

Response to Reviewer 1

Manuscript title: *‘Annual Growth Rates of Column-Averaged CO₂ Inferred from Total Carbon Column Observing Network (TCCON)’*

Author: Mostafavipak et al.

January 8, 2026

We thank the reviewer for the careful, insightful, and constructive comments, which have greatly improved the quality and clarity of our manuscript. Below, we provide detailed responses to all points raised.

Author responses

- **Line 27 – Reviewer comment:** “I’m not sure ‘monotonically’ is the best word to use here, given that it implies little-to-no variation in the rate of increase of CO₂ emissions. I would suggest removing the word altogether, but emphasising that the emissions increase annually, e.g. ‘... emissions have generally increased each year, but with occasional declines...’”

Author response: We agree with the reviewer’s suggestion. The word “monotonically” has been removed and replaced with “have generally increased each year,” to better reflect the observed interannual variability in CO₂ emissions.

- **Line 109 – Reviewer comment:** “... in the Southern Hemisphere where CO₂ growth is largely influenced by transport from the Northern Hemisphere” — please can you provide a reference supporting this statement?

Author response: We have added a supporting reference for this statement: Dar-gaville et al. (2003) , which discusses the hemispheric transport influence on CO₂ growth rates in the Southern Hemisphere.

- **Figure 3 – Reviewer comment:** “This figure is a little hard to interpret — for each year, I suggest plotting the ‘CAMS ds’ bars next to the ‘TCCON’ bars, since I think the key point is the comparison between these two. I would then have the ‘CAMS non-ds’ data on the right of the three for each year, so that the reader can see the effect of the down-sampling more easily (I would also explicitly label these ‘CAMS non-ds’ instead of just ‘CAMS’). So in summary, for each year, plot from left to right: TCCON, CAMS ds, CAMS non-ds.”

Author response: The figure layout has been revised accordingly. For each year, the bars are now ordered as **TCCON, CAMS (downsampled), and CAMS (full)**.

Labels and legends have been updated to explicitly indicate “CAMS full” to improve clarity. The new layout more clearly shows the effect of down-sampling.

- **Figure A3 – Reviewer comment:** “It would be useful for the reader to have this figure referred to somewhere in the main text; I think Section 3.1 (Data Preparation) would be most appropriate.”

Author response: We agree and have now added an explicit reference to Figure A3 in Section 3.1 (*Data Preparation*).

Response to Reviewer 2

Manuscript title: “*Annual Growth Rates of Column-Averaged CO₂ Inferred from Total Carbon Column Observing Network (TCCON)*”

Author: Mostafavipak et al.

January 8, 2026

We sincerely thank the reviewer for their thoughtful and constructive comments, which have significantly improved the quality and clarity of our manuscript. All suggested changes have been carefully considered and incorporated. Detailed, point-by-point responses are provided below.

Author responses

- **L88 – Please define NOAA GML.** NOAA GML (Global Monitoring Laboratory) has been defined at first mention.
- **L90 – Please state what value the gridded modeled total column CO₂ product adds.** The revised text now clarifies that the CAMS product provides spatially and temporally continuous CO₂ fields that complement the sparser ground-based network.
- **L95 – Please remove “specifically.”** Done.
- **L101 – Please italicize “a priori.”** Done.
- **L103 – Please define WMO.** WMO (World Meteorological Organization) is now defined at first mention.
- **L106 – Do the fossil fuel emissions occur only in the mid-latitude regions?** We agree that fossil fuel emissions are not limited to mid-latitudes. The text clarifies that the *majority* of global fossil fuel emissions occur in the Northern Hemisphere mid-latitudes, supported by zonally averaged CarbonTracker emission data (see Figure 1).
- **L110 – Why was the “at least five years of data” criterion used?** Five years of data was chosen to ensure that a meaningful long-term trend could be determined. With a five-year time series, four annual growth rates can be derived, providing a minimum basis for assessing temporal changes. Shorter records would yield too few data points to identify any robust or statistically meaningful trend.
- **L112 – Please state the latitude range.** The range (67–80°N) has been added.
- **L113 – Please define AWIPEV.** AWIPEV is now defined as the *Alfred Wegener Institute for Polar and Marine Research and the French Polar Institute Paul-Émile Victor*.

