Reply to comments on "Toward a versatile spaceborne architecture for immediate monitoring of the global methane pledge" by Yuchen Wang et al.

Reply to Reviewer #1:

The authors have updated their manuscript with suggestions from two reviewers and a reader, and the manuscript is somewhat improved. I believe it could make a useful contribution to the field of monitoring CH_4 from space. But there are still sections that are unclear and many awkward wordings. Below I have listed locations that need some clarification, along with multiple minor corrections.

Response: Thank you for your valuable feedback on our manuscript. Accordingly, we have addressed all of the comments provided by the reviewer, particularly revising the sections requiring clarification and the awkward phrasings meticulously. We are confident that these modifications have enhanced the manuscript's clarity and contribution to the field of monitoring CH_4 from space. Thank you again for your time and expertise in providing us with this constructive feedback.

Questions:

Lines 176-178: what does "subtracting the current signal from the data" mean? Which "recent enhancement estimates"?

Response: Thanks. We have revised these sentences to clarify these statements (i.e., "the current signal from the data" and "recent enhancement estimates").

The $\vec{\mu}$ and $\mathbf{\Sigma}$ represent the mean value and covariance of the background radiance, respectively. To avoid any contamination of the target spectrum into these background parameters, we estimate them with an iterative approach by removing all gas enhancement signals. More technical details are reported in previous studies (Foote et al., 2020).

Added/rewritten part in Sect. 2.2: The $\vec{\mu}$ and $\mathbf{\Sigma}$ represent the mean value and covariance of the background radiance, respectively. To avoid any contamination of the target spectrum into these background parameters, we estimate them with an iterative approach by removing all gas enhancement signals. More technical details are reported in previous studies (Foote et al., 2020).

Line 190: Is $\mathbf{\Delta XCH_4}$ multiplied by $\boldsymbol{f}$?

Response: Yes, $\boldsymbol{\Delta XCH_4}$ is multiplied by $\boldsymbol{f}$. We have revised this sentence to clarify this issue. $\boldsymbol{\Delta XCH_4}$ is then scaled by this pixel-specific scalar ($\boldsymbol{f}$) and thus normalized by the albedo term, similar to the per-pixel normalization in previous hyperspectral analysis (Kraut et al., 2005).

Added/rewritten part in Sect. 2.2: $\boldsymbol{\Delta XCH_4}$ is then scaled by this pixel-specific scalar ($\boldsymbol{f}$) and thus normalized by the albedo term, similar to the per-pixel normalization in previous hyperspectral analysis (Kraut et al., 2005).

Line 224: Why are the polygons around the plumes masked out? Please clarify.

Response: Apologies for this confusion that may have been caused by the unintentionally misleading information provided. We have revised this sentence in which the word "out" is redundant.

Added/rewritten part in Sect. 2.2: Finally, we manually draw polygons to mask such resulting plumes.

Please summarize the main results of the uncertainty analysis presented in supplement and refer to values shown in Table S1 whenever citing your emission estimates. I assume these uncertainties are used in Figures 3 and 4; please state this clearly.

Response: Thanks. We have supplemented the main results of the uncertainty analysis here, in which appropriate references are made to Supplementary Information. As demonstrated in Supplementary Information, our comprehensive uncertainty analysis establishes the robustness of our estimates, with uncertainties being entirely controllable within a range of -70% (Table S1). Such uncertainties are also used and shown in Figs. 1 ~ 4.

Added/rewritten part in Sect. 2.4: As demonstrated in the Supplementary Information, our comprehensive uncertainty analysis establishes the robustness of our estimates, with uncertainties being entirely controllable within a range of -70% (Table S1). Such uncertainties are shown in Figs. 1 ~ 4.

Lines 301 and 348: Are the Yanquan emissions 30000 kg/h or 7000 kg/h?

Response: Thanks**.** The emission rate of 30000 kg/h was detected from the hotspot (i.e., the Yangquan field) via the TROPOMI-based monitoring, while the emission rate of 7,000 kg/h was detected from the plume (i.e., a specific coal mine in the Yangquan field) via the PRISMA-based monitoring. We have thus revised the associated sentences to clarify the statements.

