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 1

R1.1

This study presents a novel method to estimate the carbon uptake period (CUP) from discrete CO_2 observation time series. The process of determining CUP from discrete time series includes two critical steps: curve fitting and CUP onset and end determination. Curve-fitting methods are needed to interpolate observation at gaps and to filter out the noise and undesirable modes of variability. When analyzing CO_2 mole fraction from background observation sites, this means removing the effects of local fluxes or synoptic scale transport variations. Previous studies have shown that the conclusions from the analysis of CO_2 time series are sensitive to the choice of the curve-fitting method. CUP estimates are also sensitive to the method used. Previous studies have proposed several methods that use the zero-crossing points or crest and trough of the detrended, zero-centered seasonal cycle. The study presents a new CUP estimation method and provides a detailed uncertainty assessment of the curve-fitting methods and compares them with other methods reported in the literature. The CUP method and the detailed uncertainty analysis of the different curve-fitting methods presented in this study are very relevant. Overall, the paper is well-written and the figures are clear. I recommend the publication of the paper after the following issues have been addressed.

We thank the reviewer for this positive and constructive review. Below, we answer all comments in detail and show the changes that we think have improved the manuscript.

R1.2

It is unclear which methods described in this paper are novel. The FDT method is new and innovative, however, I have reservations about the newness of the rest of the methods. In the abstract, the authors write "…a novel curve fitting method….". The essence of both CCG and the loess method presented here is the same, Equation 1. Is the novel part of the loess method using local regression to smoothen the residuals instead of a low pass FFT filter used in CCG? Or is it that the author's method uses a 2-degree polynomial and 4 harmonic functions while the CCG method uses a 3-degree polynomial and 4 harmonic function? Moreover, the study note that there is no difference in the performance of the loess and the CCG methods (line 254). Could the authors explain what is then the advantage of the proposed loess method? In the rest of the manuscript, the authors only claim the uncertainty generation and FDT methods are new (Line 64, 264 & 323). The ensemble-based method uses bootstrapping to evaluate the uncertainties of a metric. This is again not so new in my opinion. The main novel method presented in this study is the FDT method. I suggest that the authors (1) make clear which methods are novel. (2) restructure the method section so it does not over-emphasize the newness of the loess method.

Thank you for pointing this out. We agree with the reviewer, and have removed claims regarding the novelty of any of the methods used here. We emphasise now how the ensemble-based approach can improve uncertainty estimation by considering the year-to-year changes in the seasonal cycle.

R1.2 (continuation)

(3) if the ensemble-generation method is the same for the CCG and loess methods, describe the ensemble-generation in a separate subsection.

We agree, thank you for the suggestion. The method section has been modified as follows:

1) Added a new subsection 3.3 "Ensemble generation".
2) Moved subsection (*CCGCRV fitting and ensemble generation*) before subsection 3.3 with the following modifications:
    i) Name of section changed from *CCGCRV fitting and ensemble generation* to CCGCRV fitting.
    ii) Lines 166-171 have been removed ("*Further, we generate 500.....*). .
3) this is followed by subsection 3.4, "Ensemble of first-derivative method" , where we describe the EFD method and note the difference from Barlow et al., 2015.

R1.3

The authors have made a good attempt to describe the FDT method. However, I found it difficult to understand how CUP is calculated using the X% threshold. This statement is confusing: "The value of X is chosen to minimize the threshold value (as the rate of uptake towards the beginning and end of the CUP approaches zero) while keeping the uncertainty in timing across the ensemble members small". Does the authors mean the uncertainties are calculated as a function of threshold within the range of 0 to 20 percent, and the onset and termination times are the threshold points where CUP uncertainty is smallest? This becomes clearer in the results section but it will be good to move some of the explanation from the results section to the method section. Perhaps, a figure or an additional panel in figure 4 illustrating this would make the method easier to understand. I also have some concerns about the tested threshold values. Why only 4 discrete values of the threshold were tested? One can easily do this analysis over a continuum. Where does the choice of 0 to 20 percent come from? Why the range does not include positive threshold values, for example, something like -20 to 20 percent?

Thank you for pointing this out. We have followed up this suggestion with an analysis of the threshold over a continuum as suggested, and it is shown and discussed below.

