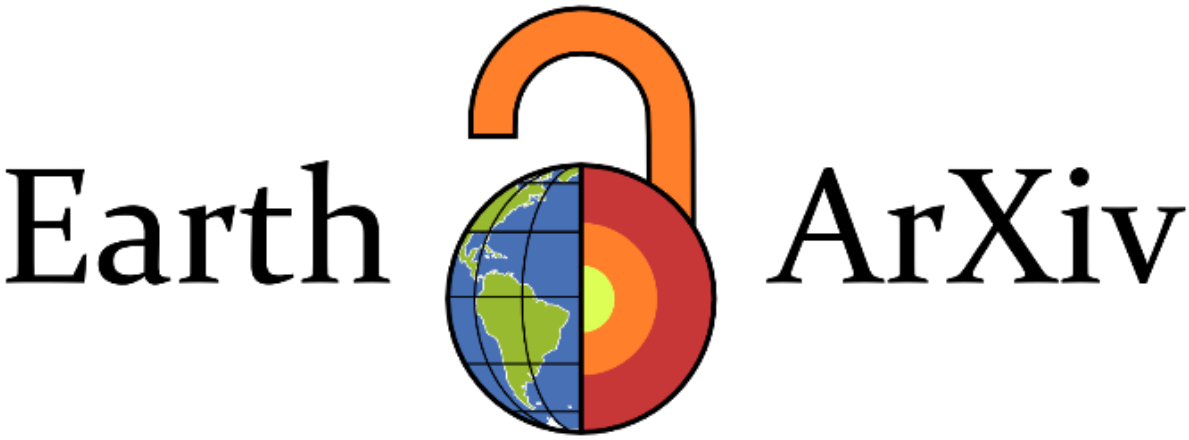

Multi-scale measurements and temporally resolved modeling of methane emissions at natural gas distribution stations

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Abstract

Methane (CH_4) emissions from natural gas distribution stations are not well characterized by measurements, contributing to uncertainty in urban emissions inventories and mitigation strategies. We conducted a multi-scale, multi-temporal study of four distribution stations in Calgary, Alberta, combining component- and facility-level measurements with modeling to quantify, attribute, and compare emissions rates. Component-level surveys found low-emitting and readily abatable fugitive emissions, vents, and emissions from catalytic heaters, which accounted for 1.6–40.1% of total emissions. Facility-level measurements using the human-portable flux plane method revealed comparatively higher rates of 3.4×10^{-2} to 7.4 kg CH_4/h that were correlated with throughput, with most emissions attributed to incomplete combustion from line heaters that combust process gas prior to pressure regulation. To compare measured with conventional rate estimates, we developed a Monte Carlo-based modeling framework integrating component-level rates, historical leak detection data, gas throughput, and source-specific emission factors (EFs). Measured rates exceeded modeled rates by factors of 1.6–148.3. Across all measurements, facility-level rates totaled 17.4 kg CH_4/h (10.8–24.1 kg CH_4/h); modeled rates totaled 2.3 kg CH_4/h (0.9–4.2 kg CH_4/h). Overall, results suggest that conventional approaches underestimate distribution station CH_4 emissions because underlying EFs underrepresent emissions from equipment incompletely combusting natural gas.

Keywords: methane emissions, natural gas distribution, transmission distribution transfer stations, city gate stations, detection, quantification, modeling, incomplete combustion

1. Introduction

In the U.S. and Canada, natural gas is a prominent fuel used for electricity generation, space and water heating, and cooking in residential and commercial sectors (Canada Energy Regulator (CER), 2024; U.S. Energy Information Administration (EIA), 2024). In major cities and urban areas in these countries, natural gas consumers are abundant and distributed widely, requiring an extensive system of facilities, distribution pipelines, and meters to regulate pressures, deliver the gas, and measure volumes. Methane (CH_4)—the principal component of natural gas and a potent greenhouse gas—can enter the atmosphere from this infrastructure intentionally through venting

or unintentionally from leaks or accidents (e.g., hit lines). These releases warm the climate (Szopa et al., 2021) and in cases can degrade urban air quality as an ozone precursor (Monks et al., 2015). CH_4 is also emitted from the exhaust of equipment and appliances that combust natural gas as combustion is never fully complete (Fischer et al., 2018; Merrin and Francisco, 2019; Lebel et al., 2020, 2022; Saint-Vincent and Pekney, 2020). In aggregate, the distribution and use of natural gas can be a large source of urban CH_4 emissions in the U.S. and Canada given the scale of infrastructure with potential to emit and large number of end users (Vollrath et al., 2025).

At the city scale, atmospheric measurements and source attribution studies show that emissions from natural gas systems contribute substantially to urban CH_4 budgets in the U.S. and Canada, and in many cases dominate the emissions profile (Vollrath et al., 2025). This dominance is not universal; landfills have been identified as a primary source in some cities, such as the San Francisco Bay Area (Jeong et al., 2017; Guha et al., 2020), and suggested by limited ground-based measurements in Montreal and Toronto (Ars et al., 2020; Williams et al., 2022; Gonzalez Moguel et al., 2025). Regardless, natural gas systems can emit large quantities of CH_4 in urban areas, and research is required to better understand the parts of the natural gas system that drive emissions (Zhang et al., 2023; Vollrath et al., 2025).

To date, most urban natural gas CH_4 measurements in the U.S. and Canada have focused on detecting subsurface leaks from distribution pipelines using vehicle-based surveys and surface techniques, revealing strong links between pipeline material and leak propensity. This supports mitigation through targeted repairs (e.g., Phillips et al., 2013; Jackson et al., 2014; Lamb et al., 2015; Hendrick et al., 2016; von Fischer et al., 2017; Weller et al., 2020; 2022; Edwards et al., 2021; Vogel et al., 2024). However, pipeline leaks represent only one component of urban natural gas emissions, and studies show that in cities with limited or no cast iron infrastructure, pipeline-related CH_4 emissions are comparatively low (Ars et al., 2020; Weller et al., 2022; Vogel et al., 2024). Other natural gas sources are likely to be important. Measurements of these non-pipeline sources remain limited: (i) distribution stations (Lamb et al., 2015; Hugenholtz et al., 2021), (ii) metering and regulating facilities (Williams et al., 2022), (iii) valve vaults (Gallagher et al., 2015), (iv) farm tap units, (v) customer meters (Williams et al., 2022; Newton et al., 2024; Vollrath et al., 2024), (vi) post-meter leaks (Fischer et al., 2018), and (vii) end-use incomplete combustion emissions (Merrin and Francisco, 2019; Lebel et al., 2020, 2022; Saint-Vincent and Pekney, 2020). Among these, natural gas distribution stations (also referred to as transmission–distribution transfer or city gate stations) are particularly understudied despite being common, above-ground facilities with multiple emission pathways, including fugitives, vented emissions, and equipment with incomplete combustion.

Distribution stations primarily exist to decrease gas pressure from transmission lines (~600 psi) into lower pressure neighborhood lines (60-100 psi). Neighborhood lines connect to point of use meter-sets (Vollrath et al., 2024), and beyond this, individual appliances. Neighborhood lines must be fed in different locations throughout a city to maintain pressure and balance gas use. Transmission lines use higher pressures fed by compressor stations to facilitate

flow of very large volumes of gas over long distances. Neighborhood lines use lower pressures to provide safe, controlled delivery of smaller gas volumes for customers and reduce leak potential under roads. Although system design varies throughout different cities, this multi-pressure design requires distribution stations throughout a city to feed the neighborhood lines.

Decreasing gas pressure at distribution stations through regulators generates immense cooling due to the Joule-Thompson effect, causing issues with gas condensation and icing that are closely related to gas throughput (not necessarily ambient temperature). Line heaters are used to heat the gas before pressure decrease to mitigate these effects. Some distribution stations (such as those in Calgary which are typical of Canadian and U.S. cities) have line heaters and additional equipment to treat, measure, or control gas flows. Line heaters combust process gas, and any incompletely combusted gas—including CH_4—is emitted to the atmosphere in exhaust. Process gas volumes used by line heaters change with station throughput and seasonal operating changes due to demand, resulting in variability to operational and total station CH_4 emissions rates.

Measuring and attributing all CH_4 emissions at natural gas distribution stations is challenging, presenting an opportunity to improve the characterization and understanding of emissions. For example, fugitive and vented emissions from components and equipment are typically located closer to the ground and can be measured with conventional measurement methods. In contrast, line heater exhaust containing incompletely combusted CH_4 is emitted from a height of ~5m a.g.l. and is hot and slightly buoyant. Conventional methods typically cannot measure elevated or otherwise difficult- or unsafe-to-measure sources. Thus, to our knowledge, incomplete combustion CH_4 emissions from line heaters are missing from aggregated component-level rates in existing studies of distribution stations in the U.S. and Canada, where rates have been used in national-level inventories (e.g., Lamb et al., 2015; Williams et al., 2022). Outside the fenceline, facility-level methods are one approach to measure emissions from all sources on site, including tall sources like line heaters, and independently confirm emissions. Research has provided a limited number of total estimates at stations (Hugenholtz et al., 2021). However, when CH_4 is measured from a standoff distance downwind, the emissions generally cannot be attributed to specific components and processes on site, hindering a better understanding of where the majority of the emissions are coming from. These examples highlight the limitations of individual methods and the opportunity to address the problem with a broader set of approaches.