Added/rewritten part in Sect. 3.1: Besides the well-known oil fields (Figs. 1c ~ 1f), methane hotspots have also emerged in developing coal mine fields such as the Yangquan field, which exhibit comparable emission levels (> 30000 kg/h) (Fig. 1g).

Added/rewritten part in Sect. 3.2: Fourth, a distinct methane plume appears in a coal mine in a mountainous area (in the Yangquan field, China), exceeding all of the detected O&G super-emitters regarding the emission rate (> 7000 kg/h) (Fig. 1g1).

Line 311: In line 281 the detection limit for PRISMA is estimated at 800 kg/h. Yet in line 311 the detection threshold is 300 kg/h. Please clarify.

Response: Apologies for this confusion. We have corrected this inconsistence.

Added/rewritten part in Sect. 3.1: Such precise distinctions benefit from the high resolution of the second-tiered monitoring, despite being limited by the relatively higher detection threshold (~ 800 kg/h).

Line 315: The authors state “the overpass timing of TROPOMI can be nearly concordant with that of PRISMA.” Ten days does not sound like good co-location. Please justify why ten days is a good enough co-location criteria.

Response: We agree with the reviewer that there are no hard co-location criteria by far. We have thus deleted this statements and revised the preceding sentence to clarify this issue. For a given set (including both a methane-abundant region and associated super-emitters), the overpass timing of TROPOMI can be nearly concordant with that of PRISMA in some cases.

Added/rewritten part in Sect. 3.1: For a given set (including both a methane-abundant region and associated super-emitters), the overpass timing of TROPOMI can be nearly concordant with that of PRISMA in some cases.

Line 337: The authors state: “To this end, we apply a multi-spectral retrieval algorithm to eliminate this effect to a large extent. The detailed illustrations are shown in Supplementary Information (Fig. S5).” Please provide a sentence or two on the algorithm used.

Response: Thanks. We have supplemented a brief description for this algorithm. To this end, we apply a multi-spectral retrieval algorithm to eliminate this effect to a large extent. We utilize two spectral bands to launch the matched-filtered algorithm separately: one that is highly sensitive to methane absorption (i.e., 2300 nm) and another that is much less sensitive (i.e., 1700 nm) but exhibit similar surface and aerosol reflectance properties. Figure S5 shows that the 2300 nm-driven matched-filtered algorithm result in noticeable methane vestiges above the storage tanks, while the 1700 nm-driven algorithm does not.

Added/rewritten part in Sect. 3.2: To this end, we apply a multi-spectral retrieval algorithm to eliminate this effect to a large extent. We utilize two spectral bands to launch the matched-filtered algorithm separately: one that is highly sensitive to methane absorption (i.e., 2300 nm) and another that is much less sensitive (i.e., 1700 nm) but exhibit similar surface and aerosol reflectance properties. Figure S5 shows that the 2300 nm-driven matched-filtered algorithm result in noticeable methane vestiges above the storage tanks, while the 1700 nm-driven algorithm does not.

Line 401: Please explain what is meant by “spatial proxies”

Response: Thanks. We have supplemented a brief description for “spatial proxies”. To establish bottom-up methane emission inventories, we need to allocate area sources to regular grids based on spatial information, like nighttime lights (so-called spatial proxies).

Added/rewritten part in Sect. 3.3: To establish bottom-up methane emission inventories, we need to allocate area sources to regular grids based on spatial information, like nighttime lights (so-called spatial proxies) (Geng et al., 2017).

Line 405: A compromise between what? Maybe the authors mean a combination of inventory data and downwind measurements?

Response: Thanks. We have revised this sentence to clarify this statement. Generally, because of technical difficulties or safety risks, we have to compromise to measure such abnormal emissions downwind rather than on sites.

Added/rewritten part in Sect. 3.3: Generally, because of technical difficulties or safety risks, we have to compromise to measure such abnormal emissions downwind rather than on sites.

Line 409: Are the authors stating that the Rumaila and Hassi Messaud EDGAR emissions are biased low with respect to the results in this paper? Please make this clearer. Please explain why the factors in this paragraph would apply only to these two locations.

