

# Reconciling Methane Emission Measurements for Offshore Oil and Gas Platforms with Detailed Emission Inventories: Accounting for Emission Intermittency

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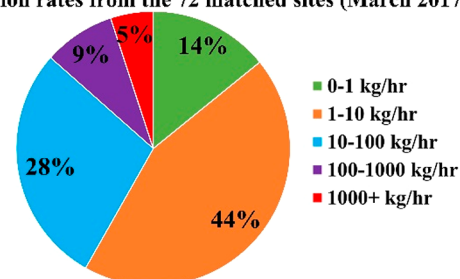
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**ABSTRACT:** Comparisons of observation-based emission estimates with emission inventories for oil and gas production operations have demonstrated that intermittency in emissions is an important factor to be accounted for in reconciling inventories with observations. Most emission inventories do not directly report data on durations of active emissions, and the variability in emissions over time must be inferred from other measurements or engineering calculations. This work examines a unique emission inventory, assembled for offshore oil and gas production platforms in federal waters of the Outer Continental Shelf (OCS) of the United States, which reports production-related sources on individual platforms, along with estimates of emission duration for individual sources. Platform specific emission rates, derived from the inventory, were compared to shipboard measurements made at 72 platforms. The reconciliation demonstrates that emission duration reporting, by source, can lead to predicted ranges in emissions that are much broader than those based on annual average emission rates. For platforms in federal waters, total emissions reported in the inventory for the matched platforms were within ~10% of emissions estimated based on observations, depending on emission rates assumed for nondetects in the observational data set. The distributions of emissions were similar, with 75% of platform total emission rates falling between 0 and 49 kg/h for the observations and between 0.59 and 54 kg/h for the inventory.

**KEYWORDS:** greenhouse gases, methane emissions, emission reconciliations, offshore emission sources, measurement based emission inventories

Emissions from intermittent sources in different ranges of emission rates from the 72 matched sites (March 2017)



## INTRODUCTION

Methane emissions from sources in oil and gas supply chains have been quantified using a variety of sensing technologies and platforms. At the scale of oil and gas production basins, emissions have been estimated using measurements from instrumented aircraft flying upwind and downwind of sources and applying mass balance approaches.<sup>1,2</sup> Aircraft have also been equipped with light detection and ranging and hyperspectral imaging instruments to perform rapid emission detection and quantification at individual sites.<sup>3,4</sup> Existing and planned satellite remote sensing is capable of monitoring large methane emissions from area sources and at individual sites.<sup>5–8</sup> To obtain quantitative measurements at smaller scales, vehicles and drones with sensing systems have been used to estimate emissions for individual sites and sources.<sup>9,10</sup> Other measurement systems with comparable detection limits and measurement times are also in use.<sup>11</sup>

Almost all of these emission measurements have concluded that a small number of sites, with high emission rates, contribute a large fraction of total emissions, and that total

emissions are larger than emissions estimated in inventories. The emission inventories most commonly used in these comparisons have been annual emission inventories, such as the U.S. Environmental Protection Agency's (US EPA) Greenhouse Gas Inventory (GHGI) and the US EPA's Greenhouse Gas Reporting Program (GHGRP). The GHGI and GHGRP inventories are based on counts of equipment and operations, coupled with emission factors, resulting in estimated annual average emission rates. Comparing emission rates, estimated based on short duration measurements, to annual average emission rates reported in inventories, presents challenges. Many emissions from oil and gas operations, both inventoried and uninventoried, are intermittent, with short

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duration periods of high emission rates and long periods with low or zero emission rates. For example, Stokes et al.<sup>12</sup> found that 80–90% of emissions from tank battery sites measured in the Permian Basin were from sites that had emission rates > 10 kg/h; when resampled less than 2 days later, only half of these sites had emissions that persisted above 10 kg/h. Similarly, Cusworth et al.<sup>13</sup> used remote Airborne Visible/Infrared Imaging Spectrometers (AVIRIS) to quantify emissions from thousands of sites in the Permian Basin. The overflight region spanned approximately 55 000 km<sup>2</sup> and the AVIRIS detection limit was reported as 10–20 kg CH<sub>4</sub> h<sup>-1</sup> for 5 m/s wind speeds. On average, 6–8 overflights of individual sites were made and the reported emission persistence fraction, defined as the percentage of detections for any individual site, divided by the number of overflights of the same site, was 26%. The average time between overflights was less than 2 weeks. These studies suggest a persistence of emissions > 10 kg/h that range from a day or less, to weeks. Uncertain durations of intermittent emissions lead to uncertainties in expected total magnitudes of emission events estimated from emission rate measurements. Emission inventories are needed that can account for emission intermittency.