For clarification: the first derivative threshold is determined separately for the onset and termination of the CUP. The threshold should be such that the uncertainty in the timing of the CUP (onset and termination) should be minimized. However, we also want the threshold to capture as much of the CUP as possible. Hence, an optimum threshold should offer a balance between the two requirements. If the seasonal cycle were regulated only by biospheric fluxes, then the CUP could be defined simply by the seasonal cycle maximum and minimum. However, higher latitude sites often have flat or multiple peaks, which leads to ambiguity in determining the onset of the CUP. Therefore, we need a metric that captures the CUP without being affected by the ambiguous timing of the peak. This metric uses the percentage of the first derivative (slope) defined by X.

When X is set to zero, the CUP then corresponds to the time period between the seasonal cycle maximum and minimum. By increasing X continuously to 25 for both the onset and end of the CUP, we see only a smaller fraction of this time period. By progressively increasing X, we truncate more of the drawdown period of the CUP, but we also avoid the ambiguity of the onset timing for the sites with flat peaks. We progressively increased the value of X from zero and found that there was no significant change in the uncertainty of the CUP timing mostly beyond 12-13% (Figure 1 , blue boxes and beyond). To be on the safe side, we chose 15% as the threshold. Incidentally, previous studies using flux measurements have also used 15% of the maximum GPP as a threshold to define the start of the growing season (e.g. Wang et al., 2019). For clarity, only values of X from 0 to 20 are shown in the manuscript. Negative X values corresponds to points before the maximum and after the minimum of the seasonal cycle, which are outside the time period of interest.

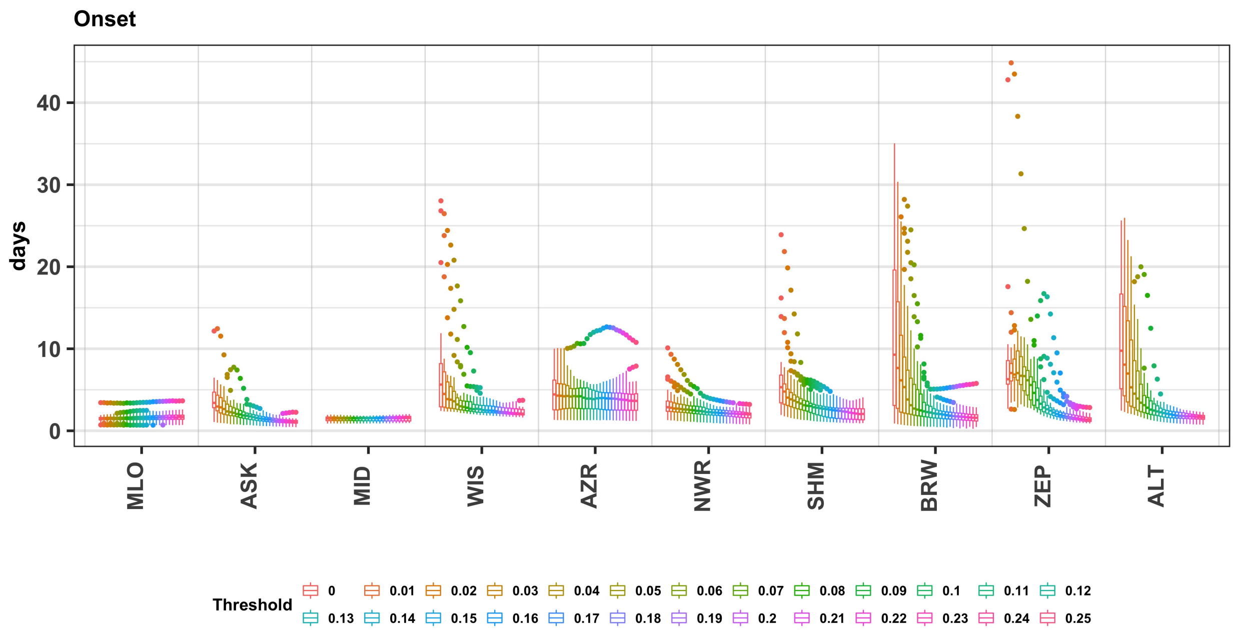

Figure 1. Similar to Fig 7 (b) in manuscript, tested for threshold over a continuum (X from 0% to 25%).

