Authors’ Response to Peer Review Comments on Original Version of Manuscript (2020AV000350)

We thank the reviewers for their thoughtful comments, which we have addressed below. All page and line numbers refer to those in the revised manuscript. Reviewer comments are in italics, our response is in plain text, and text in the revised manuscript is in blue.

Response to Comments from Mike Kuperberg

We thank Mike Kuperberg for the helpful comments and deeply appreciate his support for the analysis. We address his comments below.

1. Line 18. The authors should clarify that parts of this analysis address coal and gas-fired power plants (the U.S. analyses) while others are restricted to coal-fired power plants (the international analyses). (see, for example, lines 24 & 27 that suggests all were coal-fired). Further, there is a confusing mix of coal-fired, gas-fired, and unspecified “power plants” throughout the text.
We thank the reviewer for this comment. We now explicitly state throughout the text whether we are referring to gas and coal fired or just coal-fired power plants to avoid confusion.

2. Lines 23 & 209. The reference to “supply chains” seems like an overreach for this study. The authors provide one example of connected coal mine/power plant – and that is a nice example. However, it is a stretch to make statements about the applicability to entire supply chains based on one limited example.

We soften the language in the text to clarify these methods alone cannot quantify emission across entire supply chains.

Line 22. “we present a strategy to exploit joint CO2 and CH4 plume imaging to quantify carbon emissions across widely distributed industrial infrastructure, including facilities that co-emit CO2 and CH4.”

Line 223. “The joint CO2 and CH4 sensitivity of imaging spectrometers allows us to quantify carbon emissions across widely distributed infrastructure, including facilities with related co-emissions, opening the potential to do fuller carbon accounting of energy supply and industrial processes”

3. Line 57. Would like to see citations for the two conclusions in this sentence.

We add the following references to Lines 58 and 59:


4. Line 69. The comparability of the two U.S. approaches seems to be remarkably close which seems odd when the authors characterize reporting as faulty or divergent.

We rephrase in the text.

Line 65. Gurney et al. (2016) found that although generally EIA and EPA CO2 estimates agree within 6%, one-fifth of facilities disagree by more than 13%. For additional validation or to reconcile divergent emission estimates, we show in this
study the possibility of leveraging remote sensing to monitor emissions from strong CO2 point sources

5. Line 97. Assume the authors mean “power plants”? This seems to be the first description referring to both coal and gas-fired power plants.

We fix the typo in the text to be “power plants”

6. Line 116. Does this mean that the EPA/EIA estimates are much closer to each other than to the remotely sensed values?

On average, yes. Refer to comment #4, where we rephrase the EIA/EPA comparison. In places with good reporting, our intent for remote sensing is to add an additional dataset that can be used for validation, reconciliation of a handful of discrepancies, or (important for global accounting) provide a reliable CO2 estimate.

7. Line 117. Should clarify that Fig 1a uses GAO

We clarify in the text.

Line 124. Figure 1a shows the plume imaged by GAO on July 31, 2020, and we estimate a $1430 \pm 360$ t h$^{-1}$ emission rate, which is 14% higher, but within the uncertainty of the simultaneously reported 1250 t h$^{-1}$ emission rate from the CEMS database.

8. Line 117-123. This section is hard to follow. Is the PRISMA/GAO discrepancy from the same time or are the authors comparing observations from two different months. Is the “simultaneous CEMS” measurement from June or July? Four Corners Power Plant shows dates, but not values, while Intermountain Power Plant shows both dates and values.

We clarify in the text, making sure dates and emissions from both remote sensing and CEMS are explicit.

Line 122. Figure 1a and 1b show CO2 plumes imaged one month apart with GAO and PRISMA at the Hunter Power Plant in Utah. Figure 1a shows the plume imaged by GAO on July 31, 2020, and we estimate a $1430 \pm 360$ t h$^{-1}$ emission rate, which is 14% higher, but within the uncertainty of the simultaneously reported 1250 t h$^{-1}$ emission rate from the CEMS database.
Line 133. All three emission estimates show close correspondence with CEMS reporting (CEMS: 1100 – 1370 t h$^{-1}$; remote-sensing: 1080 – 1380 t h$^{-1}$; Table S1) and neither emission estimates varies significantly between overpasses. Intermountain Power Plant was imaged by GAO on July 31st, 2020 (Figure S4b; 560 ± 140 t h$^{-1}$) and PRISMA on August 1st, 2020 (Figure S5d; 1480 ± 302 t h$^{-1}$). Though acquisitions were spaced only one day apart, their retrieved emission rates differ by nearly 1000 t h$^{-1}$, but a similar magnitude increase in emissions was also reported in the CEMS database (July 31: 591 t h$^{-1}$; August 1st: 1110 t h$^{-1}$; Table S1).

