Compressibility of air effects on eddy accumulation flux measurements

Anas Emad* iD, Lukas Siebicke*

* Bioclimatology Group, University of Göttingen, Germany   email authors @BioclimGoe

Introduction

Motivation:

The exchange of energy and matter between the biosphere and the atmosphere (the **flux**) is a very important aspect in the study of ecology and climate. Eddy accumulation is a micrometeorological method that allows the direct measurement of ecosystem fluxes and bypasses the need for a fast gas analyzer required by the more common eddy covariance method.

Challenge:

The method requires fast and accurate sampling of air proportional to vertical wind velocity, a task which is complicated by the high dynamic range requirements and variation of pressure inside the system's limited buffer volume.

Objectives

Overall goal

test the continuous flow operation of true eddy accumulation system and estimate errors and uncertainty due to air compressibility on the accumulated sample concentration and the fluxes.

Discuss possible solutions to reduce uncertainty including reducing the variability of volume buffer residence time, controlling the average buffer residence time, and the application of weighted arithmetic means in post-processing.

Introduction

The eddy accumulation method bypasses the need for fast measurements of trace gas by accumulating air samples for later analysis.

The method requires that air is sampled at a high-frequency and samples are collected and partitioned into updraft and downdraft reservoirs based on the sign of the vertical wind velocity and proportional to its magnitude see Figure 1.

The method was proposed by Desjardins in 1972, see also (Hicks and McMillen, 1984; Siebicke et al, 2019)
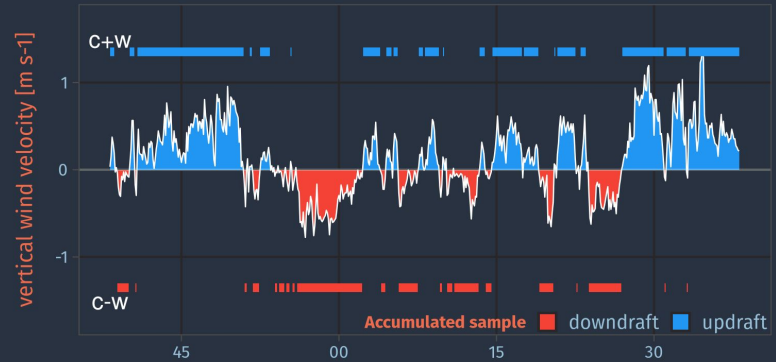

Figure 1. The eddy accumulation method conditionally samples air proportional to the magnitude of vertical wind velocity and depending on its sign into updraft or downdraft reservoirs

True eddy accumulation

The TEA flux over an averaging period T$_{avg}$ can be obtained as (Hicks and McMillen, 1984)

$$\overline{wc} = \frac{1}{T_{avg}} \int_0^{T_{avg}} (\delta^+ cw + \delta^- cw) dt = \overline{wc} + \overline{w'c'}$$

Assuming ideal conditions leading to a mean w of zero over the flux averaging period. The mass flux is calculated from the difference of concentrations (as mixing ratios) between updraft and downdraft and the mean absolute wind during the flux integration period:

$$F_c = \frac{\overline{|w|}}{2} (\overline{c^+} - \overline{c^-}) \; \overline{\rho_a}$$

Continuous flow true eddy accumulation

The continuous flow true eddy accumulation system (Siebicke, 2016) is a new method that avoids the complexity of having to store discrete air samples in physical containers by utilizing buffer volumes and a continuous flow of air throughout the system.

One important characteristic of the system is the residence time of the buffer volumes τ
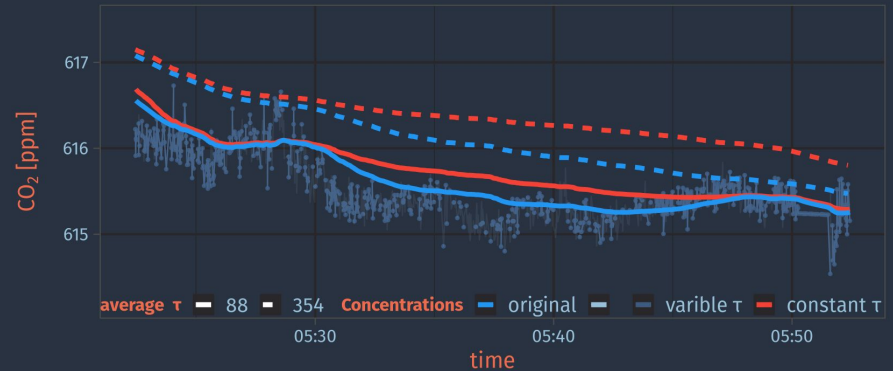

Figure 2. Concentrations in continuous flow true eddy accumulation as convolved by buffer volumes of different sizes.