Emission inventories for offshore oil and gas production platforms in federal waters of the Gulf of Mexico have some of the most detailed public information available about intermittency from oil and gas sources. For offshore oil and gas platforms in the Gulf of Mexico that are in federal waters, the US Bureau of Ocean Energy Management (BOEM) developed an emission inventory that reports emissions, by source, on individual offshore platforms, on a monthly basis.<sup>14</sup> Approximately 1100 platforms in the Gulf of Mexico have reported emissions through the Gulfwide Offshore Activities Data Systems (GOADS). BOEM's 2017 Emissions Inventory for platform sources, reported through GOADS, includes monthly emission estimates for approximately 1100 platforms with tens of thousands of individual sources. Emissions are reported monthly, but within each month, for most sources, the number of hours the source is active during the month is reported. Examples of these intermittent sources are pneumatic pumps, cold vents, and pneumatic controllers. Sources not reporting active hours include fugitives, glycol dehydrators, loading, losses from flashing, and storage tanks. A complete year-long inventory is assembled approximately every three years. BOEM's 2017 Emissions Inventory was the latest inventory available at the time this work was performed. In this work, inventories of emissions for individual platforms will be compared to short duration platform emission estimates, based on measurements made downwind of 72 platforms. The reconciliation of the measurements and inventory, also described in a preprint,<sup>15</sup> will illustrate the importance of accounting for the intermittency of emissions in developing emission inventories.

## METHODS

### Emission Inventory

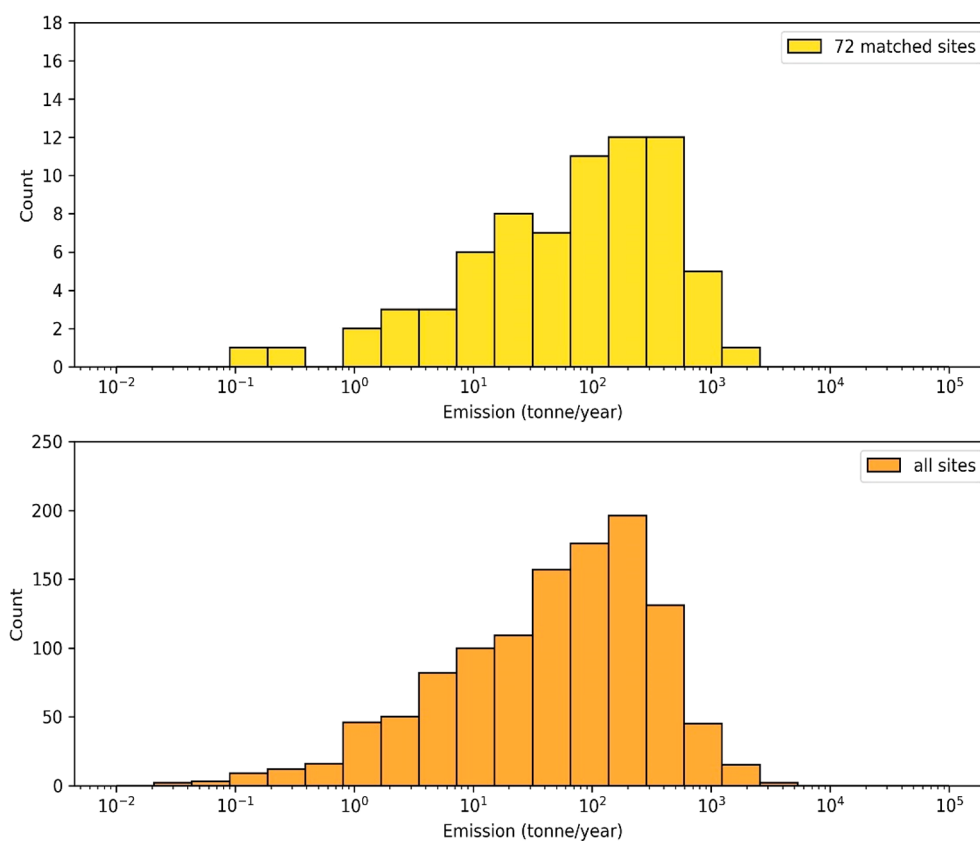
Methane emission inventory data are taken from the air pollutant emissions inventory for calendar year 2017 for the Outer Continental Shelf (OCS), developed by BOEM.<sup>14</sup> The inventory includes emission data for OCS oil and gas production sources in the Gulf of Mexico (GOM) west of 87.5° longitude, in federal waters, reported by the operators. BOEM and its contractors performed a number of quality assurance and quality control steps for the data. This included reviewing the reported sales gas compositions, validating the