Response: Yes. The emissions of the super-emitters in the Rumaila and Hassi Messaud fields in the EDGARv6.0 are still less than our results (Fig. 1b2, and Fig. 1e3, and Fig. 4), and such factors might also apply to other sources. Thus, we have revised these sentences to clarify these statements.

Added/rewritten part in Sect. 3.3: Third, the above divergence between our plant-based estimates and the EDGARv6.0 might also be explained by other causes such as outdated emission factors.

Line 485: Does the shading in the violin plots represent the uncertainty In each plume estimate? Or something else? Please clarify.

Response: Thanks. The shading represents the number distribution of the methane plumes with different emission rates. We have supplemented a brief description to clarify this issue.

Added/rewritten part in Fig. 4: The shading represents the number distribution of the methane plumes with different emission rates.

Minor editing suggestions:

Response: We are very grateful to the reviewer for such meticulous editing suggestions. We have adopted all the suggestions.

Replace multi-tiered with two-tiered wherever the current work is discussed.

Response: Thanks. We have replaced the “multi-tiered” with “two-tiered” in the full manuscript.

Line 34: within “the” narrow window…

Response: Thanks. We have completed the revision accordingly.

Line 35: We focused on several regions (United States, China, the Middle East, and North Africa,) and …

Response: Thanks. We have completed the revision accordingly.

Line 36: and uncovered …

Response: Thanks. We have completed the revision accordingly.

Line 40: and thus is sufficiently versatile for ….

Response: Thanks. We have completed the revision accordingly.

Line 46: within the narrow window….

Response: Thanks. We have completed the revision accordingly.

Line 49: it has been rising since 2007, with a surge in 2014 and a record high in 2021 (insert references I omitted)

Response: Thanks. We have completed the revision accordingly.

Line 53: policymakers

Response: Thanks. We have completed the revision accordingly.

Line 54: on the eve of the Paris target, large uncertainties in emissions remain, and thus hinder …

Response: Thanks. We have completed the revision accordingly.

Line 60: for example, field campaigns report nearly double official claims of methane emissions in the United States by detecting missing leaks.

Response: Thanks. We have completed the revision accordingly.

Line 65: defined as emission sources that

Response: Thanks. We have completed the revision accordingly.

Line 68: with dimensions varying from …

Response: Thanks. We have completed the revision accordingly.

Line 72: In contrast to area sources (e.g., cities), super-emitters are typically coal mines, wells, gathering stations, storage tanks, pipelines, and flares, with diameters on the order of dozens of metres or less, but generating plums of highly concentrated methane.

Response: Thanks. We have completed the revision accordingly.

Line 80: spatially limited

Response: Thanks. We have completed the revision accordingly.

Line 81: and miss many super emitters

Response: Thanks. We have completed the revision accordingly.

Line 87: wide swaths and high-resolution sampling have not been simultaneously available

Response: Thanks. We have completed the revision accordingly.

Line 88: Recently global methane monitoring has become possible.

Response: Thanks. We have completed the revision accordingly.

Line 90: It provides daily global methane columns,

Response: Thanks. We have completed the revision accordingly.

Line 91: and a high signal-to-noise ratio

Response: Thanks. We have completed the revision accordingly.

Line 92: Next-generation satellite missions, pioneered by the GHGSat constellation (three satellites at the moment), have emerged

Response: Thanks. We have completed the revision accordingly.

Line 96: great potential

Response: Thanks. We have completed the revision accordingly.

Line 98: Note that the regions these satellites usually observe are already know to contain many super-emitters

Response: Thanks. We have completed the revision accordingly.

Line 101: existing studies still struggle to survey global methane super-emitters due to the fact that individual satellite missions, such as TROPOMI or PRISMA, do not both have a wide swath and high resolution sampling.

Response: Thanks. We have completed the revision accordingly.

Line 103: TROPOMI

Response: Thanks. We have completed the revision accordingly.

Line 106: Using this framework, we focused on China, the United States, Iraq, Kuwait, and Algeria

Response: Thanks. We have completed the revision accordingly.

Line 107: We also monitored a single source to map multiple plumes and to look for possible methane leaks.

Response: Thanks. We have completed the revision accordingly.

Line 109: is not in place, the two-tiered satellite constellation presented in this study has great potential for measuring progress towards global methane pledges

Response: Thanks. We have completed the revision accordingly.

