

A Stable Column $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ Ratio over Los Angeles (2011–2025): An Inventory-Independent Test of Urban Methane Policy

Jiani Yang¹, Xianlei San¹, Ellin Qiao¹, Zhao-Cheng Zeng², Thomas Pongetti³, Yangcheng Luo⁴,
Carl Percival³, Yuk L. Yung¹, and Christian Frankenberg^{1,3}

¹ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA.

² School of Earth and Space Sciences, Peking University, Beijing, China.

³ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

⁴ Laboratoire de Météorologie Dynamique/Institut Pierre-Simon Laplace, Sorbonne Université, École Normale Supérieure, Université Paris Sciences et Lettres, École Polytechnique, Institut Polytechnique de Paris, Centre National de la Recherche Scientifique, Paris, France.

Corresponding author: Jiani Yang (yjn@caltech.edu)

Preprint statement. This manuscript is a non-peer-reviewed preprint submitted to **EarthArXiv**. It has been submitted to *Geophysical Research Letters* for peer review and possible publication. Subsequent versions of this manuscript may have different content. If accepted, the final peer-reviewed version will be available via the “Peer-reviewed Publication DOI” link on the right-hand side of this EarthArXiv page. The authors welcome feedback; please contact the corresponding author.

A Stable Column $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ Ratio over Los Angeles (2011–2025): An Inventory-Independent Test of Urban Methane Policy

Jiani Yang¹, Xianlei San¹, Ellin Qiao¹, Zhao-Cheng Zeng², Thomas Pongetti³, Yangcheng Luo⁴, Carl Percival³, Yuk L. Yung¹, and Christian Frankenberg^{1,3}

¹ Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA.

² School of Earth and Space Sciences, Peking University, Beijing, China.

³ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

⁴ Laboratoire de Météorologie Dynamique Institut Pierre-Simon Laplace, Sorbonne Université, École Normale Supérieure, Université Paris Sciences et Lettres, École Polytechnique, Institut Polytechnique de Paris, Centre National de la Recherche Scientifique, Paris, France.

Corresponding author: Jiani Yang (yjn@caltech.edu)

Key Points:

- Fifteen years of CLARS-FTS show no significant trend in the column $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ ratio over Los Angeles ($-0.005 \pm 0.006 \text{ yr}^{-1}$, $p = 0.84$).
- Basin methane co-varies most strongly with residential natural-gas use, implicating the distribution network and landfills.
- The ratio requires no emission inventory, giving an observation-only test that shows no detectable effect of methane-targeted policy.

Abstract

We extend the column-averaged CH_4 and CO_2 (XCH_4 , XCO_2) record from the California Laboratory for Atmospheric Remote Sensing (CLARS) through July 2025, spanning 15 years over the Los Angeles megacity. CLARS retrievals show persistent enhancements of both gases above the free-tropospheric background, with a strong excess correlation ($R = 0.93$) and an emission ratio $\Delta\text{XCH}_4/\Delta\text{XCO}_2 \approx 5.1 \text{ ppb ppm}^{-1}$ that has no significant trend over 2011–2025 ($-0.005 \pm 0.006 \text{ yr}^{-1}$, $p = 0.84$). Because the ratio is self-normalizing and requires no emission inventory, it provides an observation-only metric that is robust to transport and boundary-layer variability. The ratio peaks in winter and is lowest in summer, and the relative pattern of methane hotspots in the retrieved field is essentially unchanged, co-located with landfills and energy infrastructure. Methane co-varies most strongly with residential natural-gas consumption (R^2 up to 0.43) and negligibly with other sectors. The stable ratio does not imply that absolute methane emissions were constant: the basin CH_4 and CO_2 signals declined by comparable relative amounts and largely cancel in the ratio. What 15 years of observations do show is that methane has fallen no faster than CO_2 -correlated activity, so methane-targeted regulation has left no detectable signature on the basin's CH_4 -to- CO_2 balance, and mitigation aimed specifically at fugitive gas and landfill sources remains necessary.

¹Deceased.

Plain Language Summary

Methane is a powerful greenhouse gas, and in big cities like Los Angeles most of it leaks from the natural-gas system and from landfills. For 15 years, an instrument on Mt. Wilson called CLARS has measured methane and carbon dioxide over the city using reflected sunlight. We use these measurements to track how much methane the city releases compared with carbon dioxide. This comparison is more reliable than either gas alone, because winds and weather affect both in the same way and largely cancel out. We find that this balance has stayed remarkably steady from 2011 to 2025: it rises every winter and falls every summer, but its long-term level has not changed. Both signals declined together, so the steady balance does not mean methane stopped being released; it means methane fell no faster than carbon dioxide did. The places emitting the most methane are the same year after year: landfills and the industrial east side of the basin, and methane rises and falls with how much natural gas homes use for heating. Even though California has passed laws to cut methane, we see no sign of a reduction beyond the general decline in the city’s energy use.

