Response to the reviews of manuscript amt-2022-179: "Reducing errors on estimates of the carbon uptake period based on time series of atmospheric CO_2 " by Theertha Kariyathan, Wouter Peters, Julia Marshall, Ana Bastos, Pieter Tans, and Markus Reichstein, to Atmos. Meas. Tech.

Questions from the reviewers are written in blue, our answers in black, text copied from the manuscript is written in *italic*, and all changes in the manuscript are typed in red. When referencing page and line numbers, we are always referring to the old version of the manuscript.

During the review process we came across a study by Barlow et al., 2015, where the CUP is estimated using the first derivative approach. Although we developed our approach independently, we no longer claim the novelty of this approach. We rather emphasize the ensemble approach for uncertainty estimation and rename our method to EFD (ensemble of first-derivative method) and include an extensive discussion of Barlow et al., 2015 in our manuscript. The main changes are made to the introduction (line 65) and discussion (line 270).

Answers to Reviewer 2

This study presents a curve-fitting method and an ensemble-based approach for quantifying the carbon uptake period (CUP; onset, termination and duration) from atmospheric CO_2 measurements. The authors have applied the technique to a handful of sites in the Northern hemisphere and shown that the uncertainty associated with the onset and termination of CUP is less with their proposed approach relative to more traditional techniques prevalent within the community. While the illustrations are high-quality, the scientific relevance and the overall flow of the manuscript needs to be improved. Right now, the manuscript reads like a collection of results based on investigations that were conducted and a figure and text to support the investigation. It does not dig deep into the implication of some of the findings (for e.g., Figure 13 is fascinating from a carbon cycle perspective but not explained in any great detail). In addition, the authors have applied their approach to only one seasonal cycle metric and it is not clear if the proposed alternative can be applied to other metrics. There are also inherent assumptions related to the first derivative method that require additional investigations. Along with my comments below, I have suggested a few basic analyses and additional sensitivity test that will improve this study and make it scientifically robust and appealing to the larger carbon cycle science community. I sincerely hope that the authors consider these suggestions. for improving the manuscript.

We thank the reviewer for the critical comments and questions raised. We believe that by answering these questions, the interpretation and portrayal of our results has been improved. Overall, the results and discussion section were restructured and partly re-written to explain our results more clearly. We focus now on the utility of the ensemble-based approach to quantify the uncertainty in the estimation of the CUP using the first-derivative method.

R2.1
Line 1 in the Abstract should read – 'High-quality, long time series measurements of ...'
Thanks, Line 1 is modified as suggested.
Abstract. High-quality, long time series measurements *of atmospheric greenhouse gases show interannual variability in the measured seasonal cycles.*

R2.2 (This comment is broken down to 3 parts, which are addressed separately.)

R2.2.1

Lines 9 – 10: It is a bit misleading to claim that that the approach has been applied to analyze different seasonal cycle metrics as well as claims about the novelty of the approach. The authors have implemented this approach for quantifying one seasonal cycle metric, i.e., the carbon uptake period and associated parameters. What other metrics can be robustly calculated using this approach? It would be extremely relevant to include this in the discussion section.
We agree with the reviewer that the formulation was inaccurate. Here, the ensemble-based approach has been applied to only the CUP and associated parameters, however the approach can also be used to quantify uncertainty in other seasonal cycle metrics for example the seasonal cycle amplitude. Since this is not demonstrated in the study, line 9-10 has been modified:

Line 9-10: We use this ensemble-based approach to analyze the carbon uptake period (CUP: the time of the year when the CO_2 uptake is greater than the CO_2 release): its onset, termination and duration.