Line 114: due to its large swath (~2600 km)

Response: Thanks. We have completed the revision accordingly.

Line 115: revisit time, moderate footprint …, and excellent sounding precision and accuracy.

Response: Thanks. We have completed the revision accordingly.

Line 116: TROPOMI observes approximately

Response: Thanks. We have completed the revision accordingly.

Line 117: the first consisting of near infrared

Response: Thanks. We have completed the revision accordingly.

Line 127: super-emitters due to their unprecedented resolution

Response: Thanks. We have completed the revision accordingly.

Line 138: Two-tiered methane retrievals

Response: Thanks. We have completed the revision accordingly.

Line 139: we employ the operational TROPOMI methane products.

Response: Thanks. We have completed the revision accordingly.

Line 140: which is retrieved

Response: Thanks. We have completed the revision accordingly.

Line 160: especially for observations from instruments deployed on satellite and aircraft

Response: Thanks. We have completed the revision accordingly.

Line 163: can implicitly account for

Response: Thanks. We have completed the revision accordingly.

Line 168: the physically based method requires background concentrations that are …

Response: Thanks. We have completed the revision accordingly.

Line 173: The calculation process of methane enhancements ($\Delta XCH4$, ppb) is as follows.

Response: Thanks. We have completed the revision accordingly.

Line 179: in PRISMA, enhancements are calculated …

Response: Thanks. We have completed the revision accordingly.

Line 186: with decreasing surface albedo

Response: Thanks. We have completed the revision accordingly.

Line 197: Two-tiered attribution

Response: Thanks. We have completed the revision accordingly.

Line 203: in a versatile spaceborne …

Response: Thanks. We have completed the revision accordingly.

Line 218: progressively decreasing downwind

Response: Thanks. We have completed the revision accordingly.

Line 222: and originate from …

Response: Thanks. We have completed the revision accordingly.

Line 233: in high source regions, such as megacities, there are likely super-emitters that are undetectable following our method.

Response: Thanks. We have completed the revision accordingly.

Line 235: Two-tiered quantification

Response: Thanks. We have completed the revision accordingly.

Line 257: these processes have been described in previous studies

Response: Thanks. We have completed the revision accordingly.

Line 259: the $\boldsymbol{U10}$ term., which typically has a random error on the order of 50%

Response: Thanks. We have completed the revision accordingly.

Line 263: that can monitor global methane pledges

Response: Thanks. We have completed the revision accordingly.

Line 265: originates. We need to account for

Response: Thanks. We have completed the revision accordingly.

Line 278: As the robust relationship between the “minimum source” and the related methane enhancement developed by Jacob et al. (2016) and Guanter et al. (2021) shows, the detection threshold for the TROPOMI instrument is

Response: Thanks. We have completed the revision accordingly.

Line 280: for the PRISMA instrument …

Response: Thanks. We have completed the revision accordingly.

Line 287: shown potential for monitoring natural methane hotspots

Response: Thanks. We have completed the revision accordingly.

Line 307: plumes originate

Response: Thanks. We have completed the revision accordingly.

Line 338: the only explanation

Response: Thanks. We have completed the revision accordingly.

Line 339: This has previously only been seen in …. Therefore, our multi-tiered outcomes indicate there are more widespread methane leaks than have been previously detected. Note that the multi-spectral retrieval algorithm cannot completely remove the albedo effects on our results. However, our methods could lead to targeted on-site re-inspection on O&G fields worldwide.

Response: Thanks. We have completed the revision accordingly.

Line 343: Our framework detects

Response: Thanks. We have completed the revision accordingly.

Line 346: current satellite constellations alone

Response: Thanks. We have completed the revision accordingly.

Line 347: More satellites could capture changes during even shorter time windows.

Response: Thanks. We have completed the revision accordingly.

Line 349: Figure 2 illustrates the extent to which the second-tier of our two-tiered satellite constellation explains the regional budget detected by the first tier.

Response: Thanks. We have completed the revision accordingly.

Line 350: Delete this sentence: The overpass times (in Fig. 1) are usually different between the first and second tier observations.

Response: Thanks. We have completed the revision accordingly.

