Response to Referee #2

We would like to thank Reviewer 2 for carefully reading the manuscript and providing thorough comments.

Specific Comments

1) Line 25: When are 2020 CH_4 emissions expected to be available? (Consider updating to 2020, if the estimates are available before publication.)

Response: Thank you for this comment. The 2020 CH_4 emissions were recently published, and estimates were updated to 2020.

2) Lines 26, 94, 557: "a novel application" – this statement is vague and, should specify what is novel about the application compared with previous studies.

Response: We have specified the novelty of this method in line 26: "Our work demonstrates a novel application of the ground-based EM27/SUN solar spectrometers in wildfire monitoring by integrating regional scale measurements of trace gases and aerosols from smoke plumes."

Line 94: Deleted phrase.

Line 557 (now line 553): "Overall, our analysis contributes to the development of techniques for analyzing remotely sensed greenhouse gas and aerosol measurements from wildfires."

3) Line 62-64: "observations… focus on aerosol burden from smoke plumes with limited attention to trace gases…" This isn't entirely true - the paper should indicate that there have been a number of studies that have looked at trace gases emitted from fires using satellite data, including ratios of species and estimation of emissions for CO, NOx, NH3 (see for example, Griffin et al., AMT 2021; Adams et al. ACP 2019; Whitburn et al., Atmos. Env., 2015 and references therein).

Response: The text was modified to include trace gas studies and included the recommended references:

"While several space-based instruments can retrieve and derive emissions of important trace gases globally, observations of trace gases are limited by spatiotemporal coverage and aerosol burden from smoke plumes (Schneising et al., 2020). Recent satellite studies have focused on trace gas emissions and ratios for CH_4, CO, nitrogen oxides (NO_x) and ammonia (NH_3) (Whitburn et al., 2015; Adams et al., 2019; Griffin et al., 2021; Jin et al., 2021), but few focus on the integration of trace gases and aerosols."

4) Line 65 : ".. present a new technique…" Is ground-based FTIR is a particularly new technique?

Response: Thank you for the comment. We have changed "present a new technique" to "present an alternate technique." The ground-based FTIR is not a new technique and has been used

previously in other studies to estimate emissions of wildfires, however it is the first time that emission factors with respect to CO_2 have been calculated with this ground-based remote sensing technique.

5) Line 91: "… satellite greenhouse gas observations…" perhaps replace with "… observations of CO…"

Response: This has been changed to "observations of CO."

6) Line 97: I found this section a little bit difficult to follow. Recommend giving an overview of the various instruments involved (e.g., describing of Fig 1 to a high level) and the description of the fire to the top of the section (before Sect. 2.1), and then using the subsections to give the technical details. I would recommend that you describe/name the fires here and then use consistent naming throughout the document. (For example, the name "Shotgun" fire is used in some places – is this the same as the "North Complex" fire in Table E1?)

Response: This section was modified per reviewer's suggestion of describing Fig. 1 prior to Section 2.1 followed by subsections describing technical details of instruments used.

7) Line 150: Should panels b, c of the figure be referenced/described here?

Response: Apologies if we misunderstood but panels a, b, and c are described in the figure.

8) Line 163: "… for a novel evaluation…" – is this evaluation novel? Has TROPOMI CO not been evaluated under smoky conditions before?

Response: We have modified this sentence to add more context of the importance and novelty of our study in lines 166-168.

"There is growing intertest in using the TROPOMI XCO product for understanding global wildfire fluxes, however few studies focus on evaluating those observations (e.g., Jacobs 2021 and Rowe et al., 2021). We measured a range of X_{CO} levels of mixed smoke plumes and were able to isolate a concentrated smoke plume from a nearby fire. This allowed for a ground-based evaluation of the TROPOMI sensor under various wildfire conditions, including high X_{CO} and aerosol loading in the atmosphere."

9) Line 180: Should Sect 2.4 be moved into an appendix, since it mostly references methods described elsewhere?

Response: Thank you for the suggestion. We have moved Section 2.4 to Appendix B.

10) Line 295: For the comparisons against TROPOMI should uncertainties be included in the fits, etc?

Response: We fit the comparison between the two instruments with a York linear regression that considers uncertainties in both x and y. We added the uncertainty in the slope of the linear fit on Figure 4b.

11) Line 307 (and similar statements lines 500, 546): "These results suggest an overestimation of 9.7% X_CO from TROPOMI observations of wildfires." Is there evidence that the difference is due to overestimation from TROPOMI? Or could this be due to differences in sampling or biases in the EM27/SUN data? Is there an uncertainty attached to the 9.7%? Also, what is the reported uncertainty in TROPOMI measurements and in the EM27/SUN measurements? Is 9.7% within the range of uncertainties? Is this bias consistent with previous studies?