Continuous flow true eddy accumulation

   residence time τ is the average time a volume sample spends in the system.

   It's equal to the time it takes to reach 1-1/e ~ 63.2 % of its final value from a step increase.

   Assuming perfect mixing of accumulated samples in the buffer volume, the residence time distribution is exponential (see Figure. 3)

$$E(\tau) = \frac{1}{T} \exp(\frac{-\tau}{T})$$

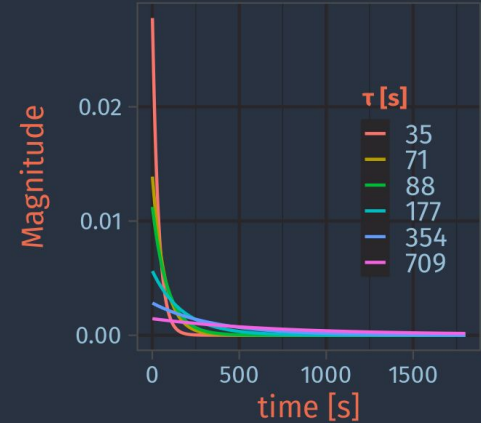Buffer volumes have infinite memory, but we will limit it to 10τ in our simulations.

Figure 3. Transfer function of buffer volumes with different values for residence time τ.

Methods

Data description

We used high-frequency data for two days (22nd and 23rd) of September 2016 from Fluxnet and ICOS flux tower Hainich (DE-Hai) as input to our simulation.

Original time series was measured at 10 hz frequency.

For a more detailed description of the site and instrumentation please see Knohl et al. (2003)

Methods - Simulation

- Wind coordinates were rotated using double rotation for half-hourly runs so that mean w is zero.
- Sampling is carried out such as V = ABkw
  Where **V** is the sample volume, **A** is scaling factor, **B** is a calibration factor, **k** is a probabilistic scaling factor for vertical wind velocity and **w** is vertical wind velocity. A detailed description of the sampling process is discussed in Siebicke et al. (2019).
- Mixing in buffer volumes are simulated by convolving the high-frequency concentration time series using the transfer function shown in Figure 3.
- Fluxes are calculated for 30 minute periods
- We assume no errors in sampling apparatus, instant and complete mixing in buffer volumes, and no errors in gas analyzer sampling.

Methods: objective 1/4

Effect of residence time (τ) variability

Two modes of operation are possible, a variable τ mode which imposes no control over output flow rate, this leads to a non-uniform distribution of τ over the individual flux integration periods.

Constant τ mode where the output flow rate is adjusted in a way to guarantee a uniform distribution of τ over individual flux integration periods.

Methods: objective 2/4

Effect of average residence time τ

    Average residence time in the buffers is a function of buffer volume and flow rate. It can be controlled by adjusting one of them. We simulate a series of buffer volumes that correspond to range of τ value from 35 to 710 s (Table 1)

```
| tau [s] | Volume [l] |
|---------|------------|
| 35      | 0.4        |
| 71      | 0.8        |
| 89      | 1.0        |
| 177     | 2.0        |
| 355     | 4.0        |
| 710     | 8.0        |
```

Table 1. The range of values for τ and corresponding buffer volumes used in the simulation.

Methods: objective 3/4

Use of weighted arithmetic means

   We investigate the use of weighted arithmetic means WMAs, suggested by (Cescatti et al, 2010) as a way to reduce the error associated with averaging discrete points samples obtained from a mixing buffer volume.