9. **Line 138-139.** With the small sets of observations available it seems unjustified to blame the discrepancies on faulty CEMS data.

   We rephrase in the text.

Line 144. Since most of the other observed examples fall close to the one-to-one line with CEMS reporting (Figure 1a), this discrepancy could be explained by scene-specific systematic bias in the GAO/PRISMA emission retrieval or issues with CEMS reporting. Follow-up observations ideally by another measuring system could help resolve the discrepancy.

10. **Line 162.** “between” should be “among”

    Fixed.

11. **Line 164.** Having shown that the U.S. does “reliable reporting information”, the authors should be clear that they are targeting non-U.S. countries.

    We add this important point to the text.

Line 171. The close correspondence between remotely-sensed CO2 emissions and in-situ CEMS data in the U.S. gives confidence in our approach. Therefore, for other global regions where little reliable reporting information or CEMS data exist, a top-down remote sensing approach can be used to infer emissions.

12. **Line 174.** This section seems to be limited to only coal-fired plants. Is the GEM data limited to coal-fired power plants? Should line 173 say coal-fired power plants?

    We update to state “coal-fired power plant”
13. Line 180. Is the Hunter Power Plant known to be the lowest emitter that can be quantified by PRISMA or was it the lowest-emitting power plant that was analyzed? I.e., is it possible that lower emissions rates could be measured by PRISMA?

This is an excellent point. This is the lowest detected emission, not necessarily a detection limit for PRISMA. We clarify in the text.

Line 195. PRISMA may have an even lower detection limit than 640 ± 130 t h⁻¹, meaning more than 60% of CO2 emissions from coal-fired power plants could be monitored from space. However, routine targeting of additional power plants with lower anticipated CO2 emissions is needed to empirically estimate this detection limit.

14. Line 186 & 190. These sentences should refer to Figure 4.

Thank you. Fixed.

15. Line 223. The authors probably mean “thank”

We are not sure which specific word the reviewer is referring to, but we reread this section to check for typos.

16. Line 390. The fuel types for these two U.S. power plants are not specified in the figure, while the international power plants in the next three figures are specified.

We now specify fuel.

Line 419. The top row shows a comparison between retrieved CO2 plumes from the airborne GAO (A) instrument and the PRISMA satellite (B) at the coal-fired Hunter Power Plant in Utah, overlaid on a Google Earth image.

17. Line 401. Should “exist” be plural?

Yes. It is now fixed.

Response to Comments from Reviewer 2

1. Could you explain how the facilities are included? How did you chose them? i.e. the criteria and whether/how they/the local stakeholders were/are included before and after the study?
We thank the reviewer for this and subsequent comments, and we clarify in the text.

Line 96. Airborne overpasses represent acquisitions from various AVIRIS-NG and GAO deployments. Some sites are located in vicinity of major oil & gas infrastructure, and were acquired in conjunction with CH4 mapping campaigns (e.g., California Methane Survey (Duren et al., 2019)). Other airborne sites were acquired opportunistically as the aircraft transited between deployments. PRISMA was specifically targeted for U.S. sites where there was possibility of joint overpass with AVIRIS-NG/GAO, or for non-U.S. sites where emissions were anticipated to be large according to bottom-up inventories (GEM, 2020).

2. End of page 9 'The joint CO2 and CH4 sensitivity of imaging spectrometers allows us to quantify supply chain GHG emissions, opening the potential to do fuller carbon accounting of energy supply and industrial processes. Ultimately, for carbon mitigation measures to be effective and validated, robust understanding of actual measured CO2 emissions from these facilities is required. This is possible through coordination of current and future airborne and satellite remote sensing missions.'

-- Please list all pertinent current/future airborne and satellite missions
-- Do current supply chain carbon/GHG emissions accounting utilize imaging spectrometer data? How could this data be embedded in the supply chain accounting in the future? Provide example please, even if it's hypothetical or a concept model.

We direct the reviewer to Line 164 for a treatment of future satellites, and include an additional reference – Carbon Mapper:

Line 165. Soon to launch spaceborne imaging spectrometers will have similar or improved spectral resolution and signal-to-noise as PRISMA, and include EnMAP, EMIT, Carbon Mapper, SBG, and CHIME (Guanter et al., 2015; Green et al., 2020; Duren et al., 2020; Cawse-Nicholson et al., 2021; Nieke and Rast, 2018).