As noted by the reviewer, some of this explanation could be found in the result section, but we will modify subsection 3.3 and Figure 4 as suggested, so that the method is clear. The revised text reads as follows:

Lines 151 is replaced with: The threshold is defined as X% of the first derivative minimum and X is determined separately for the onset and termination of the CUP. The onset/termination of CUP is defined as the closest point to the threshold value before/after the first derivative minimum (Fig. 4). The threshold for the onset and termination is chosen such that 1) the uncertainty in the timing of onset and termination is minimized across 180 the ensemble members and 2) it represents as long a period as possible within the CUP. We varied the value of the parameter X until we found the optimum threshold. When X is 0%, it corresponds to the time period between the seasonal cycle maximum and minimum, including the full CUP but additional non-CUP periods may be erroneously included due to multiple peaks or flat maxima. By increasing the value of X we remove this error, but also truncate part of the "actual" CUP. Hence, we try to select a low value of X while reducing the uncertainty in the timing of the CUP.

Lines 173 added (section 4 Results begin like): For the EFD method, we first optimize the threshold as described in section 3.4. Continuously increasing X we found the optimum for the termination is 0%, and onset is at a value of 12-13%, with maximum CUP representation and no further reduction in the uncertainty beyond it. We then chose 15% as a conservative threshold (for onset) in all our analyses. Barlow et al. (2015) derived a larger threshold value for the onset (25%, resulting in a shorter CUP in their approach) from a synthetic data trend analysis in which they applied a linear trend with Gaussian variations of the peak uptake date to a CO_2 time series. We argue, however, that the data-derived year-to-year uncertainty from our ensemble provides a more robust threshold estimate. The result from varying X in steps between 0%-20% is shown in Fig 5.