submitted location coordinates, and identifying incorrect and missing equipment descriptive and activity data. From the database, approximately 240 000 records related to methane emissions, at 1155 unique platforms, were retrieved. These records include monthly emission estimates from individual sources on specific, geo-located platforms. Emission estimates, reported as tons per month, were converted to rates of kg/h in multiple ways. One estimate was based on dividing the monthly emission rate by the number of hours in the month being reported. The emission values calculated in this way are referred to as “average hourly emissions”. Another method took the emissions for each source on an individual platform and calculated rates, by source. There were multiple cases of short duration, high emission rate events for sources on some platforms, such as pneumatic pumps and pneumatic controllers. For these short duration events, ranges of emission rates that could be expected were estimated for the platforms where observations were made.

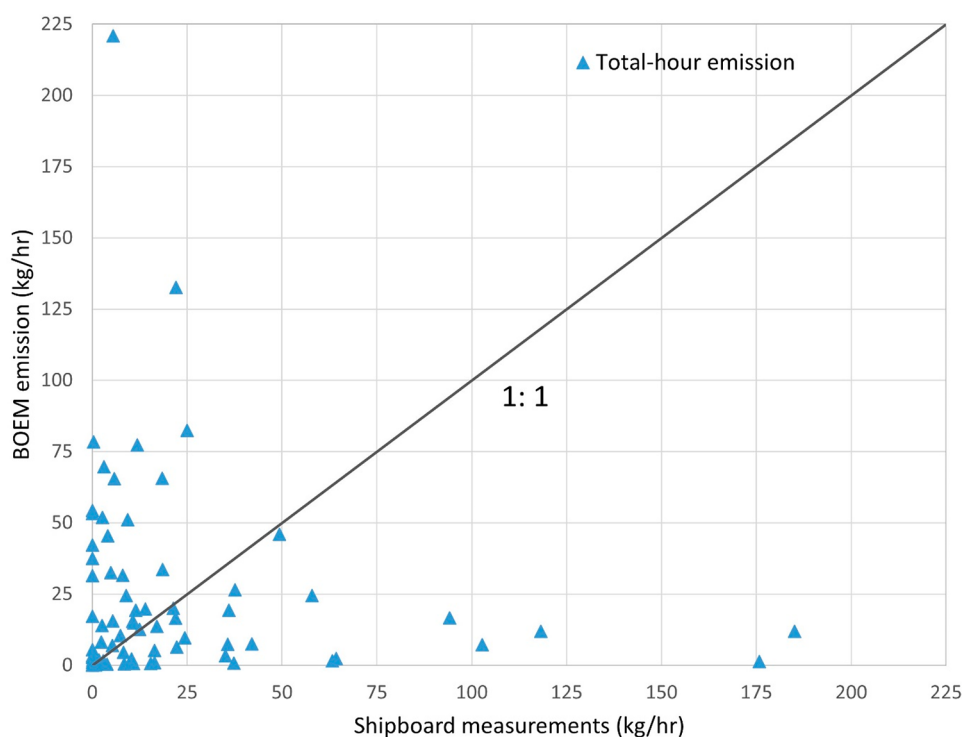
Multiple sources of uncertainty exist when comparing the inventory emission estimates to short duration emission estimates based on observations. One source of uncertainty is due to temporal variability in the emissions. The inventory reports data aggregated by month, while the shipboard measurements were typically collected in less than a day. The temporal variation in the reported inventory can be approximated based on the variation in monthly emission totals for individual platforms. The standard deviation was calculated for the monthly average of average hourly emissions for the 72 platforms. Averages and standard deviations are shown in Table S1 in the Supporting Information (SI). The average normalized standard deviation was 25%. In addition to the temporal variability, there is uncertainty associated with emission factors and activity counts that impact the calculation of emission rates. As emission rates for individual sources are aggregated into total emissions for a platform, the overall uncertainty in platform emission rates will be less than the uncertainties in the emissions from individual sources. Using similar activity data and emission factors, the US EPA has estimated that uncertainties in its GHGI are approximately 30%.<sup>16</sup> Taken together, this suggests an estimated uncertainty in platform inventories of 50%.