See response to comment #2 from Mike Kuperberg. We soften “supply-chain” language and state that this can be used to quantify infrastructure with co-emissions of CO2/CH4.

3. Comment on Abstract: 'Reporting programs, such as the IPCC National Greenhouse Gas Inventories, have latencies of 12-24 months and may not keep pace with rapidly changing infrastructure, particularly in the developing world.'

-- remove 'IPCC'. Could just state 'National Greenhouse Gas Inventories'

We update the language in the text to read National Greenhouse Gas Inventories.
Response to Comments from Reviewer 3

1. Line 64 statement “possible data manipulation” is uncalled for. So discrepancies in China between CEMS and satellite estimates could be a possible data manipulation but mismatch in US between the same uses (e.g. Fig. 1, last two data points) is not? It seems to me there is no benefit to your case by speculating without evidence. Whether it was manipulated or not and in which country, it does not diminish the need for remote sensing-based estimation.

   We thank the reviewer for this important point, and helping us solidify our reasoning. We remove the sentence stating possible data manipulation, even though those were the conclusions of Karplus et al. (2018) and not our own speculation.

2. I also do not understand the need for devoting significant space (e.g. lines 169-183) discussing differences between Annex I and non-Annex I countries. Is it because the developing countries do not use CEMS? The authors are not proposing to use the system to monitor only these countries, so what is the point of focusing so much on the difference? The world has moved on from Kyoto, justifying for the new remote sensing system in context of an old arrangement could lead to future detection and monitoring biases. Why not just focusing on proposing a consistent and complete coverage no matter where the facilities are located?

   We clarify in the text how this data can be useful to both Annex I and non-Annex I countries, as the reviewer suggests.

   Line 172. Therefore, remote-sensing can be used for additional validation, or to help resolve the few discrepancies that may continue to exist between bottom-up inventories (e.g., Gurney et al., 2016)

   Line 181. … which are not bound by the same emission reporting protocols developed by the UNFCCC and may not have CEMS implemented.

   We agree with the reviewer that our emphasis is for a unified framework, so we highlight this point into the text.

   Line 193. we could use potentially use satellites as a consistent observation framework to account for 60% of global coal fired power plant emissions.
3. **Authors confused figures 2, 3, and 4 in text.**

   We have gone over the figure numbering and corrected all errors.

4. **It would be good to add discussion for using the remote sensing technologies in GHG monitoring and global GHG accounting and understanding of uncertainties due to either of the two systems. Where are sources of uncertainty in remote sensing estimates?**

   We treat uncertainty explicitly in the SI, but we add language in the main manuscript as a brief description.

   **Line 113.** Total uncertainty for each remotely-sensed emission rate is caused by a combination of retrieval, background, and wind speed uncertainty. These details as well as details on the algorithm used for CO2 retrieval, facilities imaged, emission rate derivation, and CEMS reported hourly emissions are provided in the Supporting Information.

5. **25: The sentence “Satellites allow …” could be revised for clarity, such as “Satellite spectrometers could track high emitting coal-based power plants in the world that collectively contribute to 60% or more of CO2 emissions globally”**

   We thank the reviewer for this much clearer sentence suggestion. We add to the text.

   **Line 26.** Satellite spectrometers could track high emitting coal-fired power plants that collectively contribute to 60% or more of global CO2 emissions.

6. **49: Delete one of “such as the”**.

   We have fixed the typo.

7. **49: IPCC is not a reporting program but provides guidance to it. Please revise.**

   We change the language to reflect this point.

   **Line 50.** Global Inventories, such as the National Greenhouse Gas Inventories (IPCC, 2019),…
8. 57: “Point sources are a driving factor in these discrepancies, ...” – You showed that point sources are the largest GHG emissions, but that is different from being the major factor in discrepancies. It would be good to show this point by citing a reference or two.

See response to comment #3 from Mike Kuperberg.

9. 79: Delete “pixel”.

We have deleted this from the text.

10. 91: What does “operator intervention” mean here?

Operators used our data to guide mitigation action. We clarify in the text.

Line 87. …has led operators to use this information to help guide emission mitigation

11. 106: How could a pixel contain CO2 concentration?

Satellite and airborne retrievals of trace gases have spatial resolution intrinsic to the instrument (i.e., a grid box or pixel). We clarify in the text.