   The weighing of measurements is done to account for the probabilistic fraction of the signal generated in the averaging period (Figure 4).
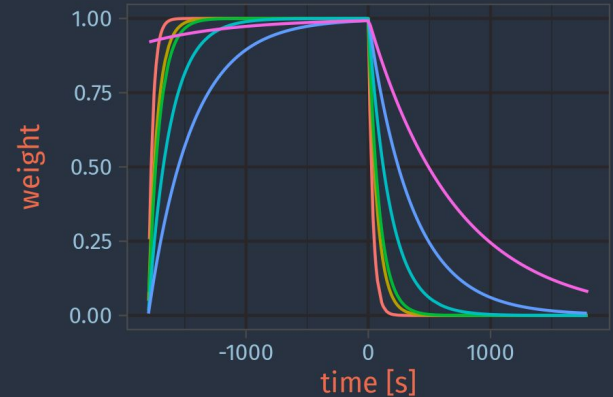

Figure 4. Weights function used for calculation of mean accumulated sample in buffer volumes for different values of residence time τ. The weights are applied for the current and next half-hour.

Methods: objective 4/4

Uncertainty analysis

Errors estimated from the numerical simulation were used as input for a Monte Carlo simulation to propagate uncertainties in concentrations of accumulated samples to the resulting fluxes. The error distribution was assumed to be normal.

Results and discussion

Effect of tau variability on the signal

The variability of τ within the averaging period increases the errors in averaged concentrations.

The error is not symmetric for updraft and downdraft reservoirs, this is expected to lead to biases in the fluxes.

The asymmetry is more pronounced at smaller τ.
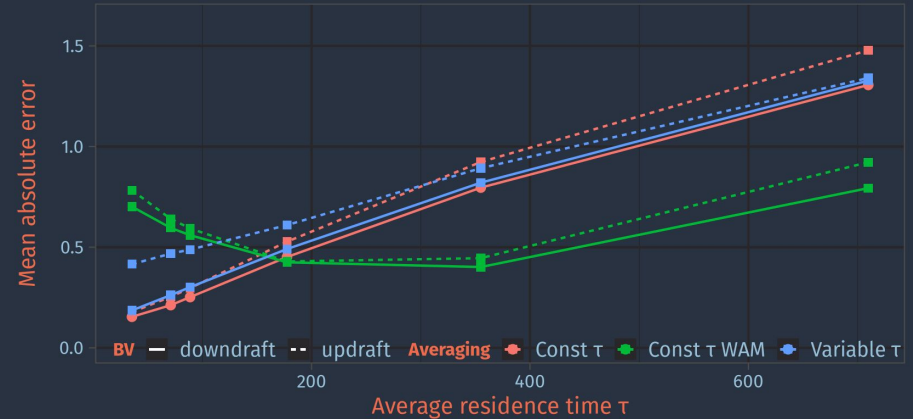
Figures 5. and 6. show these effects

Figure 5. Dependency of the mean absolute error (MAE) on τ for different averaging schemes: Constant τ, variable τ, and constant τ with the application of WAM in post-processing. Line type is for updraft and downdraft accumulated samples.

Results and discussion

Effect of τ variability on the signal

The average mean bias as shown in Figure 6. shows the asymmetric biases between updraft and downdraft.

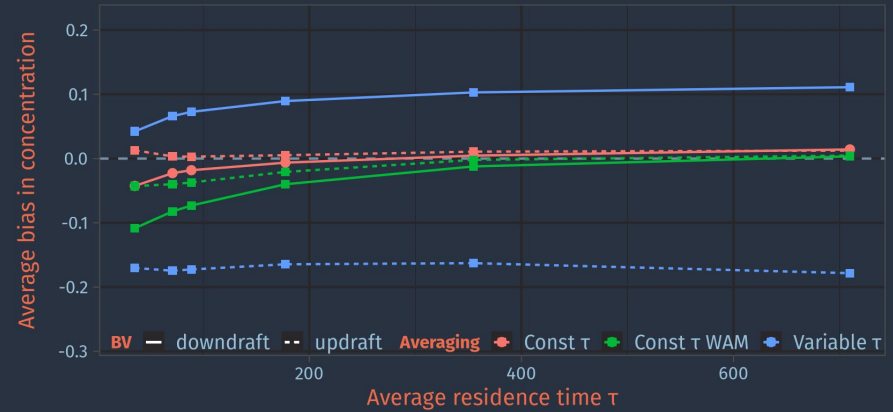Increasing tau doesn't seem to help with reducing the bias contrary to using a constant tau.

