procedure is based on ”good” fluxes.

- Where are the gaps coming from?

1) Power problems in your EC system
2) Instrument problems
3) Calibrations/mantainance
4) Quality criteria/filtering

Gap-filling is necessary, when we need to integrate the 30 min fluxes to daily/annual scale.

Basic flux gap-filling methods

- Look-up Tables (LUT)

In a look-up table, the flux data are binned by variables such as light and temperature.
Presenting similar meteorological conditions, so that a missing flux value with similar meteorological conditions can be retrieved.

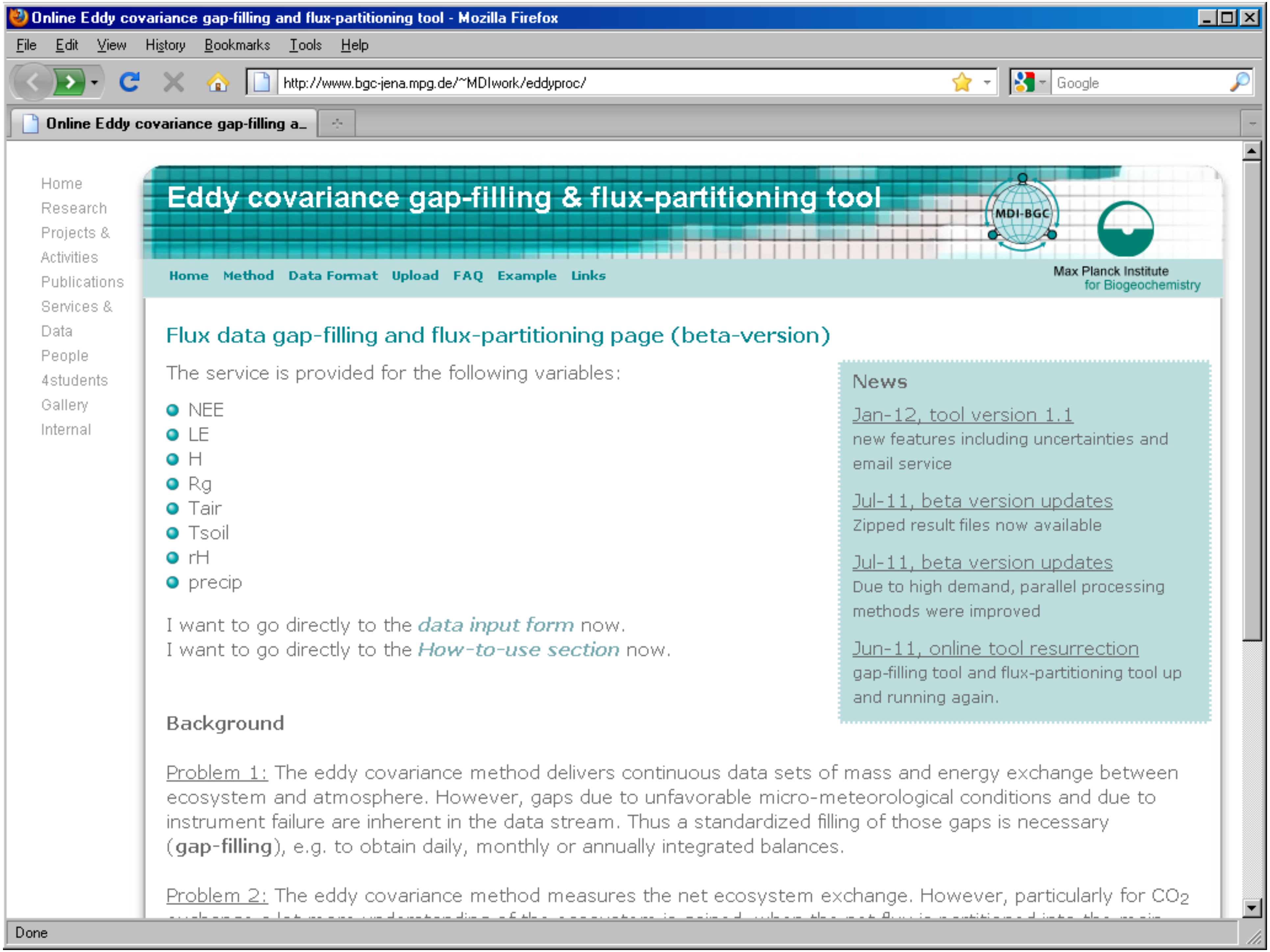
Example: Missing flux at {R_{glob}=536 W/m^2, T_{air}=20.5°C} is replaced by the mean value of accepted fluxes at {R_{glob}=500…600 W/m^2, T_{air}=20…25°C}.

- Mean diurnal variation (MDV)

Interpolation technique where the missing flux value is replaced with the averaged value of the adjacent days at exactly that time of the day.

- time window typically days to weeks.

- Interpolation
  - only for very short gaps.