### Shipboard Measurement Data

Downwind measurements of emissions from 103 platforms in the Gulf of Mexico were collected between February 12, 2018 and February 22, 2018. The details of measurement and data analysis have been described by Yacovitch et al.<sup>17</sup> Briefly, meteorological and analytical equipment was installed aboard the Research Vessel Trident (RV Trident), owned and operated by the Texas A&M University at Galveston. Methane measurements were made using tunable infrared laser direct absorption spectroscopy (TILDAS) trace-gas monitors from Aerodyne Research, Inc.<sup>18</sup> Nitrous oxide, carbon monoxide, water, ethane, and redundant methane were measured by two single-laser mini TILDAS instruments. Approximately 120 h was spent at sea during the 11 day and night measurement period, a duty cycle close to 50%. In making individual platform measurements, the ship typically made multiple downwind transects of the platform plume. The preferred sampling strategy was to navigate a zigzag path downwind of the chosen site, intercepting the emission plume at a range of distances (typically 1–10 km). Gaussian inversion methods were used to estimate the methane emission rates. Measured plume widths at sea level, determined from the ship transects, were used to estimate the stability classification, which was then used to estimate vertical dispersion. Some platforms had multiple plume measurements, and in general, the standard deviation of plume measurements was less than the uncertainty anticipated from converting downwind plume measurements into emission estimates. Overall uncertainty was estimated to be approximately an order of magnitude for an individual measurement. The Gaussian dispersion methodology itself has 95% confidence intervals of  $[0.33x, 3.34x]$  for an emission of magnitude  $x$ . To include uncertainty in either the release height or the release location, factor-of-10 errors at 95% confidence (i.e.,  $[0.1x, 10x]$ ) are asserted on all dispersion results. Averages of measurements were anticipated to have much lower uncertainty. The average of the measurements, lower and upper limits of the average are shown in



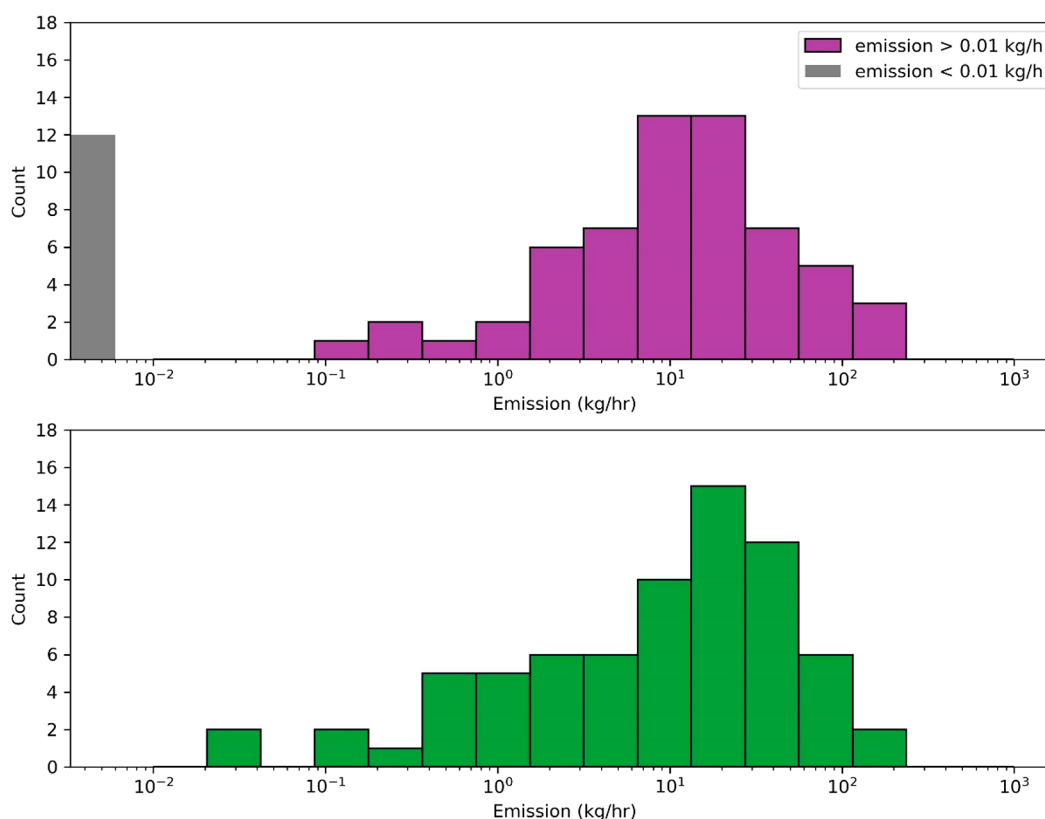
**Figure 1.** Histograms for annual methane emissions on a logarithmic scale: (top) annual emissions in 2017 from BOEM inventory for 72 matched platforms matched to observations; (bottom) annual emissions in 2017 from BOEM inventory for all the sites in Gulf of Mexico.