Line 109. Increased CO2 concentration within a pixel’s spatial resolution produces stronger absorption

12. 117: Explain that Fig 1a is derived from GAO here? Also it would be useful to add date as part of title for both 1a and 1b.

We now clarify in the text (see response to comment #7 by Mike Kuperberg)

13. 132: Report CEMS magnitude of increase in the sentence please.

We include this in the text.

Line 136. Though acquisitions were spaced only one day apart, their retrieved emission rates differ by nearly 1000 t h⁻¹, but a similar magnitude increase in emissions was also reported in the CEMS database (July 31: 591 t h⁻¹; August 1st: 1110 t h⁻¹; Table S1).
14. 136: “... airborne and satellite observations are consistent with one another,” – So far you have not shown the remote sensing platforms are consistent with each other, you have shown, largely, they are individually consistent with CEMS.

We clarify that we are speaking specifically about Bridger here.

Line 142. Though emissions between airborne and satellite observations are consistent with one another at Bridger, they differ considerably from reported CEMS emissions by 750 - 900 t h$^{-1}$.

15. 140: Figure 1c not 1a.

Thank you for this catch. We update the manuscript.

16. 147: The equation should be referenced, perhaps to a sampling book?

This equation came directly from Hill and Nassar (2019), so we include the citation again after the equations on Line 153.

17. 168: Caption of Fig 2 only mentions the two Indian power plants.

We update the figure caption

Line 427. CO2 plumes imaged and quantified at two coal-fired power plants in India (panel A: Udupi; panel B: Maithon Power) using AVIRIS-NG. CO2 plumes were imaged and quantified at the Belchatow Power Station in Poland (panel C) and the Hadong Power Station in South Korea (panel D) using PRISMA.

18. 173: IPCC is mentioned earlier.

We remove the earlier mention of IPCC, so spell it out explicitly here.

19. 175: Fig 4 should be Fig 3. Recommend adding the bold phrase in the end of the sentence to make the statement clearer to read: “…as well as the percent contribution to the global total coal CO2 emission by emission levels (GEM, 2020).”

We thank the reviewer for the catch and make the change. We also follow the reviewer’s suggestion and update the sentence.
Line 187. Figure 3 shows the cumulative distribution of estimated annual estimated CO2 emissions for global coal fired power plants as well as the percent contribution to the global total coal CO2 by emission levels

20. 179: “smallest” ➔ “lowest”?

We make this change in the text.

21. 182: Delete the first “use”

We make this change in the text.

22. 186: Figure 2 ➔ Figure 4

We make this change in the text.

23. 190: Figure 2 ➔ Figure 4

We make this change in the text.

24. 203: It should be noted that the 21% value is an average, the range of differences can be as high as 40-50% judging from Figure 1. I would recommend that both the mean and range values be given, and discussion provided on uncertainties as well as opportunities to improve using the two systems.

We include the range in the text.

Line 121. On average, remotely sensed emissions estimates were within 21% of reported CEMS emissions (range -40–65%; Table S1)

25. 208: “fossil” ➔ “fossil fuel”

We make this change in the text.

26. 211: The word “actual” is not needed. Measured is actual.

We remove “actual” from the text.

27. 212: “This is possible ...” Does this statement suggest that the proposed airborne and satellite missions are equivalent to “actual measured CO2 emissions from these
facilities”? Measurements are done in situ whereas remote sensing provides observations and estimates. Let’s not mix the two concepts.

We believe there is nuance here between the definition of “measured,” “actual,” “remotely-sensed” and “observed.” Even in situ systems have measurement and calibration error, so are not perfect systems for “true” or “actual” emission representation. We remove “measured” and “actual” from the last sentences starting on Line 226 to emphasize we are speaking directly about remote sensing.

28. 400: Add caption for 2C and 2D.

This has been added to the text. See response to comment #17.

29. 410: Should “for” be “from”? “... a certain threshold or greater” is a confusing phrase. If it is of greater value, shouldn’t the red dotted line be a flat line?

We clarify in the caption

Line 438. Red dots represent the cumulative contribution to global coal CO2 emissions from facilities of a certain threshold or greater

30. 417: Should it be “carbon and greenhouse gas”? Or just “greenhouse gas”?

Otherwise, carbon greenhouse gas does not make sense.

We clarify in the text.

Line 446. CO2 and CH4 accounting at the San Juan mine and coal-fired power plant.