Response: According to Sha et al., 2021, the systematic difference X_{CO} between TCCON and TROPOMI observations is on average 9.22 ± 3.45%. Our estimate of 9.7 ± 1.3% is very close to the systematic difference reported by Sha et al., 2021, however based on our sensitivity study biases may exist based on sampling conditions in a spatially and temporally heterogenous source. We included this information in lines: 318-322.

12) Line 332 (Figure 4): Can figure 4 be added to figure 2 as a panel? Could be helpful to see all the timeseries together and would reduce the number of figures needed.

Response: We have added Figure 4 as panel e in Figure 2.

13) Line 339: "McMillan et al. (2008) found values…" should the word "values" be replaced with "slopes"

Response: The word "values" were replaced with "slopes."

14) Line 340: "… 40 to 74…" should units be provided for this?

Response: Units ppb X_{CO}/AOD were added to the slopes.

15) Lines 339-343: I find the discussion in these sentences a bit confusing and could be organized a bit more clearly. For example, are the values from McMillan et al of 44-74 the same as the values that are for clean region described further down the paragraph?

Response: Thank you for the comment. The discussion in this section was rewritten (lines 271-288) for clarity and a table of summary statistics (Table 1) was added to provide more detail.

16) Line 348 (Figure 5 caption): There is no "teal line" on the figure – does this mean the "teal markers"?

Response: We changed "teal line" to "teal markers."

17) Line 356: "… a steady MCE as X_CO, X_CH4, and AOD increased, indicating influence of smoldering combustion" Please elaborate – why does this indicate smoldering?

Response: Figure 5, panel a-e was removed as suggested below by reviewer, thus this sentence was removed as it was referring to the timeseries in panels a-e.

18) Lines 365-371: The discussion on EFs should be merged with the discussion on lines 458-464. I also find parts of the discussion a bit hard to follow. Which studies were included in the table and why? Which values are most relevant for comparison against the present study? How does Lueker et al., 2001 compare to the results in this study?

Response: Lines 365-371 were merged with lines 458-464.

The discussion was rewritten to clarify the main points. We also included context as to why the studies were chosen to be included in Table 2 and their relevancy for comparison against this study. Our results were consistent with CH_4 emissions found in Lueker et al., 2001 (line 446).

19) Line 372 (Table 1 caption): Should mention the present study in the caption, e.g., "Summary of past airborne studies, and the present study…"

Response: Added.

20) Line 381 (Figure 6): Do panels a-e add value to the paper? Is the same/similar information captured in the broader timeseries in Fig 2?

Response: We have removed panels a-e. The data shown on panels a-e is the same as in Fig.2 and does not add value to the paper.

21) Line 388 (Figure 7): If including this figure in the paper, should describe its relevance in the text.

Response: We have described the relevance of Figure 7 (now Figure 6) in the text in lines 332-336.

22) Line 389 (Sect. 3.5 title): This section title is vague. Perhaps split Sect. 3.5 into two sections (one section about ratios for livestock vs wildfire emissions and another section about estimating total methane emissions from wildfires in California?)

Response: Section 3.5 was split into two sections: "Enhancement ratios of livestock and wildfire emissions" and "Total methane emissions from wildfires in California."

23) Lines 401-411: I found the discussion of the different ratios difficult to follow, and could use a rewrite for clarity. For example on line 407, "Similar ratios… were found in Hanford…" – I assume this means ratios similar to the non-wildfire ratios?

Response: This was paragraph rewritten and shorten for clarity (lines 376-389).

24) Line 414-415: "… dairy farm operations are the dominant source of CH4 during fire and non-fire periods." This seems to contradict the next sentence, which says that during the strong smoke influence period, CH4 from the smoke is dominant. Clarify.

Response: Thank you for the suggestion. We clarified these statements by specifying that they compare between fire and non-fire days.

25) Line 416: “The immense scale…” recommend starting a new section (or at least a new paragraph) here. Lines 430-435 and 635-640: Please provide a bit more information about how Table E1 was filled in. Why is the ER from the study in table E1 (0.0084) different from the ER given in line 362 (0.0073)? How were the ERs derived from the EFs in the literature? How were uncertainties propagated? Which values in Table E1 correspond to Pritchard and which correspond to Xu? Were there any cases where both Xu and Pritchard had different ER values for the same vegetation, and if so how did you choose which to use? (Also, check that everything is consistent between the text and the appendix: Line 434 references Xu 2020, but line 634 table caption references Prichard 2020 and Xu 2022).

Response: A new section was started after “The immense scale.”

We agree that the wording in the preprint manuscript was confusing for how Table E1 was filled out. For non-Sierra Nevada wildfires, literature values were used for three different vegetation types. The literature EF values for general vegetation types were obtained from mean values in Xu et al., 2022 that were based on EF’s found in Prichard et al., 2020. We calculated the standard deviation for the mean EF values from the Prichard et al., 2020 and propagated this as the error into the calculated ER values. We have clarified this in the main text and in the appendix.