Line 351. The share of the regional budget due to the plumes ranges from 8.2% (Hassi Messaud) to 53.8 ~ 65.9% (Rumaila, Burgan, and Wattenberg).

Response: Thanks. We have completed the revision accordingly.

Line 354: different overpass time.

Response: Thanks. We have completed the revision accordingly.

Line 361: this reinforces our hypothesis that

Response: Thanks. We have completed the revision accordingly.

Line 363: different spatial scales

Response: Thanks. We have completed the revision accordingly.

Line 366: different overpass times between the two-tiered results

Response: Thanks. We have completed the revision accordingly.

Line 369: A regional survey in a California field provides some useful data for evaluating our results, owing to

Response: Thanks. We have completed the revision accordingly.

Lines 371: The survey was conducted

Response: Thanks. We have completed the revision accordingly.

Line 373: and included five campaigns

Response: Thanks. We have completed the revision accordingly.

Line 375: The survey reports 1181 methane plumes, more than 500 times the number of plumes reported by previous aerial studies.

Response: Thanks. We have completed the revision accordingly.

Line 377: Even though some regions of interest in our study are far less well known than the California fields,

Response: Thanks. We have completed the revision accordingly.

Line 378: the plumes detected by

Response: Thanks. We have completed the revision accordingly.

Line 380: were conducted

Response: Thanks. We have completed the revision accordingly.

Line 380: Satellite observations taken over the Permian basin (one of the top O&G bases worldwide) from 2019 to 2020 (need reference here) provide additional comparison data.

Response: Thanks. We have completed the revision accordingly.

Line 381: took advantage of

Response: Thanks. We have completed the revision accordingly.

Line 383: survey acquired

Response: Thanks. We have completed the revision accordingly.

Line 387: basin reported a much higher number of strong methane super-emitters, whose median emission rates (1850 kg/h) are much closer to

Response: Thanks. We have completed the revision accordingly.

Line 388: although such comparisons are not quantitative due to many differences in measurement characteristics (e.g., spatial resolution and detection limit),

Response: Thanks. We have completed the revision accordingly.

Line 389: they provide context for the emission magnitudes of the methane super-emitters we have identified and indicate that our results are within the range of values obtained from field campaigns.

Response: Thanks. We have completed the revision accordingly.

Line 391: More importantly, these results highlight

Response: Thanks. We have completed the revision accordingly.

Line 392: possibly emit as much methane as the California fields and Permian basin.

Response: Thanks. We have completed the revision accordingly.

Line 393: Comparing emissions from our two-tiered approach with a state of the art methane emission inventory (EDGARv6.0) for 2018, (Fig. 4), we find that our emission estimates using TROPOMI data over methane hotspots are roughly consistent with the inventory, with biases ranging from -49.9% to +91.8% with an average bias of 63.2%. The exception is the Hassi Messaoud field in Algeria where the O&G sector is in rapid development: here our estimate is 498.2% of the EDGARv6.0 inventory.

Response: Thanks. We have completed the revision accordingly.

Line 398: On the other hand, our estimates using PRISMA data over plumes are orders of magnitude greater than the EDGARv6.0 emissions. This suggests that traditional emission inventories may have acceptable performance for methane abundant regions but may grossly underestimate emission from methane super-emitters.

Response: Thanks. We have completed the revision accordingly.

Line 401: There are a number of possible explanations for the low estimates from EDGARv6.0

Response: Thanks. We have completed the revision accordingly.

Line 421: We have presented a two-tiered …

Response: Thanks. We have completed the revision accordingly.

Line 422: We have demonstrated this framework with examples from around the world, with synergistic …

Response: Thanks. We have completed the revision accordingly.

Line 423: We have located new methane super-emitters, tracked potential methane leakages from storage tanks, and resolved multiple methane plumes from a single source.

Response: Thanks. We have completed the revision accordingly.

Line 426: our results suggest inventories miss unknown super-emitters and underestimate emission magnitudes, partly due to a surge in the number of oil and gas (O&G) facilities and widespread abnormalities in O&G operations.

Response: Thanks. We have completed the revision accordingly.

Line 428: Our data prove that existing satellite missions can already lead to immediate …

Response: Thanks. We have completed the revision accordingly.

