Manuscript 10.5194/amt-2024-167

Responses to Anonymous Reviewers #1

(Note: Reviewer's comment is written in black fonts, authors responses are written in blue fonts.)

General Comment

This manuscript describes an analysis of ground-based Fourier Transform Infrared Spectrometer (EM27/SUN) observations in India from 2015-2016. The authors use the EM27/SUN data to analyze emissions of methane and carbon dioxide in Southern India. The authors show the utility of the EM27 measurements to evaluate satellite observations and then compare the observations to model results and estimate emissions. The paper is a very good analysis providing satellite data validation and emission estimates for a region of the globe that has not traditionally had extensive ground-based observations of methane and carbon dioxide.

The analysis is an important contribution in the area of using ground based and satellite observations of greenhouse gases in South Asia. They do a nice comparison of satellite data to the surface observations and then use them to help evaluate emission modeling analysis. The scientific quality is also very good, they use the well-established methods for using their surface data with the satellite observations and model results. The paper is well written, concise, and effective at communicating the key results.

My comments below are mostly minor and a few wording issues or typos. I think the conclusions could be strengthened somewhat to more clearly state the key findings.

Response:

We sincerely thank the reviewer for his/her positive and encouraging feedback, as well as for the thoughtful suggestions to improve the manuscript. We have carefully addressed all the minor comments related to wording, grammar, and typographical errors.

In response to the suggestion to strengthen the conclusions, we have revised the conclusion section to more clearly articulate the key findings of our study. The details of changes are provided in reply to specific comments below.

Specific Comments

Following is a list of comments/suggestions, which we accept as it is and have incorporated corrections/suggestions in the revised manuscript.

1. Line 35: continuously (not continuous)
2. Line 38: OCO-2's gets global coverage every 16 days (not 15)
3. Table 1, bottom row, right column: forgot word spectrometer after grating
4. Line 61: Feels like a reference would be appropriate here, maybe Laughner et al., 2024 https://doi.org/10.5194/essd-16-2197-2024
5. Line 86: Type for spelling of However
6. Line 87: delete "a few"

7. Lines 104-105: maybe the sentence beginning with “KIT has developed” could be reworded to make the point more clear, how the sun tracker works.
8. Lines 114-115: Mention the “reference IFS 125HR” is the Karlsruhe TCCON site?
9. Line 122: Type, add “The” before PROFFAST
10. Line 126: Define the acronym NCEP
11. Line 167: (NASA, USA) instead of (NASA), USA
12. Line 173: This is the first time you define the acronym OCO-2, maybe that should also be done with the first mention in the Introduction?
13. Line 188: OCO-2 uses different metrics for its bias correction. TCCON data is one of the data sets used, but models, small area analysis are also used.
14. Line 191: Typo, “contain a quality flag”
15. Line 198: Define acronym NILU
16. Line 218: Define acronym GAINS
17. Line 228: Define WetCHARTS?
18. Line 242: SWAMPS, missing S at the end
19. Table 4: Because the authors are stressing the importance of the bias and standard deviation calculations meeting the CCI requirements, you could highlight somehow (red numbers? Filled in cell?) the cases that do not match the requirements.
20. Line 364-365: Maybe instead of “increase or decrease” just use “changes” or “variations”
21. Line 369: “observed” could be removed
22. Line 376: Define acronym “JAMSTEC”
23. Line 382-383: Since the FLEXPART, maybe remove “the”

Specific Comments with detailed answers

1. Line 90-91: I was not familiar with the Pathakoti (2024) study. Do the authors feel that the larger bias seen in that analysis was due to an earlier version of the OCO-2 data? The way it is phrased is confusing. Also when the authors discuss the results in Table 4, much improved biases for OCO-2, maybe refer back to the Pathakoti study and highlight reasons for the improved comparisons?

   Reply: We thank Reviewr#1 for this question and suggestions to include more discussion on differences between our study and Pathakoti et al. (2024).

   Pathakoti et al. (2024) reported a mean bias 3.81 ppm for OCO-2 data, which is significantly larger than the bias 0.163 ppm found in our analysis for 10° x 5° lon-lat region. We believe that the higher bias reported by Pathakoti et al. is unlikely to be solely due to the use of an earlier version of the OCO-2 dataset.