In our approach to calculate an ER for the Sierra Nevada wildfires, we took an average of the EF from Sierra Nevada studies in Table 1 (EF_{CH4_avg} = 5.6 ± 1.5 g kg^{-1}). From the EF_{CH4_avg} we derived an ER_{CH4_avg} = 0.0084 ± 0.0022 that was calculated from Equation 2 by solving for ER with C_T equal to 1. The ER_{SQF} that we calculated from Sept 12 plume (0.0073) was part of the averaged ER was not used directly as part of Table E1 calculations, rather it was included in the ER_{CH4_avg}. We believe using ER_{CH4_avg} would better represent temperate vegetation wildfires in the Sierra Nevada. We have added those values to the paragraph to clarify our process for calculations in lines 418-419.

Thank you for catching that mistake, line 434 (now line 415) should have been Xu et al., 2022.

26) Lines 454-457: Repetitive – delete summary of the work and save this for the conclusion/abstract?

Response: The summary of work was removed from the discussion.

27) Lines 471-487: This discussion feels a biased toward FTIR measurements. What are the drawbacks to FTIR measurements compared to the other methods? Is there information that can be provided by aircraft that can’t be provided by FTIR? Do all of these methods have similar uncertainties in, e.g., emission factors? Are the FTIRs more difficult to operate than say continuous ground-based in-situ analyzers? Is there potential for satellite (especially the next generation of satellites), modelling, or other methods to add to knowledge on fire emission factors as well?

Response: Thank you for this comment. We have rewritten this paragraph to include drawbacks of this measurement technique in lines 455-477:

"While advantages of this technique allow for understanding regional scale emissions, limitations exist with this method. The EM27/SUN solar column observations are limited to daytime hours as the instrument requires the sun as the light source. For this reason, we were not able to capture nighttime observations despite the continued release of smoke emissions and growing concern of increasing nighttime wildfire activity in the continental United States (Freeborn et al., 2022). Additionally, optically thick smoke plumes obstruct the sunlight and prohibits continued measurements when the solar disk is not traceable by the instrument's solar tracker. Exposing the instrument's mirrors to harsh conditions such as ash depositing to ground observations on Sept. 12 decreases the instrument signal and may decrease the lifetime of mirrors. Although total column measurements are sensitive to larger scales than in situ stations, the FTIR is limited to the line of sight of the instrument and on occasions can miss the plume like we did on Sept. 13 and 14. Whereas aircraft observations have extensive spatial reach and more flexibility in locating and sampling plumes to obtain spatially rich information of the plume. However, when used in tandem with satellite observations our instrument collects continued temporal observations of a site of interest that a satellite does not, thus synchronous observations provide a better spatiotemporal understanding of the emission source. EM27/SUN instruments are also costly which can limit the number of instruments deployed. Unless instruments are secured properly as they have been done in long term network studies (Frey et al., 2019; Dietrich et al., 2021), measurements require personnel to set up and operate the instrument daily. The EFs, MCE, and their uncertainties fall within the range of expected values, thus lends confidence that this technique can be used for studying combustion phases of wildfires for other vegetation types. Despite the limitations of the EM27/SUN, we demonstrate the ability to gather new information of EF, MCE and AOD for understudied vegetation types and regions. Furthermore, the EM27/SUN observations can be used as a validation tool for orbiting satellites like TROPOMI, Orbiting Carbon Observatory-2 (OCO-2), OCO-3, and future satellites. The next generation weather forecasting, greenhouse gas, and air pollutant satellites such as Tropospheric Emissions: Monitoring of Pollution (TEMPO) will have more temporal frequency and greater spatial resolution allowing for continuous monitoring of burning activity and smoke emissions (Zoogman, 2017). This may allow remote sensing products to provide new insight into fuel properties of many types of vegetation in remote areas. It is will also be important to evaluate satellite-based observations with ground-based stations like the EM27/SUN as we did in this study."

28) Line 491: "with great resolution" – subjective (remove or replace this).

Response: The phrase "with great resolution" was change to "high spatial resolution."

29) Line 520-529: Can more context be provided on the discussion of wildfire emissions of CH4? Are there other estimates of CH4 emissions from wildfires in the California or is a data gap? When discussing possible climate feedbacks, is it expected that a lot of CH4 is emitted from fires globally? Are CH4 emissions from fires considered, for example, in IPCC reports?

Response: Thank you for this comment. We have added more context of CH_4 wildfire emissions, discussed data gaps, global CH_4 emissions and global inventories including the IPCC report in lines 511 – 527.

Technical Corrections

1) Line 490: “12. Smoke event” (delete the period after 12)

Thank you for catching that. The period was deleted.