To advance understanding of CH_4 emissions from these sites, this study combines multi-scale and multi-temporal measurements with modeling at four natural gas distribution stations in Calgary, Alberta, Canada. Notably, we demonstrate the use of the human-portable flux plane method to quantify total station emissions, including incompletely combusted CH_4 from line heaters, representing a novel application of the approach (Vollrath et al., 2026). We attribute emissions using the multi-scale measurements and observations, identifying incomplete combustion from line heaters as the dominant contributor to stations' emissions. To capture temporal variability not typically resolved in estimates based on conventional approaches, we

also developed a Monte Carlo-based modeling framework to estimate CH_4 emissions from the stations, enabling a temporally resolved comparison with facility-level measurements. The framework integrates component-level rates from this study, historical leak detection data, gas throughput, and common source-specific emission factors (EFs). Comparison of modeled and facility-level estimates indicated that conventional approaches underestimate CH_4 emissions from distribution stations due to generic EFs substantially underrepresenting incomplete combustion emissions from equipment, with broader implications for estimates of CH_4 emissions from natural gas end use.

2. Methodology

2.1. Background and station selection

The City of Calgary had a population of 1,306,780 in 2021 (City of Calgary, 2025) and relies primarily on natural gas for meeting the city's electricity demand, as well as residential and commercial space heating. The city has a continental climate with strong seasonal temperature variability (mean daily air temperature is 4.5 °C for 1991-2020) and unique weather patterns, including 'chinook' downslope winds from the Rocky Mountains that warm and dry the air. Natural gas demand fluctuates dramatically on weekly and seasonal timescales. According to local gas utility data, 41 distribution stations operate across Calgary to regulate gas pressure and deliver supply to residential, commercial, and industrial users, with two additional stations under construction and a third proposed to accommodate urban growth and rising demand.

Distribution stations vary in size, complexity, and throughput, with larger facilities generally having higher potential to emit CH_4 due to more components, larger or more numerous pieces of equipment, and increased operational emissions due to throughput demand. For this study, we selected four stations—three large and one medium-sized—based on their accessibility, suitability for multi-method measurements, and physical characteristics that facilitated accurate facility-level measurements. Selected stations had porous fencelines, limited nearby obstructions, and line heaters with low-exit-velocity exhaust stacks, positioned so that plumes could be effectively captured in the vertical dimension.

Figure 1 shows the selected facilities, distributed across the city, with Table 1 detailing basic attributes (see also S1). Stations A and B were large, full-time operations. Stations C and D were smaller and seasonal, with operation dependent on natural gas demand. The primary purpose of these stations is pressure regulation from transmission pressures (~600 psi) to neighborhood line pressures (60-100 psi). In Calgary, point of use meter sets further regulate pressure prior to entering buildings. Gas metering was present at all sites, but Station B had a gas chromatograph to monitor gas composition. To manage cooling associated with pressure reductions, the stations had line heaters, of varying type, number, and size. All stations had equipment inside of process buildings, and to manage cold weather, these building were often equipped with catalytic heaters, although not all were operational. None of these sites had compressors or odorant injection equipment; odorization occurs upstream. None of these sites were dominantly powered by mains electricity, instead using self-generated energy for power.

Table 1. Simplified site attributes, see S1 for additional discussion.

Equipment / Processes	Station A	Station B	Station C	Station D
Pressure regulation	Yes	Yes	Yes	Yes
Pneumatic valves with vents	Yes	No	Yes	No
Liquid separators	No	Large	Small	Very small
Catalytic heaters	Yes	Yes	Yes, non-operational	No
Self-generated energy (with thermal electric or other generator)	Yes (thermal electric)	Yes (generator)	Yes (thermal electric)	Yes (thermal electric)
Gas chromatograph with vent	No	Yes	No	No
Line heaters	Vacuum-style	Vacuum-style	Vacuum-style	Bath-style
General operation status	Full-time	Full-time	Seasonal	Seasonal
Flow meters	Yes	Yes	Yes	Yes
Process buildings	Yes	Yes	Yes	Yes

Figure 1. Natural gas distribution stations in Calgary, AB selected for component- and facility-level measurements.

2.2. Measurement approach and methods

2.2.1. Overview

We measured CH_4 emissions at the four stations using a combination of component- and facility-level techniques. The local natural gas utility provided site access for component-level surveys, as well as historical leak detection and gas throughput data, while station operators helped contextualize the survey findings. The primary purpose of the component-level surveys was to identify CH_4 emission sources and quantify their rates where possible. Each station was surveyed three times between October 2024 and March 2025, with survey dates summarized alongside facility-level measurement dates in Figure 2.

Facility-level CH_4 emissions were measured from outside station fencelines, four to six times at each station over a slightly longer period than the component-level surveys (Figure 2). To investigate short-term variability in emission rates, we conducted two repeat facility-level measurements approximately one hour apart at Stations A and D on 8 December 2024 and 25 April 2025, respectively (Figure 2).

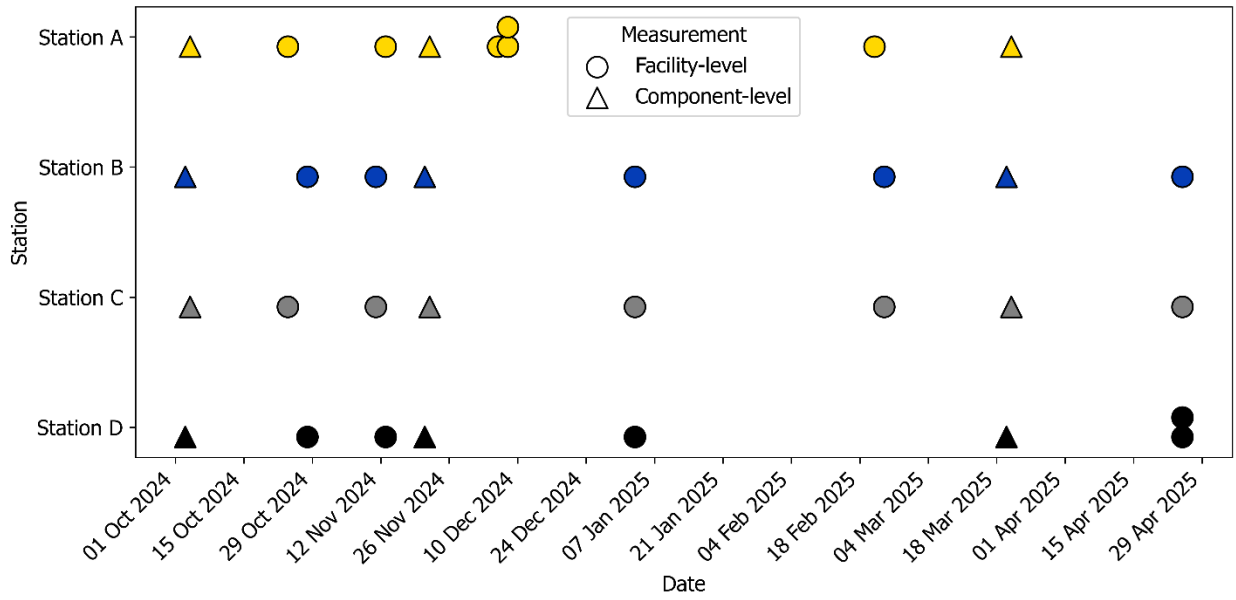

Figure 2. Timeline of measurements at the stations. Marker color is varied by station and shape is varied by measurement type—component- or facility-level. Repeat facility-level measurements were performed approximately one-hour apart at Stations A and D on the 8 December 2024 and 25 April 2025, respectively to explore short-term temporal variability to CH_4 emissions rates. The repeat measurements are shown in the figure as the stacked circular markers.

2.2.2. Component-level surveys

2.2.2.1. CH_4 emissions detection

We used a FLIR GF320 optical gas imaging (OGI) camera to detect CH_4 emissions from components at the four distribution stations. We imaged all infrastructure at the stations with potential to emit CH_4 from a distance of approximately 3 m or less, consistent with regulatory-mandated work practices for OGI surveys in the oil and gas production sector (AER, 2020).

Zimmerle et al. (2020) found that OGI had a 90% probability of detection (POD) of 1.6 kg CH_4/h for inexperienced operators, ranging to 0.13 kg CH_4/h for experienced operators. The largest source we quantified in the on-site surveys was emitting between 0.16 kg CH_4/h and 0.23 kg CH_4/h, which was easily detectable with OGI, suggesting either operator experience or good conditions for OGI surveys. We note that slow survey speeds may have improved our probability of detecting small leaks with OGI. Some small leaks were detected using mercaptan (CH_3SH) odor and snoop—a soapy water solution—when OGI effectiveness or efficiency was lower compared to these methods in some cases (see §3.1 for more details).

2.2.2.2. Component-level CH_4 emissions quantification

Detected sources of CH_4 emissions were quantified using a HETEK hi-flow sampler when emitting at rates sufficient for quantification. This included fugitive emissions (leaks) and vents.

We also quantified CH_4 emissions in the exhaust of catalytic heaters, which were accessible from the ground and generally low-temperature such that they could be reliably quantified without damaging the instrument. The hi-flow has a rated accuracy of ±10% and has a rated lower quantifiable limit of 5.0×10^{-3} kg CH_4/h depending on the operating mode. We calibrated the hi-flow several times throughout the study period following manufacturer specifications.

We did not quantify CH_4 emissions when the characteristics of the emissions or source height created limitations for the instruments or potential safety issues. CH_4 emissions from the catalyst panels (Festa-Bianchet et al., 2024) on the catalytic heaters at Stations A and B were detected but not quantified due to ambiguity over where the CH_4 was coming from. CH_4 was seeping from multiple locations on the pads and mixing, creating challenges for capturing all emissions. Furthermore, the temperature of the catalyst panels was high and could have damaged the hi-flow bag attachment. We also did not quantify CH_4 emissions from line heater exhaust stacks due to their height and temperature.

Some leaks were detected but emitting at rates insufficient for quantification. Also, in the component-level surveys on 20 and 21 of March 2025 (Figure 2), we faced a firmware issue with the hi-flow and could not quantify a number of sources. The issue was resolved and explored in a future update and servicing (A. Mohan, personal communication, April 15, 2025). To mitigate, for very low-emitting leaks we used the lower rated quantification limit of the instrument as the emissions rate. For other sources that could not be quantified on these dates, the rate for the same source quantified in a different survey or the mean of multiple quantifications of the same source (if quantified in > 1 survey) was used as the emissions rate.