**Figure 2.** One-to-one site emission comparison of the 2017 BOEM inventory (*y*-axis) and shipboard measurement (*x*-axis) for 72 matched sites. The BOEM emission rates are the average of average hourly emissions in each month in 2017. The shipboard measurement data were collected in February 2018.

Table S2 in the SI. If errors were random and unbiased, then standard deviations would scale with the inverse of the square root of the

number of measurements, if the rates were normally distributed. While the observed rates are not normally distributed and there may



**Figure 3.** Histograms for methane emissions of the 72 matched sites on a logarithmic scale: (top) shipboard measurement emissions made in February 2018; (bottom) average of average hourly emissions in each month from 2017 BOEM inventory.

be bias in the estimates, the estimated uncertainty of the average observed rate across all platforms is expected to be much lower than for individual measurements.

### Reconciling Shipboard Measurements with Emission Inventories

To make platform by platform comparisons between the shipboard observations and the BOEM inventory, the GPS locations of measured sites and sites in BOEM inventory were compared. The closest site within a distance of 300 m of the shipboard measurement site was chosen as the corresponding BOEM emission site. Of the 103 platforms with downwind measurements, 72 sites are matched with entries in the 2017 BOEM emission inventory. Geolocation data on the 103 sites, methane emission estimates from the shipboard measurements, and geolocation information on the 72 sites in BOEM inventory are summarized in Table S3 in the SI. A map showing the emission sites in the BOEM inventory (2017), the 103 shipboard measurement sites, and the 72 matched sites in the Gulf of Mexico is available as Figure S1 in the SI.

## RESULTS

Figure 1 shows the distribution of annual emission rates for the 72 matched sites compared to all of the sites in the BOEM inventory; the matched site emission rates are broadly representative of all of the platforms inventoried by BOEM. Average emissions for the 72 matched platforms are 208 tonne/year (24 kg/h); for all platforms, the average is 163 tonne/year (18.6 kg/h). There is a large range of annual methane emissions on a platform level. For platforms with large methane emissions, most of the emissions are due to cold venting; however, many factors contribute to the quantity of methane emissions from a platform. For example, emissions may vary due to platform and equipment age, activity, and

production levels and the use of combustion flares as opposed to cold vents.

Figure 2 shows platform by platform comparisons of BOEM inventory data for 2017 to shipboard emission rate information for 2018 for 72 matched sites. The emission rate estimates for every platform are listed in Table S4. The BOEM emission rates were calculated for each month using the month's total hours. The monthly rates were then averaged over 12 months (Figure 2). The shipboard measurement data were collected in February 2018. The measurement data do not correlate well with the inventory emission rates, matched by platform, because the measurements are instantaneous and the estimates from BOEM inventory are averages of monthly emission rates. The mismatch between short-term observations and longer-term emission estimates for individual sites has been reported for on-shore oil and gas production previously.<sup>10</sup> While the emission rate estimates were not well correlated with monthly average emission rates reported in the inventory, matched by platform, the distributions of emission rates across all of the platforms were in much better agreement. Figure 3 shows histograms of methane emissions for the 72 matched sites on a logarithmic scale. The similarity in the two distributions indicates that top-down measurement and bottom-up inventory are generally consistent despite the discrepancies between individual platforms shown in Figure 2.

