May 14th, 2025

Response to Reviewer 1 Comments

Title: *Orphaned Oil & Gas Well Methane Emission Rates Quantified with Gaussian Plume Inversions of Ambient Observations*

Manuscript ID: *egusphere-2025-344*

Dear Dr. Lamsal,

On behalf of the author team, we would like to thank you and the reviewers for the time and effort they have spent on reviewing and providing constructive feedback to our manuscript. The following is our response to the reviewers' comments that are in black font, with our responses in green.

• Line 79: Some satellites can detect down to 100 kg/h (GHGSat) or even below (Worldview-3) in favorable conditions. Bridger aircraft instruments can detect below 10 kg/h. Perhaps better to describe these detection limits as orders of magnitude (1–10 kg/h, 100 kg/h).

Thank you, we have revised our text to reflect these detection limits (Line 82).

• Line 126: Some punctuation is missing here.

Thank you, this has been corrected.

• Line 183: The wrong figure is referenced here.

The figure references have been corrected.

• Section 2.2.3: Why were the UAS flights done before the venting operation and not during?

Due to the constraints of the UAS, it cannot fly in areas with high wind speeds above 10 m/s and it was forecasted that day to reach wind speeds of 10 m/s. Therefore, the drone was flown early in the morning during lower wind speed conditions. This meant that the UAS was flown over Foster 1S before the Well Done Foundation team arrived to do the leak vent testing.

• Line 238: When were these enhancements observed? They're different from the value reported at 15-m downwind in line 244 (27.2 ppm).

These two locations describe different metrics for analyzing the observed plume. In line 259, we report the *maximum* values of methane observed in ppm when the wind direction was aligned with our sensors. In line 277, we report the *peak* values of the *Gaussian fit* to the observed methane vs wind direction (as shown in Figure 5) which is our best estimate of the characteristic concentration along the central flow of the plume. We use the latter value to estimate the leak rate from the vent for the ~ hour time scale.

• Line 240: Could nearby wells not have similar methane-ethane ratios?

Nearby wells could have similar ethane-methane ratios. However, we are confident that nearby wells did not significantly impact our measurements. First, our excess ethane and methane values account for background concentrations that include influence of nearby sources. The resulting ethane to methane signature of Foster 1S from the in situ sensors (Figure S4) (11.79% to 12.9%) match the grab bag gas chromatography sample (12.4%) which are directly collected from the well vent (see section 3.1.1). Additionally, Foster 1S had a large leak and we sampled close to the well limiting influences of other sources that would be much more diluted. Lastly, winds were consistently from the southwest and no known wells or other infrastructure were observed nearby in that direction. From this, we know that the measured methane downwind was likely only from Foster 1S with limited influence from other wells in the area.

• Figure 4: The time axis does not appear to be in UTC, inconsistent with text.

We have corrected the figure to represent the local time MST (Mountain Standard Time) and added parenthesis in the text clarifying the time in MST.

• Equation 3: y should be subscript in exponent.

Thank you, we have corrected the subscripts in equation 3.

