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 REVIEWER – 2 COMMENTS

General comments

The authors present a study of the impact of eddy covariance (EC) averaging time on estimation of water use efficiency (WUE). While the impact of averaging of eddy covariance flux results has been extensively studied, the impact on WUE specifically has not. Therefore, the manuscript provides a contribution to broadening understanding of the important aspect of EC flux processing on results.

- Thanks to the reviewer for highlighting the importance and need of the given study.
- We have done additional analysis in arriving at the optimal averaging period using Ogive plot for WUE fluxes, and the results are provided in the revised manuscript (lines: 394 to 401, Section 3.3 and Figure 5c).

The authors perform analysis of how different averaging times (varying over a broad range of 1, 5, 10, 15, 30, 45, 60, and 120 minutes) affect the results during different stages of Maize crop development. The main finding of the study is that, whereas the commonly applied 30 min averaging is a good choice for most of the conditions, the longer averaging times yield better results during the dough development stage. The need for longer averaging period must result from different prevailing observational and/or meteorological conditions. The authors have not analyzed the underlying main drivers that determine the need for longer averaging time. They have suggested that canopy heterogeneity might be one of the reasons. I suggestion to perform additional analysis of prevailing conditions (minimum wind speed and direction, which could hind also impact of heterogeneity, and stability) during different canopy stages to be able to make link with optimal averaging times.

- Thanks to the reviewer for an insightful thought.
- Following reviewer suggestion, temporal trends in 'wind speed' and 'wind direction' were plotted for different time-averages (1 to 120 min), and the results are presented below.

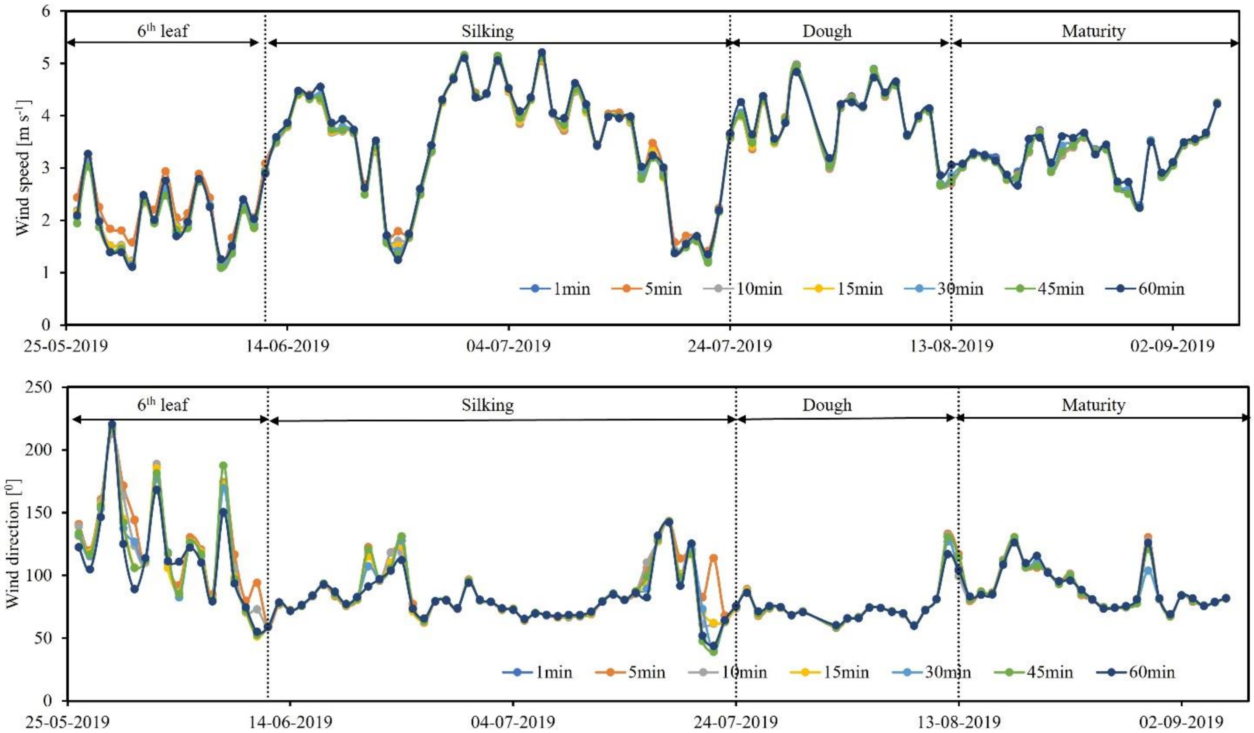

Figure 1: Temporal variations in wind speed (U) and wind direction during the crop period, considering different averaging periods (1 to 120 min)

- Transport of water and carbon fluxes carried by vertical wind speed (eddies) is highly fluctuating between vegetation and atmosphere. Hence, time-averaging of these fluxes (water and carbon) have resulted in different profiles (Figures: 3a and 3b).
- However, time-averaging has no impact on 'wind speed' and 'wind direction' profiles (Figure 1 above) as these are relatively stationary over the time-periods considered. This point was mentioned in the revised manuscript (line: 325).