2.2.3. Facility-level measurements

2.2.3.1. Pole-based flux plane method

In addition to component-level measurements, we quantified CH_4 emissions at the facility-level in a novel application of the mobile "flux plane" technique—a mass balance method commonly used with quadrotor drones (Corbett and Smith, 2022)—with a human-portable, telescoping pole-based system (see Vollrath et al., 2026). Vollrath et al. (2026) found that the pole-based flux plane method achieved a mean relative error of -10.1% across a series of 44 controlled release tests, where 68% of estimates were within ±38.3% of the release rates—providing an indication of the expectable accuracy of this technique in this application.

For this study, all equipment was identical to that used by Vollrath et al. (2026) with the exception of a taller pole to expand vertical coverage to 8.1 m. The line heater plumes were emitted at ~5 m a.g.l. and were slightly buoyant; however, with low exit velocity. We examined weather and wind forecasts to target periods with stable atmospheres and moderate to high wind speeds to limit vertical plume rise.

We followed the same work practice to perform the pole measurements as documented in Vollrath et al. (2026); however, real-world use of the method required an additional "screening" step. Upon arriving at the stations, the pole operator studied the wind direction and identified the plume's location using the kit's backpack-mounted LI-COR 7810 (LI-7810) trace gas analyzer.

This information, along with consideration of the terrain surrounding the stations, was used to optimize the location where the measurements would be performed. A total of 21 facility-scale measurements were performed across the stations over the study period (Figure 2).

Overall, data processing and quantification were performed on 20 out of the 21 measurements after quality-assuring the data following the protocol developed by Vollrath et al. (2026) for pole-based flux plane measurements (see S2).

2.2.3.2. Wind speed and direction

During the facility-level measurements, wind speed and direction were measured from an anemometer deployed nearby in an area free from obstructions. We used a TriSonica Mini (TSM) anemometer at a height of 1.9 m to measure wind from 24 October 2024 to 03 January 2025 but switched to an RM Young (RMY) 81000 at a height of 2.2 m for measurements on 21 February 2025 and afterwards. More details on the wind measurements, the approach to address data gaps on two days, and estimating a vertical speed wind profile for quantification with the flux plane method (Vollrath et al., 2026) are provided in S3.

Winds speeds were measured with the TSM and RMY on 21 February 2025 for comparison (Figure S1). Mean wind speeds for the CH_4 measurement on this date were 5.0 m/s (standard deviation = 1.8 m/s) and 4.4 m/s (standard deviation = 1.7 m/s) with the TSM and RMY, respectively. Wind speeds from the RMY were adjusted for height using the method in S3 to match the height of the TSM. Wind speed is a direct multiplier in quantifying CH_4 emissions rates with the flux plane method (Vollrath et al., 2026). Therefore, results from this single experiment indicate that CH_4 rate estimates would be 14% higher using TSM rather than RMY wind speeds.

2.2.4 Monte-Carlo modeling framework

Comparing measurements of CH_4 emissions with conventional (i.e., inventory) estimates can help identify discrepancies to improve estimates and provide new insights on emissions for mitigation. However, in some cases the two are not directly comparable. Emissions vary temporally, and distribution stations have different equipment to meter and regulate gas, both throughout the city of Calgary and internationally. The local gas utility's inventory includes estimates of emissions from their distribution stations, but rates are aggregated and annualized, requiring downscaling. This renders comparison with snapshot facility-level measurements largely unhelpful. To address these issues, we developed a time-resolved Monte Carlo-based modeling framework to produce an emissions estimate at any given time for individual stations.

To simplify we use four CH_4 source categories at the stations: fugitives (leaks), vents, catalytic heater exhaust, and line heater exhaust. We generate emissions for each of these sources on a given day using source counts, measurement data (from the component-level and historic leak detection surveys), gas throughput data, source-specific emissions factors (EFs), and knowledge of source characteristics and behavior at the stations (e.g., seasonal operating

changes). Each of the four stations were individually modeled owing to their slightly different characteristics, equipment, and operation (see Table 1 and S1).

Measured fugitive, vent, and catalytic heater exhaust rates were aggregated into source-specific emissions rate distributions for the model. The vent class had two subtypes: the gas chromatograph at Station B and the pneumatic valve vents at Station A and C (see Table 1 and S1). Rates from these sources were aggregated into separate distributions rather than a single vent distribution due to differences in rate magnitude.

We generated a distribution of leak counts using the mean and standard deviation of counts from previous component-level surveys assuming a normal distribution. The stations are visited regularly by operators and are in urban areas with passersby and therefore this distribution is unlikely to be non-normal. Source counts of one or zero are used for vents and catalytic heater exhaust emissions depending on the equipment present and operating at the station being modeled. Either the emissions from the gas chromatograph (Station B) or the pneumatic valve vents (Stations A and C) are simulated. No station had both vent source types. Vents are assumed "on" all year in the model; catalytic heaters are only "on" between October and April and "off" (i.e., not emitting) between May and September.

We drew a leak count, N_{leaks}, from the distribution, and for each leak in N_{leaks}, sampled with replacement from the aggregated fugitive CH_4 emissions rate distribution (n = 28). Measurement uncertainty, ε_i, was approximated for each rate sampled, R_i, by randomly drawing from an error distribution (with replacement) centered on zero with a standard deviation of 10%, which is the rated accuracy of the HETEK hi-flow. All rates (with uncertainty) were summed to calculate total fugitive CH_4 emissions, E_{fug}, at a station following Eq. (1), and the process was repeated 10,000 times:

$$E_{fug} = \sum_{i=1}^{N_{leaks}} (R_i * (1 + \varepsilon_i)) \quad (1)$$

The procedure was similar for estimating CH_4 from vents, E_{vent}, and catalytic heater exhaust, E_{cat}. The model generated a distribution of possible rates for these sources using the mean and standard deviation of the aggregated rate distributions. We then drew a rate, R, and error, ε, (from the hi-flow error distribution), with replacement, similar to the method for estimating fugitive emissions. E_{vent} or E_{cat} were estimated as the product of R and $(1 + \varepsilon)$, as vented or catalytic exhaust source counts ≤ 1 at the stations. The process was repeated 10,000 times to generate distributions of potential CH_4 emissions for vents and catalytic heater exhaust accounting for uncertainty.

CH_4 emissions in line heater exhaust were not quantified with component-level techniques. This is a common limitation with instruments such as the hi-flow (Vollrath et al., 2024). To estimate these emissions in the model, we used daily natural gas throughput data for the stations over the study period, estimates for the proportion of throughput consumed by line heaters as process gas (Groebner, 2020), and a generic EF for CH_4 emissions from industrial, commercial, and residential natural gas consumption (ECCC, 2025). To our knowledge, this EF

is an industry standard EF and is very similar to the EF used by the local gas utility—which they adjust based on gas composition analysis—to estimate incomplete combustion emissions from line heaters in their inventory. The gas utility's approach differs slightly from ours in that the utility combines estimated gas consumption by line heaters annually at the asset-level with their EF to estimate incomplete combustion emissions. Differences between the approaches are small, and we surmise that when downscaled, the utility's estimates would be similar to those we derived from modeling but less representative of shorter time scales. We followed Eq. (2) to estimate line heater incomplete combustion CH_4 emissions:

$$E_{lh} = \frac{(\left((Q * (1 + \varepsilon)) * P_{lh}\right) * EF)}{24} \quad (2)$$

where E_{lh} is the line heater exhaust CH_4 emissions rate in kg/h, Q is daily station throughput drawn by the model given a user input date, ε is approximated throughput measurement error drawn from an error distribution centered on zero and assuming error of ±3% (upper limit provided by the gas utility), P_{lh} is the estimated proportion of station throughput consumed by line heaters as process gas (Groebner, 2020), and EF is the incomplete combustion CH_4 EF of 3.7 x 10^{-5} kg CH_4/m^3 of natural gas consumed (ECCC, 2025). Other major sources of incomplete combustion CH_4 at the stations were not present (see Table 1 and S1). The process was repeated 10,000 times.

The resulting distributions of potential fugitive, vent, catalytic heater exhaust, and line heater exhaust CH_4 emissions were summed to generate a modeled estimate of hourly CH_4 emissions from a station, $E_{station}$, on a given day, following Eq. (3):

$$E_{station} = E_{fug} + E_{vent} + E_{cat} + E_{lh} \quad (3)$$

Only relevant sources were simulated for each station, as not all sources were present at all stations. This model provided a reasonable blend of empirical and operational elements.

3. Results and discussion

3.1. Component-level surveys

In general, we did not find many sources of CH_4 emissions in the component-level surveys and the rates quantified were low compared to other sources and rates in the oil and gas supply chain. Figure 3a shows the rates of different types of emissions detected and quantified in the component-level surveys as a proportion of total emissions quantified across all stations. We averaged the rates for continuous or persistent sources that were measured more than once to include in Figure 3.