Figure 6. Dependency of the mean bias on τ for different averaging schemes: Constant τ, variable τ, and constant τ with the application of WAM in post-processing . Line type is for updraft and downdraft accumulated samples.

Results and discussion

Effect of using weighted arithmetic means

The application of WAMs in post-processing with a time constant equal to τ seems to reduce uncertainty, in particular for longer residence times as shown in Figures 7 and 8. It, however, seems to introduce biases for shorter residence times as seen in Figure 5.
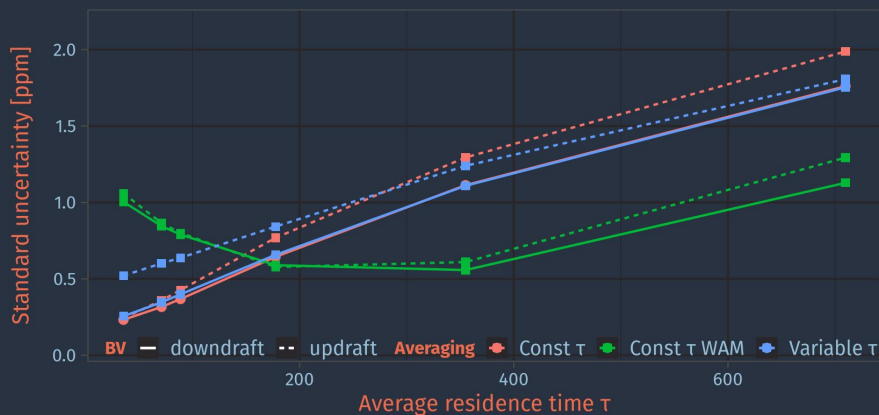
Figure 7. Dependency of the standard uncertainty on τ for different averaging schemes: Constant τ, variable τ and A constant with the application of WAM in post-processing. Line type is for updraft and downdraft accumulated samples.
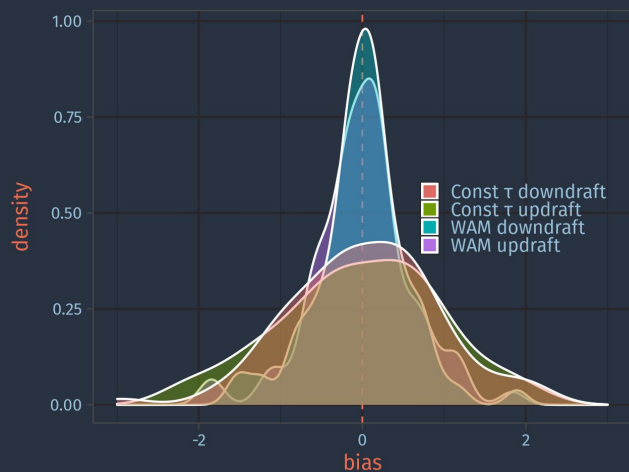
Results and discussion

Figure 8. Density distribution for biases with and without the application of WMA to Constant τ accumulated samples at τ = 355 seconds.
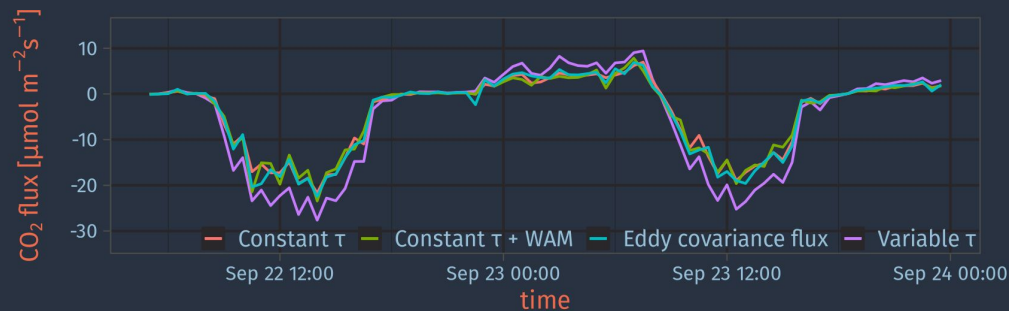

Figure 9. Time series plot for TEA fluxes calculated using different accumulation schemes and eddy covariance flux for comparison. τ=89 sec.