Online Eddy covariance gap-filling and flux-partitioning tool - Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/
Google
Online Eddy covariance gap-filling a...
Home
Research
Projects & Activities
Publications
Services & Data
People
4students
Gallery
Internal
Eddy covariance gap-filling & flux-partitioning tool
MDI-BGC
Home Method Data Format Upload FAQ Example Links
Max Planck Institute for Biogeochemistry
Flux data gap-filling and flux-partitioning page (beta-version)
The service is provided for the following variables:
NEE
LE
H
Rg
Tair
Tsoil
rH
precip
I want to go directly to the data input form now.
I want to go directly to the How-to-use section now.
News
Jan-12, tool version 1.1
new features including uncertainties and email service
Jul-11, beta version updates
Zipped result files now available
Jul-11, beta version updates
Due to high demand, parallel processing methods were improved
Jun-11, online tool resurrection
gap-filling tool and flux-partitioning tool up and running again.
Background
Problem 1: The eddy covariance method delivers continuous data sets of mass and energy exchange between ecosystem and atmosphere. However, gaps due to unfavorable micro-meteorological conditions and due to instrument failure are inherent in the data stream. Thus a standardized filling of those gaps is necessary (gap-filling), e.g. to obtain daily, monthly or annually integrated balances.
Problem 2: The eddy covariance method measures the net ecosystem exchange. However, particularly for CO2
Done

CO2 flux gap-filling

Available online at www.sciencedirect.com
ScienceDirect
Agricultural and Forest Meteorology 147 (2007) 209–232
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www.elsevier.com/locate/agrformet

Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes

Antje M. Moffat[a,*], Dario Papale[b], Markus Reichstein[a], David Y. Hollinger[c], Andrew D. Richardson[d], Alan G. Barr[e], Clemens Beckstein[f], Bobby H. Braswell[g], Galina Churkina[a], Ankur R. Desai[h], Eva Falge[i], Jeffrey H. Gove[c], Martin Heimann[a], Dafeng Hui[j], Andrew J. Jarvis[k], Jens Kattge[a], Asko Noormets[l], Vanessa J. Stauch[m]

Random and systematic errors

- Both random and systematic errors characterize our measurements.
- Typically these errors propagate in different ways when measurements are combined or aggregated.
- ***Random error*** is stochastic and unpredictable, and usually characterized by a pdf with associated standard deviation.
- ***Systematic error*** is a bias which may be constant, but it is unknown.

Random errors of the flux

- Random errors cause noise and scatter in the data, and it is impossible to correct for them.

Random errors in flux measurements arise from a variety of sources. These include:

1) The stochastic nature of turbulence, and associated sampling errors, including incomplete sampling of large eddies, and uncertainty in the calculated covariance between the vertical wind velocity (*w*) and the scalar of interest (χ_c);

2) Errors due to the instrument system, including random errors in measurements of both *w* and χ_c.

Key points on flux random uncertainty

- Random errors tend to be quite large at the half-hourly time scale.
- Typical random flux error for EC fluxes in the order of 20%. The instrumental noise ranges between 1% to 5% for the most recent gas analysers.
- Can be much larger depending on the instrumental noise (signal to noise ratio).
- Finkelstein and Sims (2001) method is recommended for estimating total random error. Lenschow et al (2000) for the estimation of instrumental noise.
- Random errors decrease with averaging as 1/sqrt(n), e.g. a daily mean flux has smaller uncertainty than 30 min flux.
- However, cannot be ignored in the context of long term flux integral(annual cumulative sum), e.g. for the integral flux they increase as n/sqrt(n).
- It is also important to consider that they propagate through to gap-filled and partitioned net ecosystem exchange (NEE) time series.
- IMPORTANT NOTE: Random flux error should not be used as quality criteria (for filtering out the data). This is valid for all fluxes (not only particle fluxes).

Systematic errors in flux measurements

Sources of systematic error are mainly due to:

- Underlying assumptions of EC technique not being satisfied (surface heterogeneity, non-stationarity, poorly developed turbulence).

- Sensor calibration and design (calibration drift error affecting gas analysers, sonic anemometer misalignment and flow distortion, high frequency flux losses for closed-path systems, density fluctuations) .

- Data post-processing and applied algorithms/methods.

Flux systematic uncertainty can be (have to be) minimized by careful considerations of its sources.

Take-home messages

Eddy covariance data are a unique source of information, very important to understand ecosystem responses to climate change and management but also useful for model parameterization and validation.

It is quite simple to use eddy data in the wrong way (eg. spurious correlations or wrong corrections), without taking into account the data processing used and without quantifying uncertainty. If you use some available software, try to understand what you are doing, and do not use it as black box.

Standardization of data processing helps to reduce uncertainty particularly in multi sites synthesis analysis.

Meteo data are fundamental to apply the best methods so it is important to avoid gaps in the meteorological dataset. Perform maintenance of these measurements as well.

Data sharing is an opportunity not a cost. You will discover this.

Further reading on gap-filling

- Dengel et al. 2013. Testing the applicability of neural networks as a gap-filling method using CH4 flux data from high latitude wetlands, Biogeosciences, 10, 8185-8200, doi:10.5194/bg-10-8185-2013, 2013.
- Falge et al. 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology 107, 43–69.
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- Gove and Hollinger 2007. Application of a dual unscented Kalman filter for simultaneous state and parameter estimation in problems of surface-atmosphere exchange. J. Geophys. Res. 111, D08S07, doi: 10.1029/2005JD006021.
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- Moffat et al. 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. Agricultural and Forest Meteorology 147, 209–232.
- Moffat et al. 2010. Characterization of ecosystem responses to climatic controls using artificial neural networks. Global Change Biology, 16: 2737–2749. doi: 10.1111/j.1365-2486.2010.02171.x
- Reichstein et al. 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11, 1424–1439.
  Online gapfilling tool http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/

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Estimating surface fluxes using eddy covariance and numerical ogive optimization

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