Although their study does not elaborate extensively on the cause of the bias, Pathakoti et al. (2024) do acknowledge that their reported bias is higher than that typically found in the literature and they cite a lower value of 0.5 pm from Wunch et al. (2017) for reference. Therefore, we consider it unlikely that the OCO-2 data version alone explains the discrepancy.

There are also methodological differences between our study and that of Pathakoti et al. (2024) that may contribute to the difference in results. For example, Pathakoti et al. used a 4° × 4° lon-lat box and paired satellite data with the **daily mean** ground-based observations. In contrast, our analysis used a larger spatial window of 10° × 5° and matched satellite observations with surface measurements within ±2 hours of the satellite overpass. Additionally, we applied an extra filtering step using model data to ensure that both satellite and surface measurements sampled similar air masses.

We believe the high bias found by Pathakoti might have been caused due to the daily mean values used by them instead of restricting to temporal collocation within few hours of satellite overpass.

We will include this discussion in the revised manuscript.

2. Line 121: Typo, space needed before pyplot

   Reply: We thank the reviewer for this observation. However, in this case, the term "PROFFASTpylot" is not a typographical error — it refers to the name of the software package used in our analysis.

3. Line 184: Typo, misspelling artifacts

   Reply: We thank the reviewer for pointing this out. We would like to clarify that we have followed British English spelling throughout the manuscript, in which "artefacts" is the correct spelling for "artifacts." We will ensure consistency of spelling in the revised version.

4. Line 274: When discussing the time coincidence criteria, I found the wording confusing. Maybe reword the sentence to make clear that you use data within two hours of the observation, but that data can come from a three-day time period.

   Reply: We thank the reviewer for this helpful suggestion. We agree that the original wording was unclear and have revised the sentence to more clearly state that satellite data within ±2 hours of the ground-based observation are considered, and the matching is carried out over a three-day window. The revised wording in the manuscript should now make this methodology clearer to the reader.

5. Line 280: Could the authors speak to the importance of step number 3? Does it make a big difference in the bias and standard deviation results?

   Reply: We thank the reviewer for this insightful question. Step 3 in our pairing methodology is designed to filter out satellite–ground observation pairs that do not represent the same airmass, based on model-derived criteria.

To assess the impact of this step on the bias and standard deviation, we conducted a sensitivity test by repeating the analysis without applying Step 3. The results are summarized in the table below.

Satellite	Bounding Box	Species	Num of Pairs		Bias (Sat – Grd)		Scatter	
	Lon x Lat		Old	New	Old	New	Old	New
GOSAT	10x05	CH4	12	40	-0.013	-0.011	0.006	0.009
GOSAT	20x10	CH4	19	97	-0.009	-0.011	0.012	0.011
GOSAT	60x20	CH4	55	166	-0.019	-0.014	0.014	0.013
GOSAT	10x05	CO2	27	40	0.983	0.684	1.587	1.518
GOSAT	20x10	CO2	59	97	0.812	0.398	1.881	1.921
GOSAT	60x20	CO2	117	166	0.644	0.196	1.698	1.326
OCO-2	10x05	CO2	41	48	0.163	0.239	0.786	0.849
OCO-2	20x10	CO2	67	96	0.342	0.303	0.806	0.827
OCO-2	60x20	CO2	120	163	0.408	0.315	0.776	0.876
ACOS	10x05	CO2	24	37	-0.212	-0.357	1.019	1.139
ACOS	20x10	CO2	54	99	0.077	0.022	1.246	0.989
ACOS	60x20	CO2	118	177	0.163	-0.042	1.089	1.083

(Note: Old referrers to collocation with model-based criteria. New refers to collocation without model based criteria.)

As expected, omitting Step 3 increased the number of matched pairs across all satellite products, species, and spatial grid boxes. For example, in the case of GOSAT XCH_4, the number of valid data pairs within the 10° × 5° bounding box increased from 12 (with all pairing steps) to 40 when Step 3 was excluded — an increase by more than a factor of 3. Similar increases were observed in other configurations, often exceeding a factor of 2.

In terms of performance, the effect on bias was mixed. For GOSAT XCH_4, the bias marginally decreased for the 10° × 5° and 60° × 20° boxes but increased slightly for the 20° × 10° box. For XCO_2 from the GOSAT satellite, the bias decreased significantly across all box sizes. Conversely, for OCO-2 and ACOS XCO_2 data products, the bias increased for the smallest box (10° × 5°) but decreased notably for the larger boxes (20° × 10° and 60° × 20°).