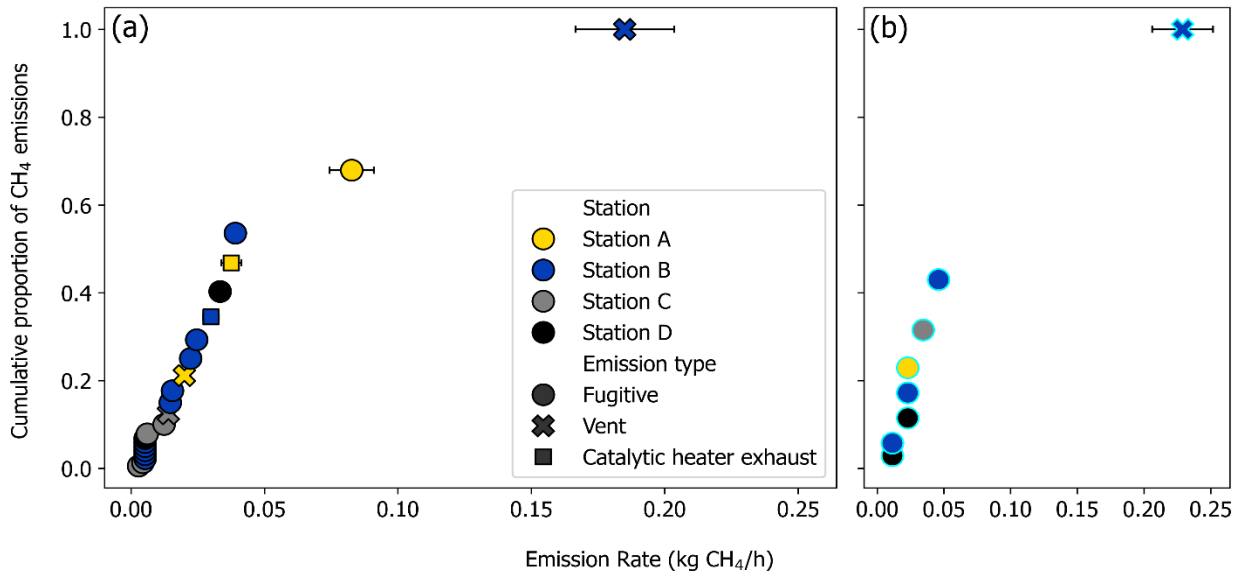

Figure 3. (a) CH_4 rates quantified in the component-level surveys by station and emission type as a cumulative proportion of total emissions quantified across all three surveys at the stations (circle markers with black outline). (b) Rates quantified in historic leak detection surveys at the stations between 2020 and 2023 (circle markers with bright blue outline). Mean rates are shown for sources measured in > 1 survey in (a) and (b). Error bars represent the rated accuracy (±10%) of the hi-flow sampler applied to rate estimates.

The largest source identified in the component-level surveys was a continuous gas chromatograph vent at Station B (Figure 3a). This instrument measures gas composition for custody transfer and billing as natural gas moves from transmission to distribution. We quantified emissions from the vent at 0.16–0.23 kg CH_4/h (mean: 0.19 kg CH_4/h, Figure 3a). Historic leak detection data similarly reported emissions of 0.16–0.32 kg CH_4/h (mean: 0.23 kg CH_4/h, Figure 3b) from the same vent, which was quantified with a hi-flow sampler four times over five surveys conducted between 2020 and 2023 (Figure 3b). The chromatograph vent accounted for 32% of total component-level CH_4 emissions measured in this study and 57% of emissions in the historic leak detection dataset. The higher contribution in the historic data set likely reflects the fact that the component-level surveys in this study captured emissions from a broader set of sources across all stations (e.g., transmission pipeline pneumatic valve vents and catalytic heater exhaust), increasing the denominator of total measured emissions and thereby reducing the relative contribution of the chromatograph vent.

For context, emissions from the chromatograph vent are comparable to the 75th percentile of fugitive emission rates reported in the Clearstone distribution for on-site sources at Alberta oil and gas production facilities (Clearstone Engineering, 2019). However, the vent emits at a rate nearly 13 times lower than the mean rate (2.4 kg CH_4/h) from individual sources reported for two

city-gate stations in Montreal (Williams et al., 2022). If emissions persist at the mean observed rate, the chromatograph vent alone would emit approximately 2 t CH_4/yr.

No other stations had a chromatograph vent. Stations A and C had pneumatic valves on transmission pipeline segments that vented—the quantified rates were an order of magnitude lower than the chromatograph vent at Station B (Figure 3a). No other vent sources were present at the stations. A previous study identified odorizer vents emitting CH_4 at distribution stations in the U.S. (Lamb et al., 2015). The natural gas distributed in Calgary is odorized upstream of distribution stations in the city.

Stations A and B had active catalytic heaters, which are used in combination with process buildings to ensure process equipment is warm, reducing potential for liquids formation or malfunction in cold temperatures. Catalytic heaters can emit through both their exhaust hoods and catalyst beds where heat is generated, both of which are known to emit incompletely combusted CH_4 (Festa-Bianchet et al., 2024). Catalytic heaters are generally turned off during warmer summer months. Mean rates at Station A and B were 0.03 kg CH_4/h and 0.04 kg CH_4/h, respectively. These are an order of magnitude lower than the mean rate (0.28 kg CH_4/h ± 0.04 kg CH_4/h) of 38 catalytic heater exhaust measurements at oil and gas production sites in British Columbia (Festa-Bianchet et al., 2024). Possible reasons for the difference between our results and Festa-Bianchet et al. (2024)'s are sample size, the measurement methods used, smaller heaters in the distribution segment, and differences in fuel gas composition that could affect hydrocarbon destruction efficiency, assuming the heaters are similar models. We measured the largest rates from the catalytic heater exhausts during the winter survey (Figure 2) at these stations. This could suggest emissions vary temporally with temperature, in addition to varying seasonally when "on" or "off" at different times of the year. We also observed CH_4 emissions from the catalyst beds (or emissions that escaped capture by the fume hood) on the units with OGI but could not quantify these due to their temperature and inability to fully capture the emissions with the hi-flow. Similar to oil and gas production sites (Festa-Bianchet et al., 2024), catalytic heaters may be a unique source to distribution stations in cold climate regions.

We detected and quantified several fugitive emissions across the stations. Figure 3a shows that the largest was responsible for 14.3% of total emissions measured across the stations. Station A's catalytic heater pressure relief valve (PRV) was emitting, indicating that the supply gas pressure was too high. During the survey, a station operator attempted a repair and shut the supply gas off to the unit. We also detected a fugitive emission that resulted from two failed mechanical valves on a small separator attached to the line heater at Station D. This caused CH_4 to emit from the end of a plugged line outside the northernmost building at the station (Figure 1d). A station operator made a temporary repair at a later date and replaced the valves after our last survey at Station D.

On average, we detected a higher number of sources in the component-level surveys (Station A: 2; Station B: 6.7; Station C: 2.3; Station D: 0.7) at the stations than reported in the historic leak detection data (Station A: 1; Station B: 1.4; Station C: 1; Station D: 2). We attribute this primarily to measuring catalytic heater exhaust and all vents for CH_4 emissions, which may

have been outside of the scope of field technicians' work as these sources are not typically considered an actionable leak, and supplementing OGI with olfactory methods and soapy water for leak detection. The emergence of new leaks may also partly explain the differences in the number of sources detected in the component-level surveys in this study and the historic leak detection data.

The number of fugitives shown in Figure 3a included many sources from the last survey at Station B (Figure 2). We detected two leaks from threaded connections on gauges attached to the line heaters with OGI that persisted from the November survey. The operator inspected these leaks in November but they were not repaired immediately because of safety reasons related to the cold temperature and risk of equipment damage. This prompted us to inspect all gauges on the line heaters using olfactory methods and snoop in the subsequent survey in March (Figure 2), revealing an additional 6 small leaks. These were below the quantifiable limit of the hi-flow and thus were assigned the instrument's lower limit as a rate (Figure 3a). The operator repaired 7 out of the 8 leaks immediately, leaving one for repair during future maintenance. The quantity of leaks indicates that line heaters may be prone to many small leaks from threaded connections on gauges. Frequent temperature changes as gas enters and exits the heaters—causing metal to expand and contract—could explain this finding.

Working collaboratively with the natural gas utility enabled abatement of fugitive CH_4 emissions as an extension of the research. We used the measured fugitive rates, assumptions on emissions duration, and repair dates to calculate that the component-level surveys avoided 0.9 t CH_4 from being emitted into the atmosphere (see S4 for details on the calculations).

Overall, the stations had relatively few CH_4 emissions. Mean aggregated component-level rates for the stations were 4.3 x 10^{-2} kg CH_4/h (Station A), 0.3 kg CH_4/h (Station B), 3.6 x 10^{-2} kg CH_4/h (Station C), and 1.3 x 10^{-2} kg CH_4/h (Station D). Operators visit them regularly and some process buildings have lower explosive limit (LEL) alarms which trigger operator call outs. The urban nature of the stations, where some are located adjacent to pathways and buildings, may also result in call-ins to the utility if passersby smell CH_3SH. These factors could limit the emissions from the stations. Despite the low rates, the mitigated emissions from threaded connections, leaking valves, and a PRV on a catalytic heater highlight that opportunities to reduce fugitive CH_4 at these stations exist. Much larger rates have been measured at city gate stations in Montreal (Williams et al., 2022), suggesting that urban natural gas distribution sites are not ubiquitously low-emitting.

3.2. Facility-level measurements

The novel application of the human-portable flux plane method in this study to measure facility-level emissions enabled capture of CH_4 emissions from all sources at the stations emitting at the time of the measurements. This included incomplete combustion emissions from line heaters owing to the vertical capabilities of the flux plane method, which were not measured in the component-level surveys because of the height at which plumes are emitted and their temperature. The method allowed for targeting of atmospheric conditions for measurements that

limited vertical plume rise from the stations due to its user-friendliness and practicality (Vollrath et al., 2026). Applying the method addressed an important knowledge gap in the existing research literature related to the sources and rates of emissions at distribution stations where large reductions in gas pressure occur such as those in Calgary. Here we report the quantified rates and explore the most likely sources of CH_4 emissions measured with facility-level measurements.