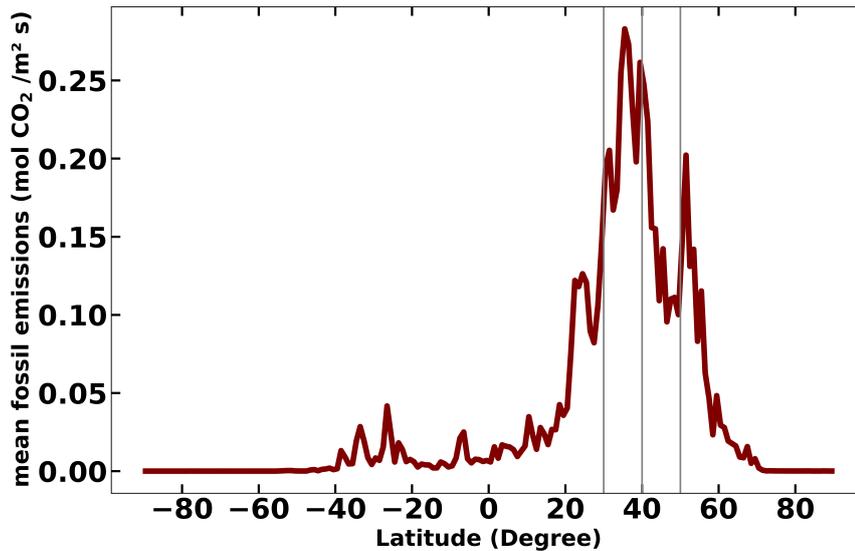


Figure 1: Zonally averaged fossil fuel CO₂ emissions by latitude, based on CarbonTracker data.

- **L124 – All three TCON stations are in close proximity. Are there other other southern hemispheric TCCON sites that can be used?** Unfortunately, there are no additional TCCON sites in the Southern Hemisphere that provide a sufficiently long and continuous record suitable for this analysis. The Réunion Island site has substantial data gaps from 2018–2019 and only partial coverage for 2020 (until July), after which no data are available. This discontinuity makes the estimation of the 2020 growth rate—one of the key years of interest—unreliable. The Ascension Island data have not been available for recent years, and Manaus (Brazil) only provides measurements from 2014–2015, which is too short to capture multi-year variability.
- **L130 – Are the data publicly available or will they be at the time of publication? Please ensure that the data are publicly available so the reader can recreate the figures from the analysis should they choose to do so.** Yes. All datasets are publicly available, and access links are provided in the manuscript’s Assets section.
- **L143 – “This approach . . .” – The rest of this paragraph might look better in the data introduction portion of the manuscript.** Implemented. The description of the CAMS reanalysis dataset has been moved to the Data introduction section.
- **L144 – Please provide a citation/data reference publication for the CAMS Reanalysis product.** The CAMS reanalysis dataset is cited using both its official publication (Agustí- Panareda et al., 2023) and the ECMWF documentation (Cheval-

lier, 2024).

- **L146 – What are the possible pros and cons of using satellite and aircraft data vicariously to fill gaps?** A short discussion has been added to the text to acknowledge both the advantages and limitations of the reanalysis product in the data introduction section.
- **L156 – “Publicly available dataset...” – except for Lauder?** Clarified. All TCCON data are publicly available except for the 2010–2012 Lauder record, which was provided privately by the site PI.
- **L158 – What value is the quality flag set to for good quality data?** Clarified. For MLO in-situ measurements, only observations marked as fully valid under the NOAA/GML three-character quality control flag were retained.
- **L161 – How much error does weekly averaging introduce?** Weekly averaging is applied to reduce synoptic-scale variability and random measurement noise, following the approach of Sussmann and Rettinger (2020). This temporal smoothing minimizes short-term fluctuations without introducing a systematic bias in annual growth rate estimates, as verified in their analysis.
- **L166 – Does sample size difference impact the outcome?** The data density indeed influence the statistical robustness of the regional averages but do not systematically bias the mean growth rate. Regions with denser sampling (e.g., mid-latitudes) yield smaller uncertainties due to higher temporal coverage, whereas regions with fewer stations show larger variability and wider confidence intervals. This effect is reflected in the uncertainty estimates of the regional growth rates.
- **L174 – “Similar studies” – Please cite.** References have been added to support the statement about the prior use of these methods. Specifically, Buchwitz2018 , Sussmann2020 and Hachmeister2024 are now cited as representative examples, while all methods are described and fully referenced in the following subsections.
- **L205 – Please add quotes around “dlmhelper.”** Done.
- **L205 – Please define DLM.** Done.
- **L208 – “Only one harmonic is selected” – Why?** The number of harmonics in each regional DLM configuration was determined objectively by minimizing the total covariance level. In the Arctic region, only one harmonic was selected because extended winter data gaps prevent stable fitting of higher-order harmonics, which would otherwise risk overfitting the limited available data. The single-harmonic model therefore provides the most robust representation under these sampling conditions.

