Manuscript Number: AMT-2023-253

Manuscript Title: Role of time-averaging of eddy-covariance fluxes on water use efficiency dynamics of Maize crop.

AUTHORS' RESPONSES TO REREREE – 3 COMMENTS

The current study utilizes micrometeorological measurements to evaluate the effect of the averaging time on turbulent flux estimates obtained by the Eddy Covariance (EC) method. This topic has been extensively explored over the last few decades. However, such investigations on sites with different characteristics are always relevant. The manuscript novelty is the determination of optimal averaging time in a drip-irrigated maize field site. The remarkable result is the determination of the optimal averaging time for the different plant growth stages. The turbulent fluxes, estimated using the optimal values, are compared with those obtained using the usual value of 30 min, widely used in unstable daytime periods. The authors also showed how the improvement in flux estimates affects the values of related variables such as water use efficiency (WUE).

The current version of the manuscript is well structured. All sections are also clearly presented. However, I suggest some questions and corrections that should be addressed to improve the overall manuscript.

- Thanks to the reviewer for a comprehensive review by highlighting the novelty and efforts in shaping the manuscript.
- All suggestions / comments were duly addressed in the revised manuscript.

I - Geral comments:

1) As the author mentioned in the manuscript, "Optimal averaging period (T1) should be long enough to reduce random error (Berger, 2001) and short enough to avoid non-stationarity associated with advection (Foken & Wichura, 1996)". In summary, the core of the presented analysis is how accurate the eddy covariance method is to account for the transport associated with eddies of different sizes. Generally, the eddies sizes in an unstable boundary layer strongly depend on the wind stress and sensible heat flux at the vegetated surface, which in turn depend on the overall characteristics of the rough elements in the surface (plants). This is briefly mentioned in the text (lines 229–231) but is not linked with the obtained results.

- We partially agree with the reviewer. The core of the analysis is to identify 'optimal time-average' to estimate carbon and water (hence, WUE) fluxes.
- Also note that, the physiological factors are not observed at the same scale as that of the flux observations, hence we could not perform any statistical analysis.
- Since these factors (such as plant height, LAI) vary across the growth-stages, we have considered growth-stage specific optimal time averages for EC flux analysis.
- This point is already presented in the manuscript (lines: 245 to 249)

"The biophysical and physiological characteristics such as plant height, crop water requirement, LAI, etc. changes with respect to the crop growth stage (Chintala et al., 2024) and have a significant effect on the EC fluxes. Since these factors vary over growth stages, time-averaging of EC fluxes is separated based on crop growth stage."

2) Turbulent transport in an unstable (daytime) boundary layer is dominated by large convective eddies with time scales larger than 15-20 minutes [1]. Is there a reason to include short averaging times (1, 5, 10, and 15 min) in the analysis?

- The objective of this study is to understand the role of time-averaging on carbon, water fluxes (hence, on WUE fluxes) during the Maize crop growing period, and also to arrive at the optimal averaging period for use with analysis.
- This is clearly mentioned in the abstract (line: 11) and introduction (line: 119) sections of the manuscript.
- For this reason, we considered both short-term (1, 5, 10, 15 min), conventional (30 min), and long-term (45, 60, 120 min) averaging periods for flux estimation. Ogive optimization was then used to fine-tune the periods of flux calculations.
- Shorter average periods can help in preserving the stationary of data series (Sun et al.,2007), and effectively represent turbulent spikes.

II - Specific comments:

1) Lines 139-140: IRGASON is the model of the integrated system anemoter 3D – IRGA. As mentioned in the text, it sounds like two sets of instruments are used.

- Sorry for the confusion. We used the integrated CO_2-H_2O open-path gas analyzer and 3D Sonic anemometer, with model number "IRGASON-EB-NC"

- We modified the given sentence as: "The flux system is composed of integrated CO_2/H_2O open-path gas analyzer and 3D sonic anemometer (IRGASON-EB-NC, Campbell Sci. Inc., USA) to measure CO_2 and H_2O concentrations at 3 m above the canopy".
- This is reflected in lines: 143 to 146 of revised manuscript.