Line 429: While window for achieving the Paris target is rapidly closing, our approach can provide improved methane emission estimates before the deployment of more advanced instruments, which can also be integrated into our system.

Response: Thanks. We have completed the revision accordingly.

Line 432: Delete sentence starting with “In addition ..”

Response: Thanks. We have completed the revision accordingly.

Line 435: It should be noted that the multi-tiered framework is extremely flexible.

Response: Thanks. We have completed the revision accordingly.

Line 441: based on multiple satellites, aircrafts, and UAVs will provide greater spatial coverages and more frequent revisits

Response: Thanks. We have completed the revision accordingly.

Line 442: This flexibility will provide effective, efficient, and economic monitoring of global methane pledges, though this will require careful balancing of coverage and resolution between instruments.

Response: Thanks. We have completed the revision accordingly.

Line 444: of our next study.

Response: Thanks. We have completed the revision accordingly.

Line 445: LIDAR instruments (e.g., MERLIN (need reference) can retrieve methane fluxes day and night at all latitudes, in all-seasons, and in all-weather.

Response: Thanks. We have completed the revision accordingly.

Line 447: Fourth, better characterizing methane vertical profiles would help to optimize our analysis, by minimizing the uncertainties in tropospheric air mass factors and subsequent methane enhancements.

Response: Thanks. We have completed the revision accordingly.

Line 448: Finally, rapid advances in artificial intelligence (AI) techniques can significantly speed up the detection of faint signals from methane enhancements, and to …

Response: Thanks. We have completed the revision accordingly.

Line 456: Still, large gaps remain in coverage and implementation (?). This is especially true for low- and middle-income countries, where tight budgets dim the hopes for filling these gaps by 2030, while methane emissions are likely to rise as countries continue to develop. In this context, the present framework can serve as a cost-effective component of the global methane monitoring network and thus support fair climate negotiations between countries. This framework harmonizes global scale and high-resolution methane retrievals, with a dual focus on mapping region-scale and plant-level drivers. In this work the framework reconciles the wide swath of TROPOMI (i.e., ~ 2600 km) with the high resolution of PRISMA (i.e., 30x30 m2), in contrast to conventional satellite-based surveys, which suffer from either low resolution or narrow swaths.. Looking forward, developments of Earth's monitoring platforms (e.g., satellites, aircrafts, and unmanned drones) and artificial intelligence will continue to strengthen the performance of methane plume retrievals and emission estimates. On eve of the Paris target, at least while a methane product obtained from an instrument with a wide swath, high resolution, and agile analysis is not in place, our multi-tiered satellite constellation has important implications for measuring global methane pledges.

Response: Thanks. We have completed the revision accordingly.

Line 464: Methane-abundant regions and associated super-emitters as captured by TROPOMI and PRISMA locations are marked by black rectangles and dots. Placenames were obtained from GoogleMaps, and are usually the names of the nearest O&G fields and coal mines. (b ~ g) Each row presents a methane-abundant region and the super-emitters detected within it (b1 ~ b4, c1 ~ c4, d1 ~ d4, e1 ~ e4, f1 ~ f2, and g1 ~ g2). For each super emitter (five-pointed stars), the overpass times of the multi-tiered satellite constellation and the consequent emissions estimate are presented. The base maps were obtained from GoogleMaps. The second color bar for PRISMA images is suitable for the super-emitters in China, while the first applies for other countries. Plume sources in the PRISMA results are marked by red circles.

Response: Thanks. We have completed the revision accordingly.

Line 483: shown in Fig. 1. The 1:1 line is shown by grey dashes.

Response: Thanks. We have completed the revision accordingly.

Line 486: The images of TROPOMI, MethaneSAT, PRISMA, and EnMAP are obtained from http://www.tropomi.eu/, https://www.methanesat.org, https://www.asi.it/en/earthscience/prisma/, and https://www.enmap.org/, respectively. The methane maps from TROPOMI and PRISMA refer to the results in Figs. 1e and 1b1. The grey marks indicate upcoming platforms (i.e., MethaneSAT and EnMAP) and techniques (e.g., AI techniques that can optimize the identification and quantification ofmethane super-emitters)

Response: Thanks. We have completed the revision accordingly.