Figure 4a shows the facility-level flux plane-derived CH_4 emission rate estimates by station over the study period. The rates ranged between 3.4×10^{-2} kg CH_4/h to 0.9 kg CH_4/h, except two measurements at Station C that resulted in substantially higher rate estimates of 2.9 kg CH_4/h and 7.4 kg CH_4/h. Station D emitted at the lowest rates (mean: 3.6×10^{-2} kg CH_4/h; standard deviation: 2.3×10^{-3} kg CH_4/h), while Station B emitted at higher rates (mean: 0.7 kg CH_4/h; standard deviation: 0.15 kg CH_4/h) more consistently than the other stations. This was unsurprising given that Station D is the smallest, has fewer components and pieces of equipment with potential to emit CH_4, and pushes more natural gas through the distribution system during periods of high demand. Station B is the largest, has sources such as a gas chromatograph vent and catalytic heater (see Table 1 and S1 for more details on the stations), and handles a high volume of throughput.

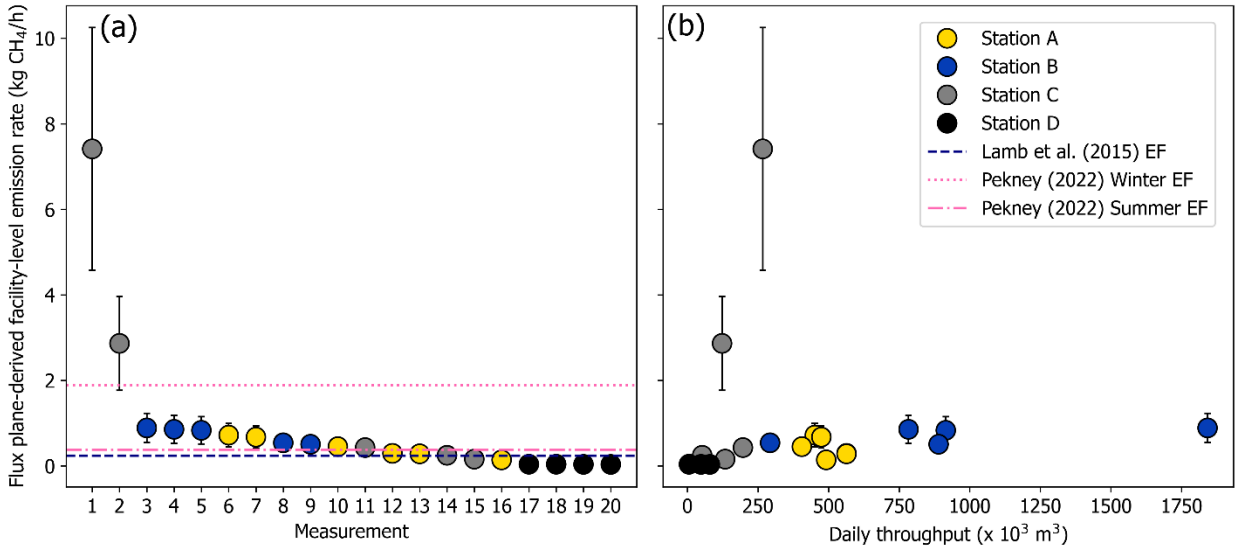

Figure 4. (a) Flux plane-derived facility-level CH_4 emissions rate estimates. Measurements 6 and 7 and 17 and 18 were repeat measurements on the same day, spaced approximately one hour apart. Horizontal lines show CH_4 emissions factors (EFs) derived from measurements at "city gate" stations in the U.S. from Lamb et al. (2015) and Pekney (2022) for comparison. (b) The facility-scale rates plotted against daily natural gas throughput at the stations. Throughput data were provided by the gas utility. Error bars represent the average uncertainty of pole-based flux plane measurements as determined in controlled release testing (Vollrath et al., 2026).

With the exception of the two elevated emission rate estimates at Station C, the CH_4 emissions rates at Stations A and C were generally similar but slightly higher at Station A (A—mean: 0.4 kg CH_4/h; standard deviation: 0.2 kg CH_4/h, B—mean: 0.3 kg CH_4/h; standard deviation: 0.1 kg CH_4/h). These stations are similar in design, equipment, and operating processes and therefore have largely comparable sets of potential CH_4 sources. One key difference is that Station A has an active catalytic heater, whereas the catalytic unit at Station C was unpowered and inactive during the measurement period. In addition, similar to Station D, Station C pushes more gas through the distribution system during periods of higher demand, meaning its throughput can be low or zero at times during the year. In contrast, Station A has higher throughput and receives and distributes gas all year. These operational differences likely explain the slightly higher emissions rates at Station A than Station C.

Mean facility-level emissions rates were 2.5 to 61.7 times larger than the mean of aggregated component-level rates from each survey depending on the station (Station B: 61.7 times, Station A: 9.9 times, Station D: 2.8 times, and Station B: 2.5 times). Despite the large discrepancy, there is little basis to directly comparing component- and facility-level rates further because not all sources were measured in the component-level surveys and measurements at each scale were performed asynchronously. However, the multi-scale measurements and observations of emissions and equipment configurations provide important context for exploring the most likely sources of CH_4 emissions measured in facility-level measurements.

We attribute the vast majority of the flux plane-derived CH_4 emissions rates to incomplete combustion from the line heaters for several reasons. First, with the flux plane method, CH_4 mixing ratios were measured and monitored in near-real time downwind of the stations close to their fencelines using the LI-7810. Based on the mixing ratios, wind direction, and location of equipment, the thermal electric generators (TEGs)—which power the sites and were not quantified on-site—were interpreted to be substantially smaller emitters. Second, other sources that could explain the additional emissions at similar magnitudes were lacking in the on-site surveys. Some fugitive CH_4—which was also not quantified on-site—may have been escaping catalytic heater fume hoods inside buildings at Stations A and B and emitted to the atmosphere through passive building vents. However, based on other measured fugitive CH_4 rates, we hypothesize that these emissions were insufficient in magnitude to explain most of the additional emissions. Third, the highest CH_4 mixing ratios—or stations' plume centerlines—measured with the pole-based flux plane method were located directly downwind of the line heaters and at similar heights to their exhaust stacks (~5 m a.g.l.). Figure S2 shows CH_4 mixing ratio by height for two facility-scale measurements. Plumes were sometimes closer to the ground, but we surmise this was due to differences in the pole operator's elevation relative to the stations during the measurements and atmospheric conditions rather than another source. For example, OGI video taken at Station D on 3 January 2025 showed approximately 1 m downwash of the line heater's plume over tens of seconds (see supplemental video). Fourth, the gas utility indicated that incomplete combustion emissions from line heaters is also the largest source of CH_4 emissions in aggregate in their inventory. These examples support attributing the majority of

facility-level CH_4 emissions that could not be measured in the component-level surveys to incomplete combustion from line heaters.

Repeat pole-based flux plane measurements conducted ~1 hour apart at Stations A and D yielded nearly identical emission rates (Figure 4a), indicating limited variability on hourly timescales and demonstrating good repeatability of the flux-plane method. In contrast, emissions varied substantially over longer timescales. For Stations A, B, and C, most facility-level emission rates were correlated with throughput (Figure 4b), consistent with emissions driven by line heater operation. This confirms the importance of incomplete combustion emissions from the line heaters to total facility-level CH_4 emissions. These stations use vacuum-style heaters that consume ~0.15% of throughput, whereas Station D uses a bath-style heater (~0.23% of throughput), and its emissions were nearly constant and uncorrelated with throughput (Groebner, 2020). This suggests fundamentally different heater operating characteristics, with emissions at Station D effectively switching "on" or "off" seasonally as the station's operations change.

Seasonal operation further implies that emissions are likely lower in summer, when both catalytic and line heaters are turned down or off depending on the station due to reduced heating requirements for equipment and lower or no gas throughput. Consistent with this, summer measurements at some of the same Calgary stations reported substantially lower CH_4 emission rates (Hugenholtz et al., 2021), and similar seasonal contrasts have been observed elsewhere, with winter emissions several times higher than summer emissions at city-gate stations in Ohio (Pekney, 2022, pink lines Figure 4a). These findings highlight challenges in annual scaling and suggest that inventories relying on non-winter measurements—such as the U.S. Environmental Protection Agency's (EPA's) Greenhouse Gas Inventory (GHGI) EF of 0.24 kg CH_4/h/station derived from component-level surveys (Lamb et al., 2015, blue line Figure 4a)—may underestimate emissions if cold-period operation is not captured.

Notably, throughput alone cannot explain the two largest emission rates observed at Station C (2.9 and 7.4 kg CH_4/h), which occurred during the coldest (-15.7 ºC) and windiest (7.7 m/s) conditions of the study. These events, combined with strong downwind odor and otherwise low component-level emissions, suggest abnormal line heater operation, potentially leading to incomplete combustion and venting of CH_4 through exhaust stacks. To our knowledge, the line heater stacks at the stations in this study operate by natural draft: hot exhaust gases rise through and exit stacks, while outside air required for combustion is drawn in. The exact root causes of the high emissions rates are unclear, but very cold conditions can reduce stack air intake by condensing and freezing exhaust gases, while very windy conditions can also disrupt air intake and line heater burner flames, thereby affecting combustion (Marlett, 1997). Measurements were performed at other stations under similar conditions at times during the study period (e.g., very cold conditions on 3 January 2025—see Figure 2), which yielded substantially smaller rate estimates. This suggests that other underlying mechanisms may have contributed to the high emissions rates at Station C, and that very cold and windy conditions alone would not likely elicit this type of response in line heater emissions more broadly. The remaining measurements at Station C were an order of magnitude lower, reinforcing the episodic nature of these events.

Similar, high emission rates from stations with line heaters have been reported elsewhere (Pekney, 2022), which disproportionately influence emissions. Given the magnitude of the rates, the frequency and duration of these events should be better understood to improve estimates of total CH_4 emitted over time.