1 Introduction

Methane (CH_4) is the second most important anthropogenic greenhouse gas after carbon dioxide, with a 20-year global warming potential roughly 80 times that of CO_2 (IPCC, 2021). Because of its short atmospheric lifetime and high radiative efficiency, rapid reductions in methane emissions offer one of the most effective near-term levers for slowing the rate of global warming (Ocko et al., 2021), and methane has consequently become a focus of both international pledges and sub-national regulation. Reliable quantification of urban methane sources, where emissions are dense, heterogeneous, and policy-relevant, remains a central challenge for the global methane budget (Saunio et al., 2020).

Los Angeles (LA) is among the most intensively studied methane “hotspot” megacities. Multiple independent lines of evidence indicate that fugitive losses from the natural-gas system, supplemented by landfills and other waste sources, dominate the urban methane budget (Wennberg et al., 2012; Hsu et al., 2010; Hopkins et al., 2016). Isotopic and ethane–methane tracer studies attribute the majority of the excess methane to fossil (natural-gas) sources rather than biogenic activity (Townsend-Small et al., 2012; Wunch et al., 2016), while aircraft and surface networks have repeatedly found top-down emissions exceeding bottom-up inventories (Wunch et al., 2009; Cui et al., 2015; Yadav et al., 2019). Discrete super-emitters, including individual landfills and the 2015 Aliso Canyon blowout, can contribute disproportionately to the basin total (Duren et al., 2019; Plant et al., 2019), complicating attribution from sparse measurements. These findings have motivated California regulations specifically targeting methane, including SB 1371 (natural-gas leak abatement) and SB 1383 (short-lived climate pollutant reductions).

Sustained, spatially resolved observations are required to test whether such policies have altered urban methane. The California Laboratory for Atmospheric Remote Sensing (CLARS), located on Mt. Wilson overlooking the LA Basin, provides this constraint by retrieving column-averaged dry-air mole fractions of CH_4 and CO_2 (XCH_4 , XCO_2) from reflected sunlight over 33 surface reflection points several times per day (Fu et al., 2014; Wong et al., 2015; Zeng et al., 2021). Early CLARS analyses mapped basin CH_4 : CO_2 ratios (Wong et al., 2015), inferred monthly emission trends (Wong et al., 2016), and established that the seasonal methane signal correlates with residential and commercial natural-gas consumption (He et al., 2019). Most recently, Zeng et al. (2023) applied a tracer–tracer inversion to a decade of CLARS data (2011–2020) and reported that the top-down decline in LA methane is much smaller than bottom-up estimates, highlighting a persistent

discrepancy in the methane budget.

Here we extend the CLARS record through July 2025, now spanning 15 years, and analyze urban methane through the column emission ratio $\Delta\text{XCH}_4/\Delta\text{XCO}_2$. Our contribution is methodological as well as empirical. Because the ratio is self-normalizing and requires neither an emission inventory nor a fossil/biospheric partitioning, it is far less sensitive to transport, boundary-layer variability, and inventory error than either absolute concentrations or inventory-scaled emissions. It therefore isolates the quantity that methane-targeted regulation is expected to change, and supplies an observation-only test of whether a decade and a half of such regulation has altered urban source behavior. We address three questions: (i) Has the observed $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ ratio changed over 15 years of active emission-control policy, and what does its behavior imply about absolute methane emissions? (ii) What governs its seasonal and diurnal variability? (iii) Can sector-resolved natural-gas consumption explain the spatial and temporal patterns of methane?

2 Data and Methods

2.1 CLARS-FTS Observations and GFIT3 Retrieval

CLARS-FTS surveys the LA Basin every 1.5–2 h, observing 33 predefined surface reflection points and a local diffuse reflector (Spectralon) that samples the free-tropospheric background (Fu et al., 2014). We adopt the retrieval configuration of Fu et al. (2014) without modification. Column abundances are retrieved with the full-physics GFIT3 algorithm, which pairs an optical-property-based principal-component-analysis (O-PCA) radiative-transfer forward model (Natraj et al., 2007, 2010; Spurr et al., 2013) with an optimal-estimation inverse model (Rodgers, 2000). Retrievals minimize the standard optimal-estimation cost function, which balances the spectral fit residual against the departure from the a priori state, and are iterated with the Levenberg–Marquardt method; the measurement vector comprises the O_2 , weak- CO_2 , CH_4 , and strong- CO_2 bands, and the state vector comprises trace-gas slant columns and aerosol and surface properties (Text S1). Aerosol scattering is treated explicitly in the forward model, and the O_2 and continuum filters remove the most heavily aerosol-loaded scenes; residual scattering nonetheless remains a source of retrieval bias that we return to in Section 3.5.

