**Answer to referee comment 1 for "Airborne quantification of Angolan oil and gas methane emissions"**

*We would like to thank the reviewer for the suggestions to improve the manuscript. Below you find our answers to their comments. The reviewer's comments are written in normal font, our answers in italics.*

**General Comments**

This study presents aircraft-based measurements of methane emissions from offshore oil and gas (O&G) operations along the West African coast, using the mass balance approach. The authors demonstrate that bottom-up inventories significantly overestimate emissions, whereas operator-reported values underestimate them. The findings highlight the need for regular airborne and in-situ measurements to improve methane emission quantification and support mitigation efforts. Given Angola's commitment to the Global Methane Pledge, these empirical assessments are critical for guiding policy and regulatory strategies aimed at reducing O&G sector emissions.

Overall, I think this study contributes valuable insights into offshore methane emissions, an underrepresented source in global emission inventories. It underscores the importance of empirical verification and identifies key areas for targeted mitigation strategies. The paper is well-written in general and may be accepted for publication after addressing the following specific comments.

*We thank the reviewer for this positive assessment and will address the specific comments below.*

**Specific Comments**

1. **Abstract:** Could the lower observed methane emissions from the aircraft measurements compared to EDGAR and CAMS inventories be due to possible unmeasured methane sources in the region?
*There should not be any unmeasured sources in the region. We received a complete list of offshore assets from the operators and covered all of them during our flights. We used the gridded inventory data to calculate offshore emissions to avoid any sources onshore. Maybe in some cases the attribution of emissions between onshore and offshore in the inventories is not precise. We believe that to be the case for CAMS-GLOB-ANT emissions, which are much too small in the offshore region.*

2. **Line 36:** Suggest removing "long-lived". The methane lifetime of approximately a decade is relatively short, especially compared to $CO_2$, which persists for centuries. This is also conflicts with the phrase "short lifetime" in Line 39)
*We removed this.*

3. There is some repeated information, e.g., Line 34 and Line 38 about "the second most significant (important) long-lived anthropogenic greenhouse gas". Please make it concise and combine the first 3 lines into the paragraph starting in Line 36.
*We also removed repeated information here.*

4. **Line 43:** The 22% figure is repeated from Line 35. Please consolidate for clarity.
*We deleted the sentence in line 35.*

5. **Figure 1:** The methane enhancements in downwind plumes are on the order of 5 ppb. What are the instrumental precision values, and how do they contribute to the overall uncertainty in the mass balance emissions estimate?

*Measurement uncertainties for each parameter are given in Table A1 in the Appendix. These measurement uncertainties propagate through the mass balance calculation with Gaussian error propagation to form the statistical uncertainty, which ranges from 1.3 to 58.4 kg $h^{-1}$ and contributes 4.3% to the total uncertainty of the fluxes.*

6. **Line 139:** How did the authors ensure that methane plumes from facilities are horizontally and vertically well-mixed from the surface?
*There is no way to ensure this completely. We kept a minimum distance of 5 km to the facilities to allow for sufficient vertical mixing. Also, we tried to cover the plume with as many tracks as possible and the lowest track close to the ocean surface. We analyzed a couple of cases with several transects (see Appendix) and found that emissions calculated from transects in the middle of the PBL generally were within the emissions estimate using all transects. Thus, we also used single-transect cases for flux estimation accounting for the increased uncertainty through the "plume mixing height uncertainty".*

7. **Line 144:** Is a 5–10 km distance from the source sufficient for plumes to be vertically well-mixed? This is a key concern, as later discussions suggest that plumes are likely not well mixed, which could introduce additional uncertainty.
*There is a tradeoff: Sampling further away from the source increases uncertainties related to measuring lower enhancements. Sampling closer to the source introduces uncertainties related to incomplete mixing. The distance at which a plume is well-mixed depends on several factors including atmospheric stability, wind speed, and plume temperature. We acknowledge that not all measurements might have taken place in the best possible distance. We account for the possibility of not well mixed plumes via the "plume mixing height uncertainty". This has been clarified in Section 2.2 and in the appendix.*

8. **Lines 149–150:** The statement "These criteria are most likely to be met in the early afternoon, when the PBLH has reached its maximum" may not be entirely valid, particularly regarding the last criterion: "the trace gas plume is well-mixed between the lowest flight track and the ground."
*Thank you for pointing this out. We agree that the assumption of a well-mixed trace gas plume between the lowest flight track and the ground may not universally hold, even in the early afternoon. While it is true that the planetary boundary layer height (PBLH) typically peaks during this period, we acknowledge that local meteorological conditions (e.g., stratification, coastal effects, or shallow boundary layers over water) can limit the degree of vertical mixing, particularly over the ocean or complex terrain.*
*In our case, we have addressed this limitation by including it in the uncertainty assessment. We will revise the sentence in the manuscript for greater precision. For example, we could modify it to: "These criteria are most likely to be met in the early afternoon, when the PBLH has typically reached its maximum and atmospheric conditions are generally most favorable for vertical mixing. However, local conditions may still limit mixing between the lowest flight altitude and the surface, particularly over water."*