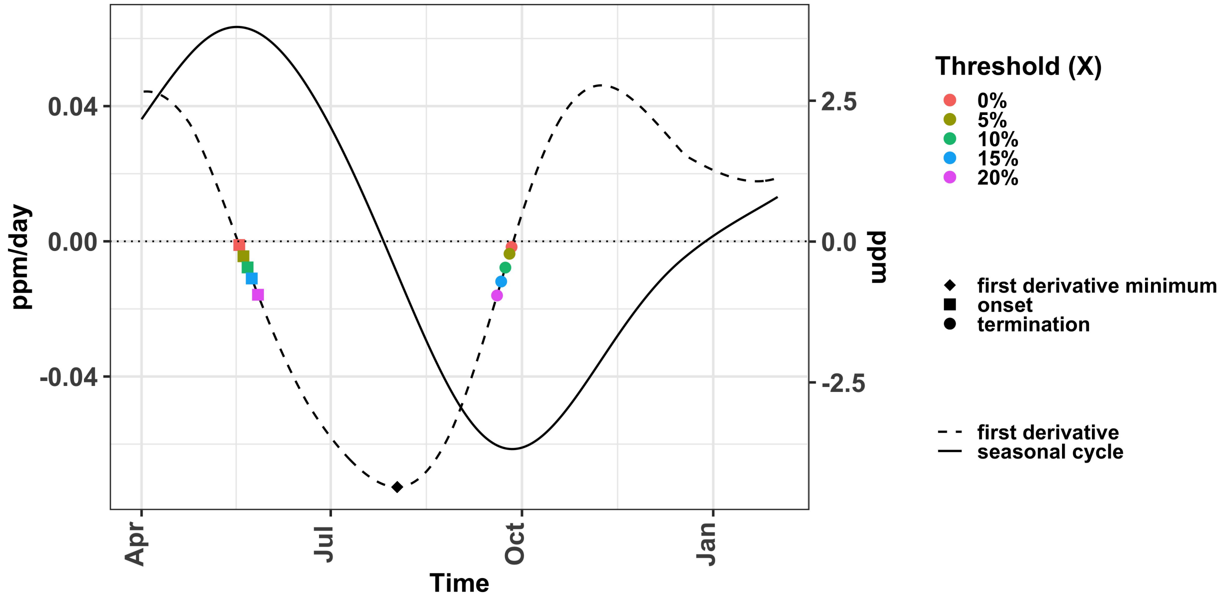

Figure 2. Schematic diagram showing the timing of the CUP as determined by the EFD method. The timing is marked by a threshold, defined in terms of the first derivative of the CO_2 seasonal cycle. It is defined as X% of the first derivative minimum. The value of X is varied from 0% to 20% and the corresponding threshold value is marked on the seasonal cycle first derivative with different colored points. Their timing then defines the timing of the CUP for the different threshold values. The day of the onset and the termination of the CUP are defined by the points before and after the first derivative minimum respectively. The squares and circles denote the onset and threshold calculated with different thresholds.

R1.4

The study focuses on the importance of uncertainties in CUP estimates of the Northern Hemisphere CO_2 emissions when estimated using discrete measurements from select background sites. There are intra-annual variations and long-term trends in atmospheric transport which would affect the relationship between the seasonal cycle of the CO_2 observations vs the actual emissions (see Krol et al., 2018, Fu et al., 2015). The transport errors will not be an issue when the FDT is applied to a discrete fluxes time series. I suggest the authors add a discussion about the transport-variation-related errors when analyzing fluxes using remote background observation sites to the discussion section.
This is a very important point, thank you for mentioning it. We have now added the following lines in the discussion section about the transport-related errors.

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 metric to sources/sinks.

R1.5

Technical corrections:

"Curve-fitting" is irregularly hyphenated in the text. It needs to be hyphenated when used as an adjective, for example in Line 6, 16, 19, and so on.

Line 256: "using two different curve-fitting methods " => "using the two different curve- fitting methods" is better.

Thank you for pointing it out, this has been corrected.

Other changes:

- We found a bug in our code. In the residual bootstrapping (Fig 3 manuscript), the resampled residuals were added to the observation, rather than the first fitted observation values. This has been corrected. 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.
- Figures 8 and 9 and Figures 11 and 12 are grouped.
- Figure 13 has been simplified by not coloring the points by year.

References:

Lintner, B. R., Buermann, W., Koven, C. D., and Fung, I. Y. (2006). Seasonal circulation and mauna loa CO_2 variability. Journal of Geophysical Research: Atmospheres, 111(D13).

Murayama, S., Higuchi, K., and Taguchi, S. (2007). Influence of atmospheric transport on the inter-annual variation of the CO_2 seasonal cycle downward zero-crossing. Geophysical Research Letters, 34(4). ¶

Barlow, J. M., Palmer, P. I., Bruhwiler, L. M., and Tans, P.: Analysis of CO2 mole fraction data: first evidence of large-scale changes in CO2 uptake at high northern latitudes, Atmospheric Chemistry and Physics, 15, 13 739–13 758, https://doi.org/10.5194/acp-15-13739-2015, 2015.¶

Fu, Q., Lin, P., Solomon, S., and Hartmann, D. L.: Observational evidence of strengthening of the Brewer-Dobson circulation since 1980, Journal of Geophysical Research: Atmospheres, 120, 10,214–10,228, https://doi.org/https://doi.org/10.1002/2015JD023657, 2015. gml.noaa.gov: Trends in CO2, [online] Available from:https://gml.noaa.gov/ccgg/trends/, accessed: 2022-06-8.

Krol, M., de Bruine, M., Killaars, L., Ouwersloot, H., Pozzer, A., Yin, Y., Chevallier, F., Bousquet, P., Patra, P., Belikov, D., Maksyutov, S.,Dhomse, S., Feng, W., and Chipperfield, M. P.: Age of air as a diagnostic for transport timescales in global models, Geoscientific Model Development, 11, 3109–3130, https://doi.org/10.5194/gmd-11-3109-2018, 2018.

Wang, X., Xiao, J., Li, X., Cheng, G., Ma, M., Zhu, G., Altaf Arain, M., Andrew Black, T., and Jassal, R. S.: No trends in spring and autumn phenology during the global warming hiatus, Nature Communications, 10, 2389, https://doi.org/10.1038/s41467-019-10235-8, 2019.