The magnitude of the emissions rates we measured and attributed to the line heaters at Station C may not be unique to the distribution segment. Tyner et al. (2021) reported rates for line heaters of 1.3 kg CH_4/h and 4.8 kg CH_4/h (approximated based on Figure 6 in Tyner et al. (2021)) at oil and gas production sites in British Columbia (B.C.) measured with aircraft. The type of emission (e.g., fugitive or incomplete combustion) was not reported in the study and the conditions at the time of the measurements are unknown, but the rates are similar to the rates we quantified from stations in Calgary. CH_4 emissions rates of this magnitude from line heaters could thus be a more widespread and frequent phenomena requiring mitigation efforts. More work is needed to diagnose root cause and confirm whether the emissions are abnormal and due to process upsets or within the envelope of routine but variable emissions. Maintenance of line heaters is required to mitigate combustion issues (Groebner, 2020).

Overall, facility-level emission rates measured in this study span and often exceed EFs derived from existing studies, reflecting differences in measurement methods, station configurations, and capture of incomplete combustion emissions from line heaters in measurements. The variability observed across stations, seasons, and operating conditions underscores the need for multi-temporal, facility-level measurements to develop representative EFs and improve urban CH_4 inventories. Finally, the measurements and attribution of emissions in this and other studies highlight line heaters as a critical and under-characterized source requiring targeted mitigation.

3.3. Comparison of modeled and flux plane-derived CH_4 emission estimates

Comparing measurements of CH_4 emissions to estimates derived from conventional approaches such as inventories can help provide insight into whether estimates—which inform climate reporting and mitigation—are representative of real-world emissions. We developed a Monte Carlo-based modeling framework integrating component-level measurements, historic leak detection data, gas throughput, source specific EFs, and understanding of station sources and processes to enable a temporally resolved comparison of snapshot measurements with estimates. The model generated an emission rate estimate for a station in kg CH_4/h on a given day based on four source categories observed at the stations: fugitives (leaks), vents, catalytic heater exhaust, and line heater exhaust.

Figure 5a compares modeled to flux plane-derived estimates for the days on which facility-level measurements were performed at the stations. On average, the flux plane estimates were 13.9 times larger than the modeled estimates (standard deviation: 33.9). Results are skewed by the two large flux plane estimates (2.9 and 7.4 kg CH_4/h), which were 57.3 and 148.3 times larger than modeled estimates, respectively. All flux plane-derived estimates were between 1.6 and 148.3 times greater than modeled estimates for stations. Given the skewed distribution, the

median ratio between facility-level and modeled estimates was 2.8, which was lower than the mean ratio. In decreasing order, the largest discrepancies between facility-level and modeled estimates for stations expressed as ratios were Station C (mean = 44.4, standard deviation = 62.2), Station A (mean = 6.1, standard deviation =3.3), Station B (mean = 2.3, standard deviation = 0.6), and Station D (mean = 1.8, standard deviation = 0.1). The very large gaps between a number of facility-level measurements and modeled estimates, such as those observed for Station C, underscore the difficulty of representing large but infrequent emissions using traditional modeling approaches that scale EFs with activity factors (AFs). Much larger measured than modeled emissions at Station C could reflect broader combustion or operational issues with its line heater requiring mitigation. Further investigation is required.

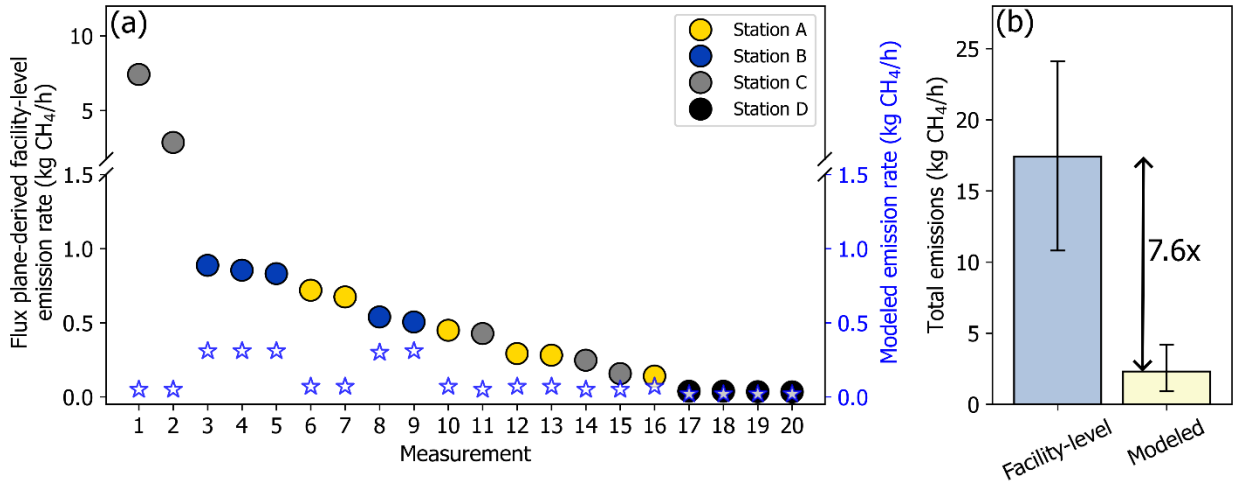

Figure 5. (a) Comparison of individual facility-level flux plane emission rate estimates with temporally-resolved estimates derived from the model developed in this study. Note the broken y-axis. Error bars for individual measurements and modeled estimates are not shown for clarity. (b) Comparison of total CH_4 emissions quantified across all facility-level flux plane measurements with total emissions estimated with the model. The error bar on the facility-level total represents the range of likely estimates based on the average uncertainty of pole-based flux plane measurements as determined in controlled release testing (Vollrath et al., 2026). The error bar on the modeled total represents a 95% confidence interval (CI), calculated by propagating errors through the model for each estimate (§2.2.4).

Figure 5b shows that measured emissions rates at the facility-level totaled 17.4 kg CH_4/h (10.8 kg CH_4/h to 24.1 kg CH_4/h based on the average uncertainty of the flux plane method) across all measurements during the study period, whereas modeled estimates totaled 2.3 kg CH_4/h (95% CI, 0.9 kg CH_4/h to 4.2 kg CH_4/h), or 7.6 times less than the sum of facility-level measurements. We attributed the vast majority of facility-level emissions that could not be measured in component-level surveys to line heater incomplete combustion (§3.2). Provided that our

attribution is correct, after accounting for emissions measured at the component-level we estimate that the incomplete combustion of process gas by line heaters was responsible for a total of 15.5 kg CH_4/h (89.1%) out of the 17.4 kg CH_4/h of facility-level measurements. The two large rates quantified at Station C contributed 10.2 kg CH_4/h or 66% to facility-level emissions attributed to line heaters and 58.6% to all emissions. In contrast, line heater incomplete combustion was only a small fraction of total modeled CH_4 emissions (0.02 kg CH_4/h or <1%), which is 775 times lower than our estimate for these emissions derived from facility-level measurements and attribution. Catalytic heater exhaust was estimated to emit a total of 0.36 kg CH_4/h with the model, with leaks and vents—primarily the chromatograph vent at Station B—estimated to emit the remainder of total modeled emissions (1.9 kg CH_4/h).

There is reasonable agreement between total measured (1.9 kg CH_4/h) and modeled (2.3 kg CH_4/h) emissions attributed to leaks, vents, and catalytic heater exhaust. Slightly higher modeled emissions for these sources are likely due to the inclusion of historic leak detection data in the model, which included a larger rate for the chromatograph vent at Station B than we measured on site. Attribution of facility-level rates did not involve the historic leak detection data and relied on our on-site measurements and other observations only. Furthermore, modeling of Station B's fugitive emissions, which was the largest station with the highest potential to emit CH_4, may have been biased toward higher leak counts, slightly increasing emissions. The distribution of leak counts from the component-level surveys and historic leak detection data that informed the modeling of this station's fugitive emissions was strongly right skewed.

Compared to the other sources modeled, estimates of incomplete combustion CH_4 emissions from line heaters are at odds with estimates derived from facility-level measurements and attribution. We explore several possibilities. First, we used a generic EF of 3.7×10^{-5} kg CH_4/m^3 of natural gas consumed to estimate incomplete combustion emissions from line heaters in the model. The EF is very similar to the EF used by the gas utility in their inventory and to our knowledge is used widely to estimate CH_4 emissions from different end uses of natural gas. It is listed as an EF by Environment and Climate Change Canada (ECCC) and is included in the Canadian Energy Partnership for Environmental Innovation (CEPEI) Emissions Estimation Manual, which provides emissions factors and methodological guidance to gas distributors, other companies, and consultants in Canada for estimating emissions (ECCC, 2025; CGA, n.d.). This EF could be too small. Second, line heaters, as well as catalytic heaters, are used on oil and gas production sites (Festa-Bianchet et al., 2024) and natural gas distribution sites. Equipment are the same but EFs listed by ECCC to estimate CH_4 emissions from natural gas end use differ by two orders of magnitude depending on sector/consumer classification (8.2×10^{-3} kg CH_4/m^3 natural gas consumed for oil and gas producers in Alberta vs. 3.7×10^{-5} kg CH_4/m^3 natural gas consumed for industrial, commercial, residential, and most other end users, ECCC, 2025). These EFs could differ due to differences in gas composition in production and distribution settings; however, the EF used in this study and more broadly by gas utilities may not represent real emissions from equipment that combusts gas if EF selection is based on consumer classification or segment of the natural gas supply chain only. Further study is required. Third, line heaters could consume

much more gas than estimated, but to our knowledge consumption rates used to model emissions in this study were based on metered consumption at a distribution station in the U.S. (Groebner, 2020). Fourth, combustion efficiencies and thus emissions rates could be highly variable, which would not be captured with traditional EF x AF approaches. Fifth, despite our efforts to resolve modeled estimates temporally with facility-level measurements, conventional EF x AF approaches typically fail to capture larger but infrequent emissions such as those observed at Station C. Overall, some combination of these possibilities probably explains the differences between estimates.