The major difference between distributions of emission rates derived from the inventory and based on shipboard measurements are the nondetections in the observations. It is possible, but unlikely, that emission plumes from the platforms would not reach the sea surface. Hysplit back-trajectory simulations were performed hourly for the duration of the measurement campaign. The meteorology used in these simulations suggests



that boundary layer heights range between 300–2400 m close to shore and 300–1200 m further offshore. Emission release heights on the order of 7–31 m were used based on platform heights in BOEM planning documents; downwind measurements were conducted between 400 and 18000 m downwind. This suggests it is unlikely that platform emissions would be injected above the boundary layer. For sites with multiple downwind transects at different distances, there was no increase in the retrieved emission magnitudes with increasing distance (see Figure S4). Additional discussions of the sensitivity of the measurements to platform height and plume rise is present in Yacovitch et al.<sup>17</sup> and associated SI.

It is also likely that nondetects by the measurement system do not correspond to true zero values. Upper limits for experimental nondetects were determined through forward simulations, and are a function of the variability in methane background at a given distance downwind. An approximate upper bound on the true value of the nondetects can be estimated by replacing the nondetects with either an average value of the platforms with detected emissions or their estimated upper limits. This would increase the platform average emission rate from 22 to 26 kg/h for the average or 24 kg/h for the upper limit, excluding one no-detect site with an upper limit an order of magnitude larger than the highest measured site. Average emission rates in the BOEM inventory were 24 kg/h (range of 0.023 to 221 kg/h) based on total hours. Figure 3 reports data averaged over the 12 months of reporting in 2017; the distributions of emissions of individual months in 2017 for the 72 sites are shown in Figure S2 in the SI. To further characterize the uncertainty of the measurements, average values of the emissions in each bin in the histogram (Figure 3, top), with the lower and upper limits of the averages, are shown in Figure S3 in the SI.

It is notable that total emissions reported in the BOEM inventory for the matched sites were within ~10% of the observed rates. This contrasts with on-shore observations, where observationally based emission estimates have generally been greater than emissions reported in inventories. Alvarez et al.,<sup>19</sup> for example, reported in a meta-analysis of data from nine on-shore basins that observation based estimates of emissions were, on average, 63% greater than emissions reported through US EPA GHGI, due to large uninventoried emissions such as equipment malfunction and other abnormal operating conditions.

The comparisons shown in Figures 2 and 3 also highlight the importance of considering intermittency in emissions. The frequencies of nondetects in measured emission rates (17% of matched sites) from shipboard measurement might suggest that, even for some emissions that are reported as active at all times, releases can be intermittent. For example, intermittent pneumatic controllers are active at all times but only emit during discrete periods.

If the active hours of individual emission sources on individual platforms are used, extreme values of expected emission rates emerge. Two platforms with extreme emission rates are discussed as examples. Table S5 in the SI shows data for the 40 emission sources for one platform for May 2017. Total emissions for this platform, for the month of May 2017, were 64 tons. Of the 40 sources, 19 report being active for all hours of the month (744 h), accounting for 34% of total emissions (22 tons), and corresponding to an emission rate of 29 kg/h. There were 21 sources with active operation hours less than 744 h. The top three largest of the 21 intermittent

sources had emission rates of 651, 23, and 12 kg/h. These three sources have active hours of 40.5, 1, and 2 h out of the 744 h in the month. The largest source (651 kg/h) is reported as a cold vent. Table S6 in the SI also shows data for 31 emission sources of another platform in May 2017. Total emissions for this platform were 50 tons for May 2017. There were 9 sources with intermittent emissions and 22 sources being active for all hours of the month. The total emissions from 9 intermittent sources were 36 tons, accounting for 71% of total emissions. The largest intermittent source, a pneumatic pump with 61 active hours, was reported to have a monthly emission of 9.4 tons. This corresponds to an emission rate of 155 kg/h. These platforms are extreme examples of the importance of intermittent emissions.