  "We could not observe any significant differences in temporal trends of 'wind speed' and 'wind direction' between averaging periods, hence meteorological conditions were not analysed by varying the time-average"
- However, we observed that, optimal averaging period is inversely related wind speed variation.
- For example, 6th leaf and silking stages, where the variation in wind speed is high (2.04 ± 0.55 m s^{-1}; 3.66 ± 0.96 m s^{-1}) have resulted in a shorter time averages (15 min). Similarly, Dough and maturity stages, where the variation in wind speed is low (3.54 ± 0.57 m s^{-1}; 3.19 ± 0.42 m s^{-1}) have resulted in a longer time averages (45 min).
- We could not observe the role of wind direction in selecting the optimal time average, as wind direction is found to be constant (100 ± 0.5^0) throughout the crop period, except for the 6th leaf stage.

One important clarification is needed regarding the detrending and averaging. Section 2.2: Did you use linear detrending and then block averaging? Since linear detrending performs as additional high-pass filter then this is very important to be very specific and emphasize also in Abstract and Conclusions. Without linear detrending the optimal averaging times could be different.

- Sorry for the confusion created.
- Detrending was performed to obtain the turbulent fluxes (by subtracting mean from the instantaneous values).
- We considered either 'block averaging' or 'linear trend removal' for detrending (Burba, 2022), but not both.
- This sentence is re-phrased in the revision document (lines: 168 to 169) as below: "Either block average method or linear trending method were considered to compute the turbulent fluctuations"
- Appropriate detrending method was used for carbon and water flux computation, and this is mentioned in lines: 169 to 173 of the revised manuscript 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 al., 2006). Hence, linear trend removal method was used to compute the fluxes for 120 min averaging period".

The main emphasis of the manuscript is to evaluate the impact of the averaging time on WUE. Please also conclude if the choice of averaging time for accurate determination of WUE is different from energy and carbon fluxes (fluxes of scalars).

- Thanks to the reviewer for this valuable suggestion.
- Following reviewer suggestion, we estimated WUE fluxes for different time-averages (1 min to 120 min), and correspondingly plotted 'Ogive plots' of WUE considering different averaging periods (Figure 5c of revised manuscript).
- Interestingly, we arrived at the same optimal averaging periods (15 min for 6^{th} leaf and Silking stages; 45 min for dough and maturity stages), as we observed for carbon and water fluxes.

- We have added the above figure (Figure 5c) and related text in the results section (lines: 394 to 401) of the revised manuscript.

Detailed comments

1. 9. The low-frequency flux inclusion is not the only factor and not under all observation conditions that might affect the accuracy of the EC flux estimates. Please be more specific with statement.

- Error sources that affect accuracy of EC fluxes are grouped into:
  1) Unrepresentative (due to footprint heterogeneity, unsatisfied underlying theory)
  2) Measurement uncertainties (due to random errors, interference and contamination, sensor drifts)
  3) Measurement biases in fluxes (tilt, frequency losses, air density fluctuations etc)
- Among these, we considered the effect of "frequency losses" alone in this study. This is also because, a majority of error sources are either unavoidable or uncontrollable.
- This was mentioned in the Introduction section of the revised manuscript (lines: 68 to 72) as below:

"Error sources that affect the accuracy of EC fluxes are grouped into: i) Unrepresentative (due to footprint heterogeneity, unsatisfied underlying theory), ii) Measurement uncertainties (due to random errors, interference and contamination, sensor drifts) and iii) Measurement biases in fluxes (tilt, frequency losses, air density fluctuations etc)."

- Since Abstract is the concise version of the entire work, only the applicable cause is mentioned.

2. 13-14. Canopy heat storage should net be a significant factor over a relatively long period of time.