The scatter (standard deviation) increased slightly in most cases. There were a few instances where it decreased, although insignificantly — with the exception of ACOS XCO_2 in the 20° × 10° box, where it reduced from 1.246 to 0.989.

Overall, while Step 3 does not appear to have a uniformly large effect on the bias and scatter, we have chosen to retain it in our final analysis. This decision ensures consistency with previous studies and enhances the comparability of our results. A summary of this sensitivity analysis has been added to the revised manuscript.

6. Lines 394-403: Maybe expand a bit more about the importance of the box sizes and the trade off between number of comparisons and improvement in bias and standard deviation. The GOSAT studies used larger boxes to improve the number of comparisons, the authors could expand on their conclusions relative to this.

Reply: We thank the reviewer for this useful suggestion. We agree that the manuscript would benefit from an expanded discussion on the role of box sizes and the trade-off between the number of comparisons and the resulting bias and standard deviation. We have revised the relevant section in the manuscript as follows:

"The biases in methane mixing ratios derived from the GOSAT satellite ranged from –9 ppb to –18.5 ppb, depending on the spatial criteria used for collocating satellite and ground-based observations. As expected, larger latitude–longitude boxes resulted in a greater number of matched data pairs; however, this did not consistently lead to reduced bias or scatter. In fact, for methane, the smallest box (10° × 5°) yielded the lowest bias and standard deviation. Notably, even when the biases differed across larger boxes, they remained within one standard deviation of the values observed for the smallest box size. These findings suggest that larger spatial boxes may not be necessary, particularly when longer time series of ground-based data are available. Similar patterns were observed in the carbon dioxide analysis.

For methane, the bias values for the smallest box size met the ESA Climate Change Initiative (CCI) requirement for systematic errors (<10 ppb). However, the biases were marginally higher for the medium box size and exceeded the threshold for the largest box (±30° longitude × ±10° latitude).

For carbon dioxide, the lowest biases were observed with the ACOS v9.2 dataset among the three evaluated. Both ACOS and OCO-2 datasets met the ESA CCI requirement for XCO_2 bias (<0.5 ppm), while GOSAT v3.05 exhibited higher biases ranging from 0.644 ppm to 0.983 ppm. All three datasets satisfied the CCI precision criterion for XCO_2 (<8 ppm), with standard deviation values ranging from 0.776 ppm to 1.88 ppm."

This revised paragraph has been incorporated into the manuscript to better highlight the role of box size and the observed trade-offs.

7. Lines 404-408: Similarly, the conclusions relative to the model results and comparisons to the observation could be spelled out a little more clearly. What is the key message the authors would like to get across from that part of the analysis?

   Reply: We thank the reviewer for this helpful suggestion. We agree that the conclusions regarding model results and their comparison with observations needed clearer articulation. We have revised the text in the manuscript to read:

   "We used the model to investigate seasonal changes in methane mixing ratios driven by local and regional emissions, as well as the sectoral contributions to these emissions. The model captures the broad seasonal trends in methane enhancements, with elevated values during certain months (e.g., November) and lower levels in others (e.g., June–July). On an average, agricultural emissions contribute approximately 55% to the modeled methane signal, followed by emissions from waste and wetlands.

   However, when comparing the modeled seasonal variability (ΔXCH_4, representing the contribution from emissions over the preceding 10 days) with observed seasonal changes in total column methane, the model underestimates the amplitude of variability. For instance, observed changes can reach ~100 ppb, whereas the model simulates only ~20 ppb. This indicates that a substantial portion of the seasonal signal arises from changes in *background methane levels and/or changes in photolysis rate. This differences suggests a potential limitation in using short-timescale inverse modeling approaches to accurately estimate local/regional emission fluxes.*

Overall, our study highlights the utility of satellite-based greenhouse gas observations for emission characterization over South Asia. Given the recent expansion of satellite missions by both public and private entities, there is a pressing need to develop a wider and denser network of ground-based Fourier Transform Spectrometers (FTS) in the region. Such a network would enhance the validation of satellite and model-based greenhouse gas products, leading to more robust emission assessments and improved climate modeling."

This revised text has been incorporated into the manuscript to clarify the key messages from the model–observation comparison.

Once again, we would like to thank Reviewer#1 for the time he/she dedicated to review our manuscript and to provide constructive comments which greatly contributed to its improvement.