Moreover, we added a sentence on how the method can be applied to other metrics in the discussion (added in Line 320):

Line 320: *In this study we show that CO_2 seasonal cycle metric estimates can be strongly sensitive to the method used, hence any method must be thoroughly evaluated before it can be used to draw conclusions from the data.* In Barlow et al. (2015) the robustness of the first derivative is tested by evaluating its ability to capture a known trend from a synthetic time-series. The synthetic time-series were given a linear trend and interannual variations in peak uptake of ±10 days, allowing their method to retrieve the ensemble members provide an uncertainty range, hence allowing the robustness of estimated values to be estimated. the true linear trend to within 10-25%. Our EFD-approach provides uncertainty on the year to year variability in the seasonal cycle metrics based on the fitted data residuals, which could be used in a trend analysis to give differential weights to each year. Also, trend analysis on the individual ensemble members would allow uncertainty on the trend to be calculated. Our demonstration of the EFD-method on the CUP could be extended to other metrics that are derived directly from the seasonal cycle in a similar way, for example the peak to trough amplitude especially when curve-fitting discrete data, or at sites with broad or multiple peaks. In a similar fashion, the ensemble-based approach could be used to evaluate a newly proposed method or select an optimal method for evaluating any other metric based on reduced uncertainty.

R2.2.2
Right now, the Discussion section reads more like a collection of results than a true Discussion that provides scientific implications (see also comment #7) and relevance of this method for the carbon cycle community.
This will be addressed along with comment 7 (R2.7)

R2.2.3
In addition, the technique proposed by the authors are not new per se, but its application for quantifying the seasonal cycle metric is novel – the authors need to clearly distinguish this throughout the manuscript.
Thank you for pointing it out. The parts of texts which claim the novelty of the methods used here have been modified (e.g., Lines 7, 64, and 264). Further changes were made to address a similar comment from Reviewer #1 (See R1.2). We also include an extensive discussion of Barlow et al., 2015, a study that had previously introduced the first-derivative approach.

R2.3
Lines 21 – 22 – the statement is applicable to not just measurements made at Mauna Loa, but almost all atmospheric CO_2 measurements, be it in situ or remotely-sensed. Kindly rephrase to either make it more generic or more specific to Mauna Loa.
Thank you, we agree that this should be corrected. Lines 21--22 have been modified based on this comment as follows:

Line 21: Ongoing in-situ measurements of the atmospheric CO_2 mixing ratio have revealed an increase in CO_2 mole fraction in the atmosphere. *The increase in atmospheric* CO_2 *due to release of carbon from fossil fuel burning and land-use change is buffered by net* CO_2 *uptake by the ocean and land biosphere (Keeling, 1960).*

R2.4

Line 50 – The authors should be more specific about which metrics they are talking about and specify the ones that are highly sensitive to data gaps or noise in the time- series.

Thank you for the comment. An example is given in Line 51 (*One example is the timing of the carbon uptake period (CUP)*), but the lines were rephrased to improve clarity. Lines 50 -55 have been modified as follows:

Metrics derived from CO_2 time series such as the seasonal cycle peaks can be highly sensitive to data gaps and noise. This is especially true for metrics associated with the growing season onset at higher latitude sites, where CO_2 time series show flat or multiple peaks in winter (Barlow et al., 2015). Hence, deriving other metrics like the timing of the carbon uptake period (CUP) from the seasonal cycle maximum results in less robust estimates.

R2.5

Line 69 – 70 - What about checking an alternate approach? In the Introduction, the authors made the argument that multiple approaches should be tested. Why haven't they implemented that rationale here?

We agree that the lines are confusing. Here, we want to test the robustness of the EFD method. We want to understand if the low uncertainty while using the EFD method is dependent on the specific curve-fitting method used here. This is why we use another curve-fitting method and test the EFD method using both. We observe that, for both curve-fitting methods used, the EFD method leads to lower spread in the estimated CUP.

We corrected the sentence as follows:

Line 69 : We also tested if the EFD method is sensitive to the specific curve-fitting method applied by fitting the data with the commonly-used CCGCRV method, which is a frequency-domain-based filter, similar to the wavelet transform approach of Barlow et al. (2015).