2) Line 140: "to measure CO2 and H2O fluxes …". These instruments do not measure fluxes directly but wind speed components, air temperature, and H2O and CO2 concentrations.

- Agree, and we modified the sentence as: "The flux system is composed of integrated CO_2/H_2O open-path gas analyzer and 3D sonic anemometer (IRGASON-EB-NC, Campbell Sci. Inc., USA) to measure CO_2 and H_2O concentrations at 3 m above the canopy".
- This is reflected in line: 143 to 146 of revised manuscript.

3) Line 163: "The block average method and linear detrending method". The authors used a series of corrections and quality control tests to ensure the best flux estimates. However, the block average acts as a high-pass filter depending on the block size, neglecting the fluxes associated with the low-frequency fluctuations. This influences the results obtained in the paper. What is the block size used for this analysis?

- We considered either 'block averaging' or 'linear trend removal' for detrending (Burba, 2022), to compute the turbulent fluxes.
- While 'block averaging' is used for 1, 5, 10, 15, 30, 45, and 60 min averaging periods, linear trending method was used for 120 min averaging period.
- Please note that: block averaging smoothens the variations of signal within each block, where as a high-pass filter removes low-frequency components from the signal. Hence, the two are not the same (Massman, 2000; Peltola et al., 2021).
- The block size used for analysis is equal to averaging period.
- Since we observed inconsistency in the obtained fluxes at higher time averages (120 min), we applied linear detrending method for 120 min time averaging period.
- The same was mentioned in the modified manuscript (lines: 169 to 173) as below:
- "Block averaging method was used for detrending the fluxes at 1, 5, 10, 30, 45, and 60 min averaging periods. Longer averaging periods (e.g. 120 min) has resulted in inconsistency in the obtained fluxes, which is a weakness of the block averaging (Renhua, 2005; Sun et

4) Line 194: equation (2) – This equation defines the mass fluxes, as represented in eqs. (3) and (4), used to obtain WUE. To avoid being misunderstood, it is also useful to define the expressions for the turbulent energy fluxes (Le and H) used in the definition of EBR (eq. (1)).

- Agree with the reviewer, and the expression for turbulent fluxes is added in the revised manuscript while discussing the terms of EBR (lines: 199 to 200)

- where, sensible heat is computed as:

  $H = \rho_a \, C_p \overline{w'T'}$

  and latent heat is computed as:

- $LE = L_v \overline{w'\rho_v'}$ (energy form, J m^{-2} s^{-1} or W m^{-2})

- where ρ_a is the air density; C_p is the specific heat of air, w' is the wind velocity fluctuation, T' is the temperature fluctuation, L_v is the latent heat of vaporization and ρ_v' is the H$_2$O gas concentration fluctuation.

5) Line 243: equation (7) The therm [(Rn-G)i – (H+LE)i] should be squared to ensure real values by the root squared.

- Sorry, this is typo. We modified the expression as:

  $$RMSE = \left[\frac{\sum_{i=1}^{n} \left((R_n - G)_i - (H + LE)_i \right)^2}{n} \right]^{0.5}$$

6) Figure 1: To increase figure quality. The axis labels and ticks are too small. The author should indicate which subplot corresponds to each averaging time.

- Thanks for pointing this.

- Each sub-plot of Figure 1 now contains the respective averaging period, in the inset.

7) Line 281: What does "r" represent? It was not defined before.

- 'r' represents the Pearson correlation coefficient

- Since 'r' is a widely used statistical metric, it was not defined earlier.

- However, for the benefit of the reader, expression for 'r' is given in section 2.4 of modified version.

$$r = \left\{ \frac{\sum_{i=1}^{n}\left[(R_n-G)_i - \overline{(R_n-G)}\right]\left[(H+LE)_i - \overline{(H+LE)}\right]}{\sqrt{\sum\left[(R_n-G)_i - \overline{(R_n-G)}\right]^2 \left[(H+LE)_i - \overline{(H+LE)}\right]^2}} \right\}$$

8) Line 283: I suggest using "short" and "long" averaging periods.