The results shown here apply to the timing of the facility-level measurements and modeled estimates, and caution should be taken in scaling the findings from this study up temporally. Measurements and modeled estimates, as well as discrepancies between the two, only represent snapshots in time. However, results do suggest that distribution stations are emitting more CH_4 than estimated using conventional approaches and that line heater incomplete combustion emissions are substantially underrepresented.

The modeling framework developed in this study is an improvement over conventional inventory approaches in that it integrates source counts, component-level measurements, operational data (throughput), and process-based understanding to generate time resolved estimates of CH_4 emissions. This noted, we do not attempt to reconcile modeled estimates with rates derived from facility-level measurements because underestimated line heater incomplete combustion emissions in the model could be due to a number of factors, which should be revisited by researchers and workers at gas utilities. Additionally, revising the EF used in modeling would still underestimate total incomplete combustion CH_4 emitted by line heaters at distribution stations; conventional EF x AF approaches cannot capture the heavier tail of rates that occur less frequently, such as those measured from line heaters in this and other studies (Tyner et al., 2021; Pekney, 2022), which can disproportionately affect emissions. This underscores the need to compliment modeling with facility-level measurements, to identify emissions that escape conventional estimates for reporting and mitigation.

Our results have broader implications. Given the potential issues we highlighted with the incomplete combustion EF, CH_4 emissions from natural gas end use could also be substantially underestimated in other cases where it or similar EFs are used to estimate and track emissions. Notably, recent city- and neighborhood-level atmospheric studies in New York, NY (Zhao et al., 2026) and Calgary, AB (Xing et al., 2026) have indicated that emissions from natural gas end use dominate the CH_4 signal across seasons in these urban areas. Incomplete combustion emissions were also identified as a large source of urban CH_4 emissions in aggregate in a reanalysis of data from several city-level studies by Vollrath et al. (2025), demonstrating an area where mitigation is needed. We resolved line heaters as a pathway for these incomplete combustion emissions and a mitigation target. While some emissions are expected as combustion is never fully complete, strategies to ensure high efficiency combustion should be developed and implemented for line heaters. Finally, large rates that disproportionally affect emissions should also be better

understood to eliminate their occurrence through improved maintenance or other methods, yielding material reductions of urban CH_4 emissions and climate benefit.

4. Conclusion and outlook

This study combined component- and facility-level measurements and modeling to characterize and advance understanding of CH_4 emissions from four natural gas distribution stations in Calgary, Alberta, addressing key gaps in understanding station-level contributions to urban CH_4 budgets and mitigation.

On-site surveys showed that fugitive emissions were generally low and readily abatable, confirming that periodic component-level inspections remain valuable for identifying degraded equipment and reducing climate and safety risks. However, these methods only captured 1.6–40.1% of total emissions depending on the station, as they could not quantify incompletely combusted CH_4 emitted in line heater exhaust due to the height at which plumes are emitted and their temperature.

The novel application of the human-portable flux plane method enabled quantification of total station emissions, including emissions from line heaters—which combust process gas prior to pressure regulation and are generally outside of the capabilities of component-level methods—in a user-friendly and practical manner. Facility-level flux-plane measurements revealed substantially higher emission rates, ranging from 3.4×10^{-2} to 7.4 kg CH_4/h, with most emissions attributable to the incomplete combustion of process gas by the line heaters. Two extreme emission events, measured at the same station under very cold and windy conditions, were likely caused by line heater operating issues, underscoring the importance of facility-level measurements for detecting episodic events that contribute disproportionately to total emissions. Measured rates were similar in magnitude to rates quantified from line heaters at oil and gas production sites in B.C. using aircraft (Tyner et al., 2021), suggesting that larger emissions from line heaters may be a more widespread phenomenon across the oil and gas supply chain in production regions and cities. There is a need to investigate these larger rates further and determine their root cause for mitigation.

Emissions were stable on hourly timescales but varied over weeks and seasons at most stations. Facility-level, flux plane-derived CH_4 emission rates were generally correlated with daily throughput, consistent with incomplete combustion dominating emissions and line heaters operating more intensively during periods of high demand. Situating the rate estimates from this work in the context of other studies of CH_4 emissions from distribution stations indicated that seasonal operating practices, including heater turndown or shutdown in summer, can further contribute to temporal variability of emissions, highlighting the need for inventories to account for seasonal effects.

The Monte Carlo-based modeling framework developed in this study generated temporally resolved estimates of CH_4 emissions, addressing issues with comparing snapshot measurements with estimates typically derived from annualized inventories and downscaled. Measured facility-level rates exceeded modeled rates by factors of 1.6–148.3, totaling 17.4 kg

CH_4/h (10.8 kg CH_4/h to 24.1 kg CH_4/h based on method uncertainty) across all measurements compared with 2.3 kg CH_4/h (95% CI, 0.9 kg CH_4/h to 4.2 kg CH_4/h) from the model. Emissions attributed to leaks, vents, and catalytic heater exhaust in measurements and modeling were similar (1.9 kg CH_4/h vs. 2.3 kg CH_4/h); emissions attributed to incomplete combustion from line heaters in facility-level measurements were 775 times greater than modeled estimates, indicating that stations may be emitting more CH_4 than previously recognized due to conventional estimates underrepresenting line heater emissions. Further investigation of incomplete combustion CH_4 emissions from line heaters, underlying EFs, and other modeling assumptions is required to improve estimates of total emissions from stations generally.

Overall, the results show that line heaters are the dominant and most variable CH_4 source at the distribution stations studied, facility-level measurements capturing all CH_4 emissions offer a complementary perspective needed to identify episodic high-emission events that fall outside of the scope of component-level surveys, and that conventional approaches are underestimating CH_4 emissions from distribution stations because emissions from the incomplete combustion of process gas by line heaters are underrepresented. Consistent with results from city-level measurement and source attribution studies in Canada, the U.S., and other locations, this study identifies the incomplete combustion of natural gas as an important source of urban CH_4 emissions and line heaters as a specific and under-characterized pathway for those emissions with potential mitigations.

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Supplemental material to "Multi-scale measurements and temporally resolved modeling of methane emissions at natural gas distribution stations"

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S1. Descriptions of the stations

In Figure 1 in the main text, Stations A, B, and C are all large with similar infrastructure on site. In general, these stations each have line heaters which heat the gas prior to its pressure regulation, a large "main run" building where the high-pressure gas is regulated, and several segments of above-ground pipe with connectors and mechanical valves. Stations A and C have additional segments of transmission pipeline above-ground where the direction and flow of gas through the transmission system can be adjusted using a remotely operated manifold that controls three gas-driven pneumatic valves. To maintain gas flow, the valves on these pipelines continuously vent gas.

Stations B and C each have a separator to remove additional impurities in received gas. The separator at Station B is several times larger than the separator at Station C, possibly reflecting much higher throughput. Both separators have pressure relief valves. Stations A, B, and C each have one catalytic heater, which are a known source of CH_4 emissions in the Canadian upstream oil and gas industry (Festa-Bianchet et al., 2024), to heat process buildings and associated equipment. The catalytic heater at Station C was not operational because this station did not have direct current (DC) electricity to power the unit. These three stations generated their own electricity using thermal electric generators (TEGs) or other generators, but the TEGs (two units) at Station C were smaller and did not produce DC power. Furthermore, these three stations had standalone buildings to house electronics and wiring related to Supervisory Control and Data Acquisition (SCADA) systems. Station B was the largest of all stations and had a gas chromatograph—which continuously vented—connected at the point where the gas transfers custody from transmission to distribution within the facility to determine its composition.

Station D was unique from the other stations in that its spatial footprint was smaller and it had fewer equipment with potential to emit CH_4. No pneumatic valves or catalytic heaters were present on site. This station had a bath-style line heater with a single exhaust stack (main text Figure 1d), where process gas is used to heat a liquid bath at atmospheric pressure, which in turn heats the gas that flows through the station. In contrast, the other stations had one or two vacuum-style line heater units with multiple exhaust stacks (Station A: one unit, six stacks; Station B: two units, four stacks/unit for eight stacks total; Station C: one unit, four stacks) where

the liquid bath is under vacuum to reduce the energy required to raise the bath's temperature, and the gas is heated indirectly with steam (Groebner, 2022). A y-strainer separator was attached to the line heater at Station D to filter impurities from the received gas and had a series of mechanical valves attached to it.

Stations A and B operate continuously throughout the year, whereas Stations C and D are currently seasonal operations, pushing more gas through the system when temperatures drop and demand increases. The line heaters at Stations C and D are turned down or off in summer due to little or no station throughput and thus lack of a need to heat the gas. New residential development is underway around Station C—it is unclear if this station will remain a seasonal station or not with urban growth. Ultrasonic flow meters measured throughput at all stations.

S2. Flux plane quality assurance

We quality-assured (QA'd) the flux plane measurements following the protocol developed by Vollrath et al. (2026) to ensure that the majority of stations' plumes were captured by the pole in the vertical dimension, as there is a fixed limit to the height of the measurements. The QA protocol attempts to understand the vertical geometry of the experiments using the height and characteristics of the emissions source, the height of the receptor, atmospheric conditions, and the downwind distance of the measurements. We refer readers to Vollrath et al. (2026) for further details. We also used OGI to confirm the behavior and dispersion of the line heater plumes prior to performing the pole-based measurements.

A total of three measurements were flagged by the QA protocol based on geometry (i.e., potentially insufficient measurement height). We examined the time series of CH_4 mixing ratios for these measurements in more detail found that all captured the majority of plumes vertically, as indicated by decreasing CH_4 with height and the shape of plumes in the vertical dimension, as observed in the data (Vollrath et al., 2026). This confirms that most measurements were valid.