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Results and discussion

Effect on the fluxes

The various treatments on the fluxes show that accumulating samples with variable τ introduced bias to the fluxes (20% ~ 30% increase on average).

The best results were achieved for τ=177s with only 4% loss of the fluxes (slope =0.96) for a constant τ and with the application of WMA

Application of WMAs improved the slope by a small fraction (up to 2%)

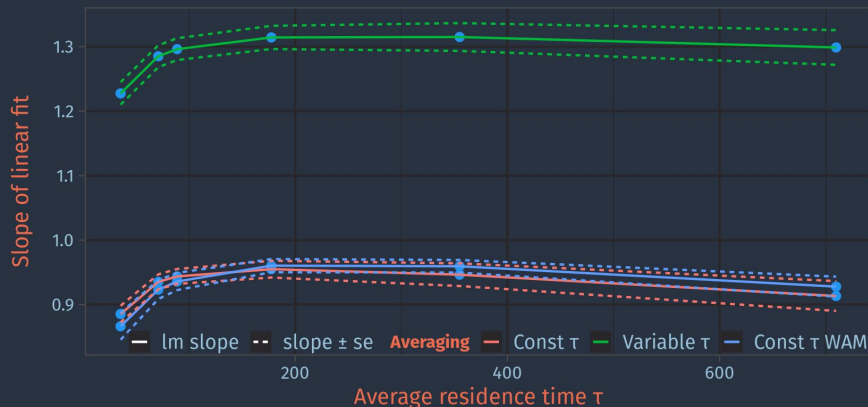Figure 10. Dependency of the slope of linear fit between different treatments of TEA flux and eddy covariance flux on average residence time τ. Dashed lines are slope ± standard error of the slope.

Results and discussion

Flux uncertainty

Using two estimates for accumulated sample uncertainty (Figure 7). We propagated uncertainty for τ=88 s and τ=177 s. Figure 11 shows the resulting flux with uncertainty estimates. The standard uncertainty average was 2.17 umol $m^{-2}s^{-1}$ for the best-case scenario and about 3.5 umol $m^{-2}s^{-1}$ on average for τ=177 sec. For higher τ the uncertainty will be higher.
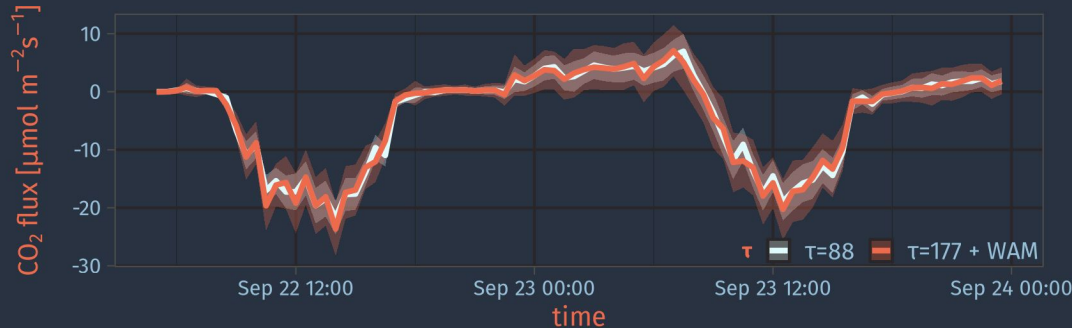

Figure 11. Time series of TEA fluxes and uncertainty estimates based on two approaches, Constant τ with an average of τ=88s and τ=177s with WAM. Standard uncertainty values for accumulated sample concentration were 0.36 and 0.58 ppm.

Conclusion

We simulated a number of operational modes and parameters for the continuous flow true eddy accumulation

- Good results can be achieved by the optimum control of residence time of buffer volumes and the use of WMAs
- The best results had a 4% loss in the flux and a standard uncertainty of 2.17 umol m^{-2}s^{-1} for CO_2 fluxes.
- The operation in variable τ mode created up to 20% bias in the fluxes.
- The application of WMAs improves the bias and uncertainty of the fluxes for fairly larger τ (τ > 177) otherwise it introduced bias and uncertainty.

References

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