- We politely disagree with the reviewer.
- A high canopy cover (LAI > 3) was observed during the dough and maturity stages (Table 1). Ignorance of this canopy storage term (ΔS) is one significant cause of low energy balance closure (EBC).
- Since energy balance is calculated on a daily basis, canopy storage is a significant sink, resulting in lower EBR (Figure 2).

3. 16-18: what were the main driving factors that the optimal averaging time differed for different stages of canopy development? See my main comment.

- Please refer to our detailed response against main comment.
- Referring to Figure 1 above, it can be concluded that, the choice of optimal averaging period is related to wind speed. For example, 6th leaf and silking stages, where the variation in wind speed is high (2.04 ± 0.55 m s^{-1}; 3.66 ± 0.96 m s^{-1}) have resulted in a shorter time averages (15 min). Similarly, Dough and maturity stages, where the variation in wind speed is low (3.54 ± 0.57 m s^{-1}; 3.19 ± 0.42 m s^{-1}) have resulted in a longer time averages (45 min).
- We could not observe the role of wind direction in selecting the optimal time average, as wind direction is found to be constant (100 ± 0.5^0) throughout the crop period, except for the 6th leaf stage.
- However, it can be observed that time-averaging has no affect on the temporal trends of 'wind speed' and 'wind direction (Figure 1 above). For this reason, wind speed and wind direction were not presented / analysed for different averaging periods.

4. 32. The abstract states the error compared to 30 min averaging was marginal except for dough stage. Be more specific, e.g. 30 min averaging is not sufficient for all conditions.

- Agree with the reviewer, that 30 min averaging is not sufficient for all conditions.
- However, 30-min is the widely accepted conventional time-averaging period in EC flux estimation.
- To highlight the importance of using optimal averaging period, we analysed the error in representing the fluxes.
- To be more specific, we have added the following sentence in the abstract (lines: 24 to 26) "Error in representing WUE with conventional 30 min averaging is marginal (< 1.5 %) throughout the crop period except for the dough stage (12.12 %). We conclude that the conventional 30 min averaging of EC fluxes is not appropriate for the entire growth stage".

5. 34. The sentence is missing some word, for example "Different averaging time need to be used following the crop growth stage".

- Agree with the reviewer, the given sentence is slightly confusing.
- Research highlight 4 is now modified for a better readability, as follows:

"Different time averaging periods are to be considered to compute the EC fluxes considering the crop growth stage".

6. 51, the symbol colon (:) looks redundant after "water productivity"

- Corrected (line: 103 of revision manuscript).

7. 61-62, readability would benefit from re-arranging the parenthesis, e.g. "WUE is estimated as the ratio of gross primary product (GPP: proxy for photosynthesis) to evapotranspiration (ET: proxy for water consumption).

- Agreed. The sentence is modified as:

  "WUE is estimated as the ratio of net primary product (NPP: proxy for photosynthesis) to evapotranspiration (ET: proxy for water consumption)".

8. 112, the average +- error after "Temperatures are high during summer" and "low during winter": what do these errors represent?

- No, these are not the errors.
- We presented the data in the form of ($\mu \pm \sigma$), where μ denotes data mean, and σ denotes one-standard deviation.
- It is convention in statistics to present the data variability in ($\mu \pm \sigma$) format, that provides average amount of variability in the datasets.

9. 142-143: Did you use linear detrending and then block averaging? Also, I assume this was "to derive" turbulent fluctuations and not "to correct".

- Sorry for the confusion.
- We considered either 'block averaging' or 'linear trend removal' for detrending (Burba, 2022).
- This sentence is re-phrased in the revision document (line: 168) as below:

  "Either block averaging method or linear trending method were considered to compute the turbulent fluctuations"
- Appropriate detrending method used for carbon and water flux computation is mentioned in lines: 168 to 173 of the revised manuscript 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 al., 2006). Hence, linear trend removal method was used to compute the fluxes for 120 min averaging period".

- In order to preserve the low frequency flux loss during averaging, we applied linear trend removal method for 120 min averaging.

10. 151, what is friction velocity correction? Do you mean filtering of night-time observations according to friction velocity threshold? Be specific here.

- Yes, we applied friction velocity (u*) correction to filter out the night time observations by specifying a velocity threshold (> 0.25 m s^{-1}).
- This was mentioned in the revision (line: 179) as follows:

"There is a need to perform secondary corrections on the data that include flux spike removal (Vickers & Mahrt, 1997), friction velocity corrections (to filter night time observations), gap filling and uncertainty analysis (Finkelstein et al. 2001), skewness & kurtosis removal, spectral corrections, and frequency corrections."