- **L216 – Do edge effects introduce higher uncertainty?** Yes, the larger uncertainties at the beginning and end of the time series arise from edge effects inherent to the DLM framework. At these boundaries, the model has fewer observations to constrain the state estimates, relying more heavily on prior assumptions, which leads to larger posterior variances.
- **L218 – “at three sites” – located at different latitudes. How does this impact the results?** As a sensitivity study, we selected three sites with contrasting data characteristics to test the robustness of the methods: Mauna Loa (continuous in-situ), Lamont (dense mid-latitude TCCON), and Eureka (high-latitude TCCON with seasonal gaps). The inclusion of these sites enables evaluation of method performance across sampling conditions ranging from continuous to highly intermittent records.
- **Page 12 – What are the cons of using the DLM method? What are the possible trade-offs, even though relatively few, of using this method? How much of an improvement does the DLM method provide over the FF and MM approaches?** One limitation of the DLM method is its higher computational cost, as it requires fitting an ensemble of models and selecting the optimal configuration, which can be sensitive to the chosen selection criterion. In contrast, the Monthly Mean (MM) method is computationally simple and fast, while the Fourier Fit (FF) method is also computationally demanding due to its bootstrap resampling. The key advantage of the DLM approach is its robustness to data gaps and irregular sampling, which makes it particularly suitable for remote-sensing datasets where temporal coverage is uneven. Overall, DLM provides a clear improvement in stability and reliability of the estimated growth rates, especially for sparse or seasonally interrupted records.
- **L293 – What was the reason behind the sudden increase in CO₂ growth rates in 2016? Why was the growth rate relatively lower in the 40-50 N region?** The elevated CO₂ growth rates in 2016 coincide with the strong El Niño event, which enhanced fire emissions and suppressed biospheric uptake, particularly in tropical and arid regions. The smaller response in the 40–50° N band reflects the weaker and more lagged coupling between ENSO and gross primary production (GPP) at these latitudes. This is consistent with our correlation analysis, which shows lower R² values and higher p values in this region compared to the southern hemisphere and mlo, indicating a weaker statistical linkage with ENSO variability. As shown by Zhang et al. (2019), ENSO–GPP correlations peak mainly in tropical and arid regions, whereas temperate and boreal zones exhibit more heterogeneous and lagged responses, leading to a reduced CO₂ growth signal during strong El Niño years.
- **L297 – Please consider splitting into two sentences.** Done.
- **L299 – Why was there an increase in the 40-50 N latitude band, but a decrease in the 30-40 N latitude band regions?** The difference between

the 30–40° N and 40–50° N bands likely reflects the different dominant influences on CO₂ variability: anthropogenic emissions in the lower mid-latitudes versus biospheric processes in the higher mid-latitudes. Site-specific factors and sampling differences may also contribute to the observed contrast.

- **L303 – Why wasn’t the reduced fossil fuel activity observed anywhere else besides the 30-40 N? Is it only due to dense urbanization?** The 30–40° N region includes the highest concentration of anthropogenic CO₂ emissions globally, encompassing major industrial and urban areas such as the eastern United States and East Asia. As shown by the CarbonTracker emission inventory, this latitude band dominates global fossil fuel emissions, making it the most sensitive to short-term reductions in human activity, such as those observed in 2020. Other regions are either less urbanized or more strongly influenced by biospheric fluxes, which likely masked the signal of reduced emissions in the total column CO₂ growth rates. In addition, in the Southern Hemisphere, the transport of air masses from the Northern Hemisphere introduces a time lag, delaying the reflection of such emission changes in the observed growth rates.
- **Table 1 – 1. For Avg Measurement/year the sample size varies. Does this introduce uncertainty in the analysis?** We agree that varying sample sizes influence the statistical uncertainty of the growth-rate estimates. This effect is accounted for in our analysis, as the confidence intervals reflect the number of available observations. As shown in Figure 4, years or sites with fewer measurements exhibit larger confidence intervals, illustrating the direct relationship between sampling density and uncertainty. We have added a clarifying sentence in the Results section to make this point explicit.
- **Table 1 – 2. What are the possible cons of comparisons for sites with uneven latitude windows, i.e., 40-50N, 30 -40N vs. 10-50S)?** We acknowledge that using latitude bands of unequal width introduces some limitations when comparing regions. The 10–50° S band covers a wider range of climatic zones—from tropical northern Australia to mid-latitude New Zealand—than the narrower Northern Hemisphere bands. However, previous studies (e.g., Stephens et al., 2013) have shown that CO₂ variability in the Southern Hemisphere is relatively subdued, with smaller zonal gradients than in the Northern Hemisphere. Consequently, combining the three Southern Hemisphere sites still provides a representative regional average. Nonetheless, we recognize that local climatic differences, such as between Darwin and Lauder, may contribute to additional variability not captured by the broader regional mean.