For all 72 matched platforms, over all sources for May 2017, there were 399 sources that reported intermittent emissions, an average of 6 per platform. The average emission rate for these sources was 14 kg/h, however, the average is significantly impacted by extreme values. The median emission rate for individual intermittent sources is 0.4 kg/h. Intermittent emission rates ranged from near zero to hundreds of kg/h during the periods when the emissions were active. The total emissions from intermittent sources were 520 tons for the month of May (34% of total emissions) and the total number of hours that the emissions were active was 152 000 h, an average of 380 h of the 744 h in the month, per source, for the 399 intermittent sources on the 72 platforms. This means that for the 72 platforms, in any given hour, approximately half of the intermittent sources would be active, if their distribution was random. Some of these intermittent emissions would be large. For example, emission rates over 50 kg/h had collective durations of 1505 h for the month of May, compared to a total of 744 h in the month. Emission rates over 25 kg/h had collective durations of 3018 h. This suggests that, on average, at any given time, approximately two platforms would be expected to have an intermittent emission in excess of 50 kg/h and four platforms would be expected to have an intermittent emission in excess of 25 kg/h, contributing to some of the extreme values expected in observed emission rates.

The distribution of the number, magnitude, and duration of intermittent emissions is shown in Tables S7–S9 in the SI. For all 72 matched platforms, over all sources for March 2017, the monthly total emissions were 1384 tons. For continuous sources, the total emissions were 1134 tons (about 82% of total emissions). Emissions from intermittent sources were 245 tons for March 2017 (about 18% of total emissions). There were 367 sources that reported intermittent emissions (about 25% of the total sources). The intermittent emission rates were divided into five different emission ranges (0–1, 1–10, 10–100, 100–1000, and >1000 kg/h); the numbers of intermittent emission sources in these ranges were 272, 59, 21, 13, and 2. About 74% of the intermittent sources have emissions less than 1 kg/h. The monthly total emissions from these five ranges were 35, 110, 71, 21, and 13 tons. Additional analyses could be conducted for other months, and Tables S10 and S11 in the SI contains data for two platforms in March 2017 with their equipment type, active hours in March, and active hour emission by source. The two examples provided in the SI have large intermittent emissions from sources such as pneumatic pumps and cold vents.

## CONCLUSION

Overall, ranges in emissions are much broader and include higher maximum values when emissions from individual sources are calculated based on operationally active hours. The active hours and emission rates for individual sources on individual platforms can be used to establish expected values for observations above particular thresholds. These results highlight the importance of including data on intermittency in emission inventories, as has been done in the BOEM inventory. The BOEM inventory demonstrates that it is possible to collect data related to emission intermittency on a broad scale. Despite discrepancies on a site-to-site basis, attributed to mismatches in timing and averaging times for the inventory and measurements, the BOEM inventory reproduces the experimentally measured distribution of emitters. The relative importance of intermittency associated with different sources needs further investigation, but the BOEM inventory illustrates the types of approaches that could be used.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsenvironau.2c00041>.

Average and standard deviation for the average hourly emissions of the 72 matched sites; average of ship measurement emission estimates, lower and upper limits of the average; geolocation data, methane emission estimates and reported lower and upper limits from the 103 shipboard measurement sites; geolocation data and methane emission estimates of the 72 matched sites in BOEM inventory; histograms of average hourly emissions for the 72 matched sites from BOEM inventory for individual months; average values of the emissions in each bin in Figure 3 top, with the lower and upper limits of the averages; methane emission data for individual emission sources for two platforms for May 2017 from the BOEM inventory; Methane emissions from continuous and intermittent sources for the 72 matched sites in March 2017 from the BOEM inventory; discussion of emissions going above the vessel (PDF)

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## Notes

One of the authors (D.T.A.) has current research support from multiple natural gas producers and Environmental Defense Fund. He is a member of the EPA Science Advisory Board and in this role is a Special Governmental Employee. D.T.A. has done work as a consultant for multiple companies in recent years, including British Petroleum, Cheniere, Eastern Research Group, ExxonMobil, KeyLogic, National Institute of Clean and Low Carbon Energy and SLR.

The authors declare no competing financial interest.

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