- We used 'short' and 'long' averaging periods consistently throughout the manuscript.

9) Line 283: "Our findings show that averaging period has minimal influence in representing the energy balance terms". This sentence is true on average for several days (and different plant stages). Individually, the averaging time effects the components of the energy balance, as represented by the large scatter in the inset plots for the short average times.

- Sorry for any confusion.
- A high correlation (r > 0.8) is observed between available energy (Rn-G) and turbulent fluxes (H+LE) for all averaging periods. This conclude that, averaging period has minimal influence in representing the energy balance terms.
- However, a high data scatter around 1:1 line for shorter averages (Figure 1) is due to: large sample size, and data randomness.
- This is clarified in the revision (lines: 302 to 305) as below:

"Our findings show that averaging period has minimal influence in representing the energy balance terms. However, data scatter around 1:1 line is high for shorter time-averages due to large sample size and data randomness".

10) Line 301: "Low EBR during the crop cycle can also be attributed to the ignorance of energy transport associated with large eddies from landscape heterogeneity, which is not captured by the EC system". Can you explain this hypothesis better? Is there such landscape heterogeneity at the studied site? In this analysis, the mentioned large addies should have characteristics time scales greater than 60–120 minutes to not be taken into account by the EC method. Is there another reason why the EC system fails to account for such eddies?

- Land scape heterogeneity we mean refers to the 'spatial composition of land-parcels within the footprint of the EC flux tower'
- EC method assumes the landscape within the footprint of measurement is flat and homogenous.
- Any violation results in landscape heterogeneity, thus affecting the EC fluxes and EBR.

- We have not considered the effect of landscape heterogeneity (if any). Our hypothesis is: During unstable atmospheric conditions, flux footprint is relatively smaller, hence completely contributed by the homogenous maize crop. This is one limitation of our research, which is mentioned in the revision document (lines: 322 to 325) as:

  "Low EBR during the crop cycle can also be attributed to the ignorance of energy transport associated with large eddies from landscape heterogeneity. However, EC method assumes the landscape within the footprint of measurement to be flat and homogenous. This violation might have lowered the EBR."

11) Line 325: "RE in estimating water vapour fluxes is found to be insignificant at all averaging periods, irrespective of growth stage." Again, it is important to emphasize that this is true for the averaged result (several days), not for each individual flux measurement. Figure 4b) (dough and maturity) shows the large variability in the relative error determined using either shorter or longer averaging times.

- Agree with the reviewer, we have provided a general / concise finding, which is not appropriate for all time-averaging periods.
- The consideration of averaged result is provided in lines: 347 to 348 of the revision as:
- "The RE is obtained by considering daily averages in the deviations for each growth stage."
- Variability in RE for water vapour fluxes is provided in lines: 351 to 354 of the revision as:
- "RE in estimating water vapour fluxes is found to be insignificant at all averaging periods for the 6th leaf and silking stages. However, dough and maturity stages have shown a large variation in RE considering either too-short (1, 5 min) or too-long (60, 120 min) time averages".

12) Figures 4a) and 4b) (dough and mature stages): Following the above argument, the large variability of RE, varying between positive and negative values, suggests that larger eddies (with time scales larger than 30 min) contribute to both positive and negative transport. This fact, by itself, is an indication that averaging times greater than 45 minutes are accounting for the effects of the submesoscale (non-turbulent) motions [2][3]. Therefore, 45 minutes can be approximately the timescale of the spectral gap.

- Thanks for the valuable insight. We have incorporated this point in the revision document (lines: 355 to 358) as:

"A high variability in RE for time scales larger than 45 min indicate the effects of sub mesoscale (non-turbulent) motions. Hence, 45 min average period can be considered as optimal in isolating the turbulence components for use with flux representation".

13) Figures 5a) and 5b): Just a suggestion: normalize the ogive by the maximum value of each curve (integrated up to the lowest frequency). This parameter indicates the fractional contribution of each frequency to the total cumulative energy.