R2.6

Lines 146-152, Page 7 – A big assumption in implementing the FDT approach is that "the first derivative of the CO_2 dry air mole fraction is a proxy for the flux", thereby completely ignoring the role of atmospheric transport. This is especially relevant as the majority of sites the authors have selected are the marine boundary layer sites, which are designed to sample the background flux and not necessarily changes in local flux. Can the authors demonstrate the robustness of their assumption by doing pseudo-data / simulated data experiments? For example, the authors can use known fluxes from CarbonTracker or CarbonTracker-Europe, generate pseudo-data at the sites used in the study, and demonstrate that the first derivative is indeed an approximation of the flux signal.

Thank you, this is a very important point. We consider the first derivative to be a proxy for the seasonal cycle of hemispheric-scale NEE, not a one-to-one measure of local fluxes. The seasonal variability in atmospheric CO_2 at background sites should reflect the spatial integral of the fluxes over large latitudinal or hemispheric scales, but the area of integration is affected by atmospheric transport, especially at marine boundary sites as mentioned by the reviewer. To address the reviewer's concern, we performed a synthetic data experiment using known NEE from the Jena CarboScope inversion to test the accuracy of the EFD method in deriving a prescribed change in CUP.

We did simulations in which idealized NEE fluxes were transported forward and the atmospheric concentrations were sampled at the location of the measurement sites. In the baseline simulation, a fixed year from the Jena CarboScope Inversion (Rödenbeck et al., 2003) (version ID: sEXT ocNEET v2021) was used to generate an idealized NEE flux time_-series that has no inter-annual variability (IAV) in the CUP_NEE (CUP of the NEE flux) at any given pixel. Then, we prescribe changes to the CUP_NEE at Northern Hemisphere land pixels with clear seasonal cycles by steps of -10,-8...+8,+10 days, creating different ΔCUP_NEE scenarios (change from baseline CUP_NEE). The fluxes were transported forward using the atmospheric transport model TM3 (Heimann and Körner, 2003) with wind fields from a fixed year (to remove transport IAV) and the resulting ΔCUP_MR (change of CUP_MR (CUP of the simulated CO_2 mixing ratio) from the baseline simulation) was compared to the ΔCUP_NEE. We calculate ΔCUP_MR using both the EFD method and zero-crossing method and compare their sensitivity to ΔCUP_NEE.