11. 159: lack of conservation should be "lack of energy balance closure".

- Sorry for any confusion. We modified this sentence (line: 189) as follows:

"Violation of law of conservation of energy resulting from the EC observed energy terms is referred as energy balance closure (EBC)"

12. 168: where this specific threshold EBC >= 0.7 comes from that ensures reliability of EC fluxes? Please be more specific and/or provide references.

- The threshold for EBC (> 0.7) is used to comment on the reliability of EC fluxes. A number of studies such as Barr et al., 2006 and Kidston et al., 2010 have considered a similar threshold (0.7 ± 0.03) under unstable day time periods.
- As suggested, references were provided in the revision (line: 206)

"A high EBR (EBR ≥ 0.7) ensures reliability of EC observations for use with flux estimation (Barr et al., 2006; Kidston et al., 2010)."

13. 180: the main challenge with real-world data is data the spectral gap is obscure or difficult to identify. Otherwise, the choice of the averaging time would be simple task.

- Agree with the reviewer.

- For this reason, we considered Ogive method to choose the optimal averaging period to compute the fluxes.

14. 195, also section 2.2, did you perform coordinate rotation at the same time interval basis as the averaging?

- Yes, we performed double coordinate rotation at the same interval as averaging period.
- This was clarified in the revision (lines: 167 to 168) as follows:

  "Tilt corrections were made by the double axis rotation method for each averaging period".

15. 203-204: how did you define the optimal averaging period?

- For ease with understanding, we added the following point in arriving at optimal averaging period using the Ogive plot (lines: 241 to 242)

  "In other words, the point at which the Ogive plot flattens out represents the optimal averaging period"

16. 207, eq. (5), since this is RMSE error, the square root should be taken from the value in squared? Which is missing in the expression.

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

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

17. 221-222, fig 1. Denote the subplots with relevant averaging times. Currently it is not possible to follow which plot corresponds to what averaging time.

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

18. 267, and the main comment: please analyse the potential impact of meteorological conditions (wind speed and direction, stability). The wind direction variability might provide better insight related to landscape heterogeneity; currently this remans a hypothesis.

- Thanks for the important suggestion.
- This point was clarified in the response under main comment.

- We performed additional analysis on the role of meteorological conditions (wind speed, wind direction) on CO_2, H_2O and WUE obtained using optimal time average periods. Here are the key observations / findings:
- From the dynamics of wind speed, it is observed that the mean wind speed was initially low (2.04 ± 0.55 m s^{-1}) in 6^{th} leaf stage and then starts increasing and reached a mean of 3.66 ± 0.96 m s^{-1}s in silking, 3.54 ± 0.57 m s^{-1} in dough stages after that it slowly decreasing towards the end of crop stages and finally reached a mean of 3.19 ± 0.42 m s^{-1} in the maturity stage which is obtained using optimal time averages i.e. 15 min and 45 min.
- We observed high fluctuations of wind speed in the initial stages i.e. 6^{th} leaf, silking stages and these fluctuations were slowly stabilized at end of the crop stage, towards winter months. The optimal time average of 15 min is able to capture the random fluctuations in the wind speed.
- We could not observe the role of wind direction in selecting the optimal time average, as wind direction is found to be constant (100 ± 0.5^0) throughout the crop period, except for the 6^{th} leaf stage.
- Regarding stability, we only considered day-time unstable atmospheric conditions (08:00 am to 04:00 pm) which are the active photosynthetic hours for carbon uptake.
- 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 as follows:(lines: 485 to 489)

"This study is limited to understand the role of different time-averaging periods on EC observed carbon, water fluxes as well as EC derived WUE fluxes contributed by homogeneous Maize crop which is having relatively smaller flux footprint in an unstable atmospheric condition".

19. L. 361, Fig. 8: what does the circle size represent? Also, how did you compare e.g. 45 min and 30 min averaging (45 min period does not fully overlap with 30 min period)? Plot c) looks inconsistent (or difficult to interpret). How do you interpret that for carbon dioxide and water the correlations between different averaging times are all very good but for WUE not. One would expect that closure averaging times (for example 45 min and 30 min) correlate better than more different (e.g. 45 min and 15 min). Could the specific "pattern" of this plot be the result of periods mismatch?

- The circle size represents the value (strength) of "r" in proportion to the size of the square box.
- A larger size of the circle between any two averaging periods denotes a high correlation strength between the two datasets, and vice-versa.
- Rather than inconsistent, 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_2O [μmol^{+1} s^{-1} m^{-2}]		Deviation in H_2O 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".