9. **Methane Emission Variability:** while relatively consistent CH4 fluxes were observed for some facilities across different days, flight-to-flight variations — such as the two high-emission events from two facilities — are not explicitly accounted for the uncertainty analysis. This should be addressed.
*We agree that variability between flights, including high-emission events, should be reflected in the uncertainty analysis. When multiple measurements are available for a facility or group, we compute the mean emission $\bar{F}$ and its uncertainty $u_{\bar{F}}$ by combining the uncertainties of*

*individual measurements $u_{F_i}$ with the standard deviation σ of the observed fluxes. The uncertainty is calculated as:*

$$u_{\bar{F}} = \sqrt{\left(\frac{1}{n}\sum_i u_{F_i}\right)^2 + \left(\frac{\sigma}{\sqrt{n}}\right)^2}$$

*This ensures that both measurement uncertainty and day-to-day variability are captured in the reported uncertainties. The description is in the appendix and we added the information to the section.*

10. **L.539-542:** this paragraph seems more appropriate for the Acknowledgement section.
*We rephrased this paragraph to make it sound less like an acknowledgement: "This study was conducted in close coordination with ANPG, MIREMPET, and local oil and gas operators. Results were presented to stakeholders in Luanda, Angola, in October 2022, where facility-specific feedback was provided. In response, operators expressed interest in continued monitoring, and ANPG is considering enhanced reporting requirements and emission reduction mandates for $CH_4$."*

11. **Appendix A:** the authors provided a thorough analysis of mass balance method uncertainties, covering statistical errors, background concentration, and plume height. However, another two key uncertainties should be addressed or at least mentioned: how well the $CH_4$ plume is mixed within the planetary boundary layer (PBL) and day-to-day variability of emissions.
*The uncertainty associated with how well the $CH_4$ plume is mixed within the planetary boundary layer (PBL) is indeed addressed through what we previously referred to as "plume height uncertainty." To better reflect this, we have renamed it "plume mixing height uncertainty" to avoid ambiguity. Regarding day-to-day variability, this is incorporated into the uncertainty of the mean facility emissions by including the standard deviation of individual measurements alongside their respective uncertainties.*

Fig. A1 shows a factor of 5-6 variation in fluxes at different altitudes, suggesting that the plumes were not very well mixed at typical distances of 5- 15 km downwind from the facilities. This is back to my earlier comment that this distance range might not be enough for plumes to be well mixed within the PBL. This is particularly relevant for surveys with fewer transects, as insufficient sampling could lead to larger uncertainty, i.e., less transects will have large uncertainty due to not being well mixed.
*We agree that significant variation in fluxes across different altitudes, as shown in Fig. A1, suggests that plumes are not always fully mixed within the planetary boundary layer (PBL) at distances of 5–15 km downwind. This is particularly relevant for cases with only a few transects, where insufficient sampling may result in larger uncertainties.*
*Our uncertainty estimate—now renamed plume mixing height uncertainty to better reflect this issue—explicitly accounts for incomplete mixing. The number and vertical coverage of transects are key factors: fewer transects or strong vertical gradients lead to increased uncertainty in the flux estimate.*
*Figure A1 illustrates this with an example from a racetrack flight pattern (Fig. 1b), where fluxes from seven transects show a factor of 5–6 variation. The transect at 250 m aligns closely with the average $CH_4$ emission across all transects, with lower transects underestimating and higher ones overestimating the mean. This pattern, while not universal, was commonly observed. From this, we conclude that single-transect mass balances can be*

*considered reliable when conducted near the middle of the PBL. Measurements below 150 m should be treated with caution, while those above the midpoint may lead to overestimation. This altitude-dependent uncertainty is reflected in our reported total flux uncertainties and is one reason why we prioritize flight designs with multiple vertical passes where possible.*

12. **L.620-625:** Fig. B1: the caption and text refer to $CO_2$ emissions, but the figure scale label shows $CH_4$ fluxes. Please ensure consistency.
*We changed the label to $CO_2$ emission.*

13. **Temporal Variability**: The study was conducted over a three-week period, which may not fully capture seasonal variations in emissions.
*We acknowledge that our three-week measurement period cannot fully capture potential seasonal variability in methane emissions. However, by conducting a large number of measurements during this time and comparing operator-reported oil and gas production data from September 2022 with that of 2021, which showed no significant differences (mentioned in Section 3.6), we conclude that our observations are representative of typical operational conditions. Nonetheless, we agree that further sampling over longer timeframes would be valuable to more comprehensively characterize temporal variability.*

14. **Limited Facility Access**: While the study covered a significant number of facilities, more extensive coverage across different offshore production environments could provide a more comprehensive picture.
*During the METHANE-To-Go Africa campaign, we determined methane fluxes from all offshore oil and gas facilities in Angola. This included 30 individual facilities and 10 facility groups. This full coverage is clarified ~~this~~ at the beginning of Section 3.1 and visually represented in Figure 1. While broader regional or global comparisons would benefit from extended coverage across diverse offshore production environments, our dataset provides a comprehensive snapshot of emissions from the entire Angolan offshore sector.*