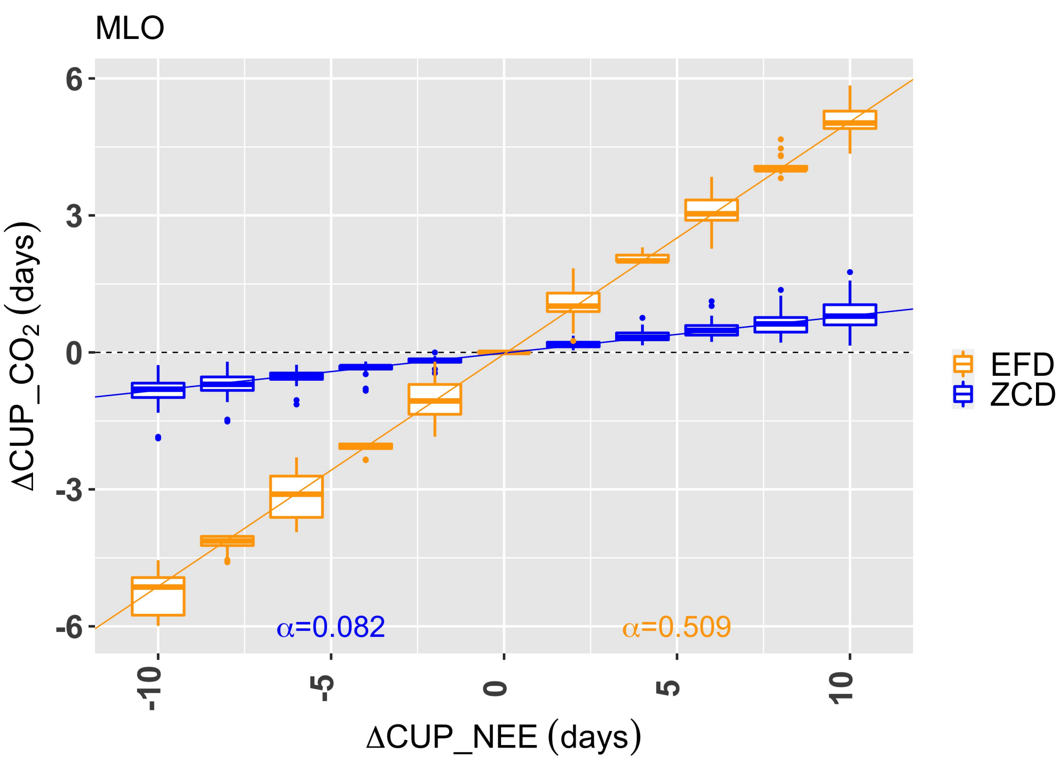

Figure 1: The boxplot shows the ΔCUP_MR over the studied years estimated using the zero-crossing method (blue) and the EFD-method (orange) at MLO. 'α' denotes the slope of the regression line fitted to the median of the boxplot.

We find that the EFD-estimated ΔCUP_MR has a strong linear relationship to the applied ΔCUP_NEE, but it returns ΔCUP_MR by a factor smaller than what was applied in flux space. This factor depends on the station, as for MLO (shown in the figure), it's quite close to a factor of 2. The zero-crossing-estimated ΔCUP_MR has weaker one-to-one relation relative to EFD estimation which shows that the zero-crossing method is relatively less sensitive to the changes in the "actual" CUP. These differences are shown for the station MLO in Figure 1. This implies that the EFD-derived CUP is likely a more robust metric than the zero-crossing-approximated CUP, but indeed should not be interpreted as a direct one-to-one signal of the underlying flux field. Transport to the sites, and mixing of spatially varying NEE signals with differing CUP timing, integrate to a reduced atmospheric expression of CUP changes in biospheric fluxes. That integration depends on the site location, which is what we will consider next. We believe this requires a more detailed study about the influence of transport on signals received at the background sites, which is not within the scope of this study. Therefore, we have modified the discussion to indicate that the role of transport should be considered when studying the observed CO_2 seasonal cycle.

Line 300 replaced: In this study we use the first derivative of the concentration time series as a proxy for the large-scale, spatially-integrated flux. However, this should not be directly interpreted as a measure of the underlying flux fields. The atmospheric transport plays an important role in explaining a significant portion of observed CO_2 variations at various surface stations (e.g. Krol et al., 2018; Fu et al., 2015) that will affect any interpretation of the CUP metrics. An extensive study was carried out by Lintner et al. (2006), confirming the importance of atmospheric transport to account for some of the inter-annual variations in CO_2 observed at Mauna Loa. Murayama et al. (2007) showed how year-to-year changes in the atmospheric transport create significant inter-annual variations in the downward-zero crossing day (DZCD) of the CO_2 seasonal cycle that cannot be neglected. Hence, we recommend that while using the EFD method, the contribution of atmospheric transport at the studied background sites should be evaluated before interpreting and relating the CUP metrics to sources/sinks.

R2.7 and R2.2.2

Section 5 – Discussion – other than a few segments, this section seems to be a continuation of the previous section. The authors need to rethink the way they present this section, move the results to the previous section and/or focus more on the scientific implications of their findings. It would also be useful to dig deep into a couple of the results and talk about the scientific findings rather than present one result after the another.

Thank you for the suggestion. The separation of the results and discussion section has been improved. To do this we have reordered some of the sections, separating the results from the discussion accordingly. A summary of the resulting structure is given below.

Results

- Comparison of the three CUP calculation metrics is presented in Figures 6, 7, 8 and 9.
- Fig 13 (now Fig. 8) and its explanation (Line 297) and additional observation that: The X-axis range, showing the CUP from ZCD in Fig.8, is unlikely to represent the "actual" year-to-year variation in the CUP, with the largest variation seen at MLO, NWR and MID. (This will be further explained in the discussion)
- Further testing using CCGCRV fitting, presented in Figure 10 and 11.