- Since our interest is restricted to obtain the optimal time-averaging period (inflection point on Ogive plot), we have not normalized.
- However, we will consider this suggestion in our future studies.

14) Lines 404-405 and Figure 8): "This conclude that, the need for optimal averaging period is more crucial in estimating WUE fluxes rather than individual carbon and water fluxes." This is what can be observed in Figure 8. However, it is not clear why the large linear correlation between the fluxes with different averaging times is not observed on the WUE chart. According to May appointments 9) and 11), a large variability in RE is observed. By definition of the WUE, we have to consider the ratio of two fluxes and their respective RE. My first guess is that this loss of linear correlation is associated with the difference in RE between the fluxes of CO2 e H2O.

- Agreed with the reviewer. Its is observed from the figure 8, the need for optimal time averaging period is more crucial in estimating WUE rather than its individual fluxes i.e. carbon and water.
- Rather than poor correlations, this is an interesting finding. Though carbon and water fluxes are strongly correlated individually, their ratio term (WUE fluxes) is poorly correlated between any two averaging periods.
- For any two averaging periods (refer link: https://zenodo.org/badge/latestdoi/528291820), variation in carbon sink and water vapour are low, whereas variation in WUE is high.
- For example, the following table provides the carbon, water, and WUE fluxes at 15 min and 45 min averaging periods for some selective dates.
- Observe the huge differences in WUE (5.42 to 20.21 %) in comparison to the differences in carbon (0.14 to 10.37 %) and water (0.25 to 8.60 %) fluxes.
- Hence, variation in WUE between any two time-averages is much larger than variation in carbon or water fluxes.

- For this reason, we are highlighting that, choice of optimal time-averaging is crucial in WUE analysis, rather than carbon or water flux analysis.

Day	CO$_2$ [μmol^{+1} s^{-1} m^{-2}]		Deviation in CO$_2$ Flux [%]	H$_2$O [μmol^{+1} s^{-1} m^{-2}]		Deviation in H$_2$O Flux [%]	WUE [μmol mmol^{-1}]		Deviation in WUE Flux [%]
	15 min	45 min		15 min	45 min		15 min	45 min	
1	-0.3719	-0.37144	0.1415	1.4518	1.4555	0.2571	0.3714	0.29669	20.1315
2	-0.7048	-0.63173	10.3755	1.1326	1.1164	1.4354	1.3640	1.08831	20.2168
3	-1.4137	-1.4207	-0.4905	1.0586	1.1497	8.6037	1.7367	1.48193	14.6742
4	-0.7963	-0.7929	0.4221	0.9210	0.9152	0.6357	1.4913	1.41033	5.4297

- Also note that, the correlation strengths were plotted considering the entire crop cycle dataset, rather than individual growth stages.
- These causes are explained in the revised manuscript (lines: 448 to 451) as follows:

"However, a poor linear association in WUE fluxes was observed between any two averaging periods, which is attributed to a larger variation in individual WUE fluxes between averaging periods. However, the corresponding individual carbon and water fluxes have recorded low variations between time averages".

III- Thecnical corretions:

1) Whole text: "min" is the symbol for the time unit "minute". Therefore, the form "min." with a dot is unusual.

- Thank you for the suggestion.
- We replaced "min." with "min" to represent "minute" in the entire manuscript.

2) Line 130: Change "0C" to "oC".

- Thank you for the suggestion. Correction applied.

3) Line 244: Change "Where" by "where".

- Thank you for the suggestion. Correction applied.

4) Figure 3 a) and b): If possible, write the flux units in the correct notation.

- Thank you for the suggestion. Units are properly represented in Figure 3a and 3b.

5) Figure 6: Legend – change "(red)" by "(dotted)".

- Thank you for the suggestion. Figure 6 legend got changed.

6) Figure 4 and 7: Change time units from "[Min]" to "[min]".

- Thank you for the suggestion. We modified the time units from "[Min]" to "[min]" in Figure 4 and 7.

7) Line 488 and 581: To correct these references, there are typing errors.

- Thank you for the suggestion. References got modified.