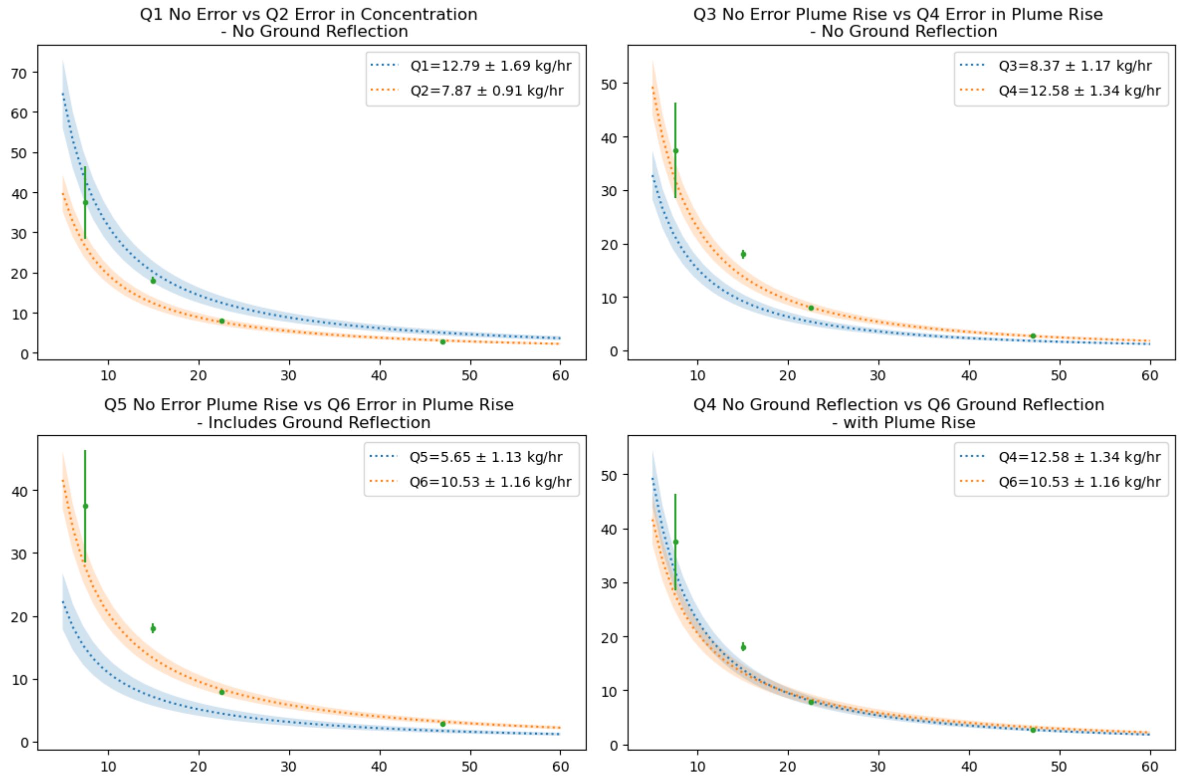
• Line 323-325: Was the wind speed averaged over the full course of the release to obtain this estimate? Would it be possible to estimate the time-varying release rate with your methodology?

Time varying windspeed and direction is considered in analysis of the data collected by the UAS. As described in the text and in Dooley et al., 2024, the flux of CH_4 at each downwind location that was sampled was calculated. These locations include the entire plume cross-section and are integrated to estimate the total emission rate from the source.

Each flight segment consisted of a set of transects that the UAS sampled the cross section of a plume which we used to calculate a leak rate (Table 3). So, we can in principle assess the time-varying release rate. However, for Foster 1S, we do not observe a significant change in the release rate between the different flights.

• Line 336: It would be useful to report the range of values/assumptions used for the error analysis.

To clarify, we ran several iterations of our Gaussian Plume model accounting for errors in the different parameters of the Gaussian plume equation (as shown in the figure below). We account for error based on measured concentration values, plume rise, and ground reflection. This is where we derive these estimates of 5.6 – 12.8 kg CH_4 h^{-1}.



We have added the following text to clarify this statement:

"An error analysis was ran accounting for propagating errors in the model parameters of plume rise, ground reflectance, and the measured concentration of our empirically constrained dispersion Gaussian plume model. This error analysis resulted in estimates from 5.6 - 12.8 kg CH_4 h^{-1} that is within –62% to + 42% of the directly measured leak of 9.0 ± 0.25 Kg CH_4 h^{-1}."

• Discussion/conclusions sections: It would be helpful to articulate any practical advantages of the downwind Gaussian plume approach compared to the flow meter. E.g., could it be easier to deploy at scale? How would that be done? The paper evaluates a methodology but it is unclear how the approach would be operationalized.

This is a good suggestion to help guide future research in this field. The goal of this paper was to demonstrate an empirical method for estimating plume dispersion parameters applied to a Gaussian plume model. Operationally, this method would be most useful for wells without a surface casing vent, such as those where the pumping equipment has been removed, or previously plugged wells. The Ventbuster (flow meter) method requires connecting piping to existing infrastructure, which isn't always available, and does not necessarily measure the fugitive leak rate through the infrastructure, such as the leak observed through the surface casing at Foster 1S. The demonstration of this method could be further developed for operational use by understanding the effects of wind speed, wind direction, terrain, and measurement time on the accuracy of this method. To make this method more appropriate for O&G operations, additional work would also need to be done to scale this down to fewer methane concentration instruments, and development of an acceptable range of error allowed for quantification of a leaking well.

The most practical advantage of this work is to use empirical estimates of plume dispersion rather than EPA plume dispersion look-up tables based on indirect measurements like solar insulation, terrain, and wind. We hope this work will help refine quantification techniques that use Gaussian plume models.

Sincerely,

Emily Follansbee, on behalf of the author team.