One measurement at Station D on 13 November 2024 had very high and variable background CH_4 mixing ratios (2.4 ppm to 2.7 ppm). These fluctuations were larger in magnitude than the CH_4 enhancement from the station. As such, we were unable to disambiguate between target and non-target emissions in this measurement and discarded it. We noted a potent smell consistent with the combustion of organic matter upwind, which could explain the substantially elevated background emissions. On this date, the wind was blowing from the south. The CH_4 emissions could have been coming from a large, closed landfill, wastewater treatment plant, or a small cattle operation hundreds of meters to kilometers upwind of the target source.

Overall, data processing and quantification were performed on 20 out of the 21 of the facility-level flux plane measurements after quality-assuring the data.

S3. Additional details on wind measurements and vertical profile estimations

On 11 November 2024 wind data were not recorded with the TriSonica Mini (TSM) at Stations B and C due to a wiring error. On 3 January 2025, we experienced temperature-related reliability issues with the TSM at Stations B, C, and D and wind data were not recorded. The temperature

during the facility-scale measurements on 3 January 2025 was -19 degrees Celsius, which is near the lower limit for the TSM's operating temperature. We collected wind data at the stations with an RM Young 81000 after 3 January 2025. We also collected data with both anemometers on 21 February 2025 to compare measured wind speeds (Figure S1).

We used wind data from a Calgary Regional Airshed Zone (CRAZ) air quality monitoring station located at 50.955120, -113.969787 to fill in wind data gaps. We selected this station due to its proximity in between Stations B, C, and D in south Calgary. The alternative was the Environment and Climate Change Canada (ECCC) weather station at the Calgary International Airport which is in the northeast of the city. Wind speed and direction are measured at a height of 10m at the CRAZ station, while trace gases and particulate matter are measured at lower heights.

Wind speed and direction were measured at 2.2m with the RM Young 81000. The pole-based flux plane method requires estimating a vertical wind profile, for which we used a power law (Vollrath et al., 2026). For the coefficient in the power law, we used 0.17 (Heier, 2014) and 0.24 depending on the location of the station in Calgary and the surrounding land use (more rural vs. urban). The coefficient of 0.24 chosen to represent vertical wind shear at urban locations is similar to 0.25 recommended by the U.S. Environmental Protection Agency (EPA, 2000) for urban environments under D atmospheric stability classes (similar to almost all of our measurements). The power law was used with these coefficients to extrapolate wind speed estimates at the various heights to the heights of the grid cell centers in the flux plane (see Vollrath et al., 2026 for more details).

Temperature and atmospheric pressure were taken from the Environment and Climate Change Canada (ECCC) weather station at the Calgary International Airport (WMO ID: 71877) to use in converting CH_4 concentration in ppm to mass concentration in quantifying the emissions with the flux plane method (Vollrath et al., 2026).

S4. Tracking CH_4 emissions avoided through on-site detection and abatement

To calculate the CH_4 emissions avoided, we assumed that detected and repaired fugitive sources would have continued emitting for one-half a year if they had not been identified as part of the research. Some fugitives were not immediately repaired. We tracked these repair dates and subtracted the CH_4 emitted from the date that the fugitive emission was detected until it was repaired by operators from the total potential avoided emissions. Following this approach, we estimate that the quantity of fugitive emissions avoided by the on-site research at the stations totaled 0.9 t CH_4/yr over the duration of the study.

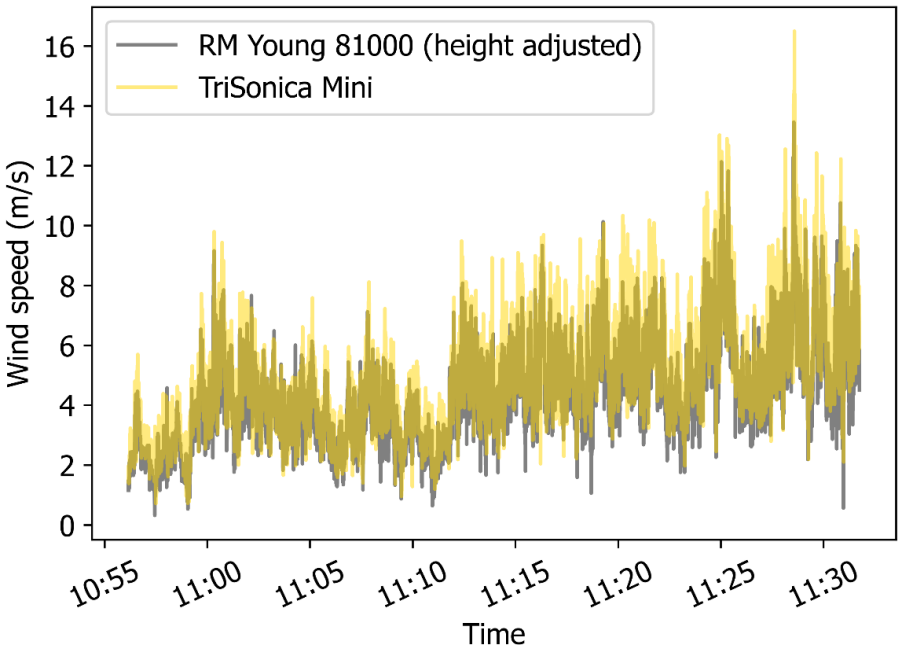

Figure S1. Comparison of wind speed measurements with the TriSonica Mini (TSM) and RM Young (RMY) 81000 anemometers on 21 February 2025. Mean wind speeds were 5.0 m/s (standard deviation = 1.8 m/s) and 4.4 m/s (standard deviation = 1.7 m/s) for the TSM and RMY, respectively. RMY measured wind speeds in the figure were adjusted for height using the method in S3 to match the height at which wind was measured with the TSM (1.9 m) for comparison.

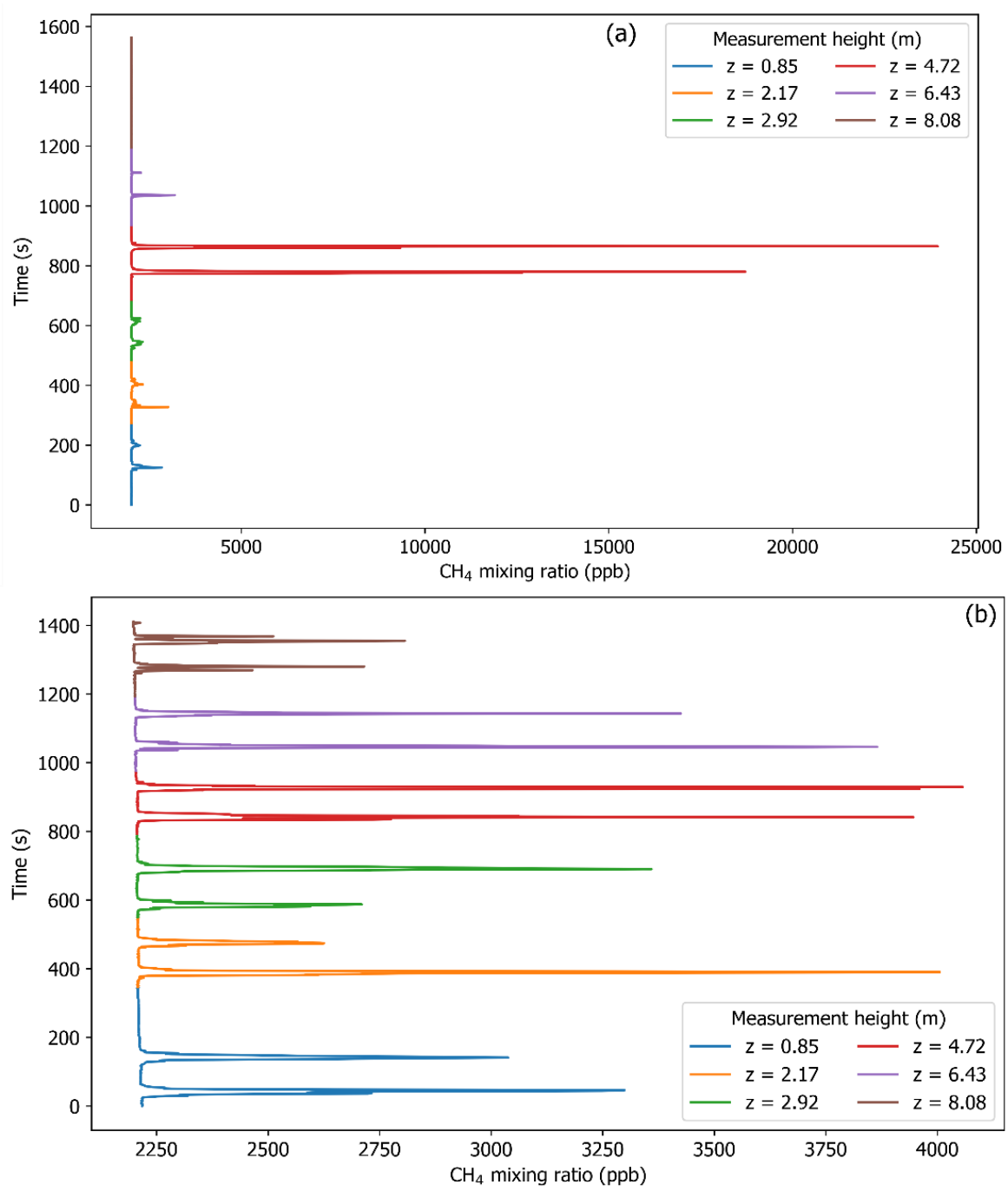

Figure S2. Pole-based measurements of CH_4 mixing ratios by measurement height relative to the surface performed outside of stations' fencelines (see Vollrath et al., 2026 for more details on the flux plane pole method). (a) Station C on 24 October 2024 and (b) Station B on 3 January 2025. The heights at which the highest mixing ratios were measured were generally consistent with the heights of line heater exhaust stacks and their incomplete combustion CH_4 plumes.

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