Discussion

In the Discussion we draw upon Figures 5 and 10 to interpret the figures presented in the Results section above. We have further included the other modifications following the reviewer comments. Figure 10 shows that years with a similar duration of the "actual" CUP can have different CUP duration when determined with the zero-crossing method, explaining the large year-to-year variation in the X-axis of Fig. 13.

R2.8

Figure 13 - What are the conclusions from this figure? Do we show any important trends? Any relevance to carbon cycle science? Similar to the previous comment, this seems another missed opportunity to delve

deeper into the results and provide scientific implications and context for the results. I would strongly recommend the authors to select a few key results and figures, and then delve deeper into them rather than presenting all results and figures generated during their investigation.

Thank you for these questions. Analyzing Fig 13 in light of these questions improves our understanding of the obtained results. Our observations are summarized as follows and will be included in the discussions.

We find that in addition to having a larger annual uncertainty, the ZCD-approximated CUPs have a larger range over the study period compared to the EFD-estimated CUPs (Fig 8). For example, at MLO the zero-crossing--approximated CUP ranges from 100 to 250 days, corresponding to a difference of 3-8 months. This is unrealistically large, considering that (a) MLO receives signals mainly from North America and Eurasia (Buermann et al., 2007), where the growing season has lengthened on average by 2.6 days per decade (Park et al., 2016), and (b) phenology statistics indicate that at MLO the average CUP of 155 days varies by ±17.4 days between 1969 to 2013 (Gonsamo et al., 2017), a variation that is 10x smaller than the ZCD-derived one. The ZCD includes changes in the both latter part of the net uptake period and the early release period, making it difficult to separate the contribution of the net uptake and net release periods to the changes in the CUP estimate. To understand this large spread in CUP, we compare two years with different ZCD approximated CUP at MLO, shown in Fig 11. We find that the difference in the CUP estimate in this case is due to the change in the early release period, whereas the uptake periods are essentially the same. The EFD method, by definition, is not affected by differences in the net release period and can therefore provide a more robust metric of CUP duration.

Atmospheric transport can contribute to the IAV in CUP estimates while using both the EFD and ZCD. However, the ZCD is influenced by transport variability in both the late uptake and early release periods. Hence, changes in the early release period could be erroneously interpreted as changes in the CUP when using the ZCD. Years with extreme CUP approximated by the ZCD suggest that there is reduced net respiration in the early release period, thereby prolonging the time to reach the UZCD. This is determined by the interplay of the CO_2 uptake and release processes, which are influenced by physical factors like temperature, soil moisture and solar radiation. For example, in dry conditions there is less respiration by plants and slower decomposition of organic matter in the soil, resulting in reduced CO_2 release to the atmosphere (Yan et al., 2018). The rate of decomposition further depends on the snow cover and available detritus content in the soil following leaf senescence. Furthermore, in the early release period, when the solar radiation is not limited, plants may continue to photosynthesize depending on water availability and temperature, leading to reduced net CO_2 release. Thus, in years with extreme CUP as approximated by the ZCD, the physical processes that affects the release period should be investigated. In comparison to the CUP definition, the approximation by the ZCD is also sensitive to variations after the summer minimum, i.e. during the early release period. A more thorough investigation of the sensitivity of the EFD and ZCD to CUP interannual variability would require dedicated modelling experiments, which is beyond the scope of the current study.

Other changes:

- We found a bug in our code. In the residual bootstrapping (Fig 3 manuscript) the resampled residuals were added to the observations, we corrected this by adding the residuals to the first fitted observation values. However, there are no significant changes in the results. The revised manuscript has the corrected values and figures.
- We now use acronyms ZCD replacing "zero-crossing dates" to be consistent with previous studies.
- Figure 8, 9 and Figures 11,12 are grouped.
- Figure 13 is simplified by not coloring the points.

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