Soundings are screened to remove cloud- and aerosol-contaminated data: O_2 ratio outside 0.85–1.02, signal-to-noise ratio < 100, solar zenith angle > 70° , and spectral-fit residuals exceeding 1σ above the mean (Figure S1).

2.2 Excess Mole Fractions and the Emission Ratio

Excess (enhancement) column abundances are computed by subtracting the background values ($\text{XCH}_{4,\text{BK}}$, $\text{XCO}_{2,\text{BK}}$), constructed from the Spectralon free-tropospheric retrievals and NOAA/Mt. Wilson Observatory nighttime flask measurements, from the in-basin values (Zeng et al., 2023):

$$\Delta\text{XCO}_2 = \text{XCO}_{2,\text{LA}} - \text{XCO}_{2,\text{BK}} \quad (1)$$

$$\Delta\text{XCH}_4 = \text{XCH}_{4,\text{LA}} - \text{XCH}_{4,\text{BK}} \quad (2)$$

The column emission ratio $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ (ppb ppm⁻¹) indicates methane emissions relative to CO_2 . Because the lifetimes of both gases greatly exceed the basin mixing time, their excess mole fractions are highly correlated within source regions, and the ratio is insensitive to common transport variability. Two caveats accompany the differencing in Equations 1–2. First, the in-basin and background retrievals are not strictly comparable partial columns: the basin view follows a

long, low-elevation grazing path to Mt. Wilson that double-weights the boundary layer, whereas the Spectralon target is sampled along a near-vertical solar path through the free troposphere. The excess is therefore an operational enhancement rather than a formal partial-column difference, and taking the CH₄-to-CO₂ ratio (rather than either excess alone) is what makes the metric robust, because the differing air-mass weightings largely cancel between the two co-located tracers. Second, ΔXCO₂ carries a biospheric seasonal component that is not part of the fossil signal; we discuss its treatment and the associated uncertainty in Section 2.3 and evaluate its impact in Section 3.5.

2.3 CO₂ Inventory and Methane Emissions

Following the tracer–tracer inversion method (He et al., 2019; Zeng et al., 2023), monthly methane emissions are derived by scaling a CO₂ emission inventory by the observed ratio:

$$E_{\text{CH}_4} = \left(\frac{\Delta\text{XCH}_4}{\Delta\text{XCO}_{2,\text{ff}}} \right) \times E_{\text{CO}_2} \times \left(\frac{\text{MW}_{\text{CH}_4}}{\text{MW}_{\text{CO}_2}} \right) \quad (3)$$

where E_{CO_2} is the monthly CO₂ emission from the inventory, ΔXCO_{2,ff} is the fossil-fuel component of the CO₂ excess, and MW_{CH₄}/MW_{CO₂} = 16/44 is the molecular-weight ratio. The CO₂ inventory is a continuous 2011–2025 Basin product: ODIAC (Oda and Maksyutov, 2011) provides the historical fields through 2023, and the 2024–2025 fields are extrapolated from the GRACED near-real-time inventory (Dou et al., 2022) using the mean ODIAC/GRACED scaling factor over the overlapping 2019–2023 period, regridded and clipped to the basin domain (Text S2).

The distinction between total and fossil CO₂ excess in Equation 3 matters because ΔXCO₂ contains a biospheric seasonal cycle (photosynthetic drawdown in spring and summer, respiration in autumn and winter) that is absent from the fossil-fuel inventory. We isolate the fossil component ΔXCO_{2,ff} by removing the biospheric contribution estimated from the seasonal cycle of background (Spectralon) CO₂, following Zeng et al. (2023); the residual scales the inventory. This correction is the largest single source of uncertainty in the absolute methane emissions: the fossil CO₂ inventory has only a weak intrinsic seasonal cycle, so an imperfect biospheric removal maps directly onto the seasonal amplitude of the derived emissions. For this reason we frame the trend analysis in terms of the directly observed ratio ΔXCH₄/ΔXCO₂ (Figures 1–3), which requires neither the inventory nor the fossil/biospheric partitioning, and treat the absolute emissions (Figure 4a) as a secondary, inventory-dependent product.

2.4 Natural-Gas Consumption Data

Monthly natural-gas consumption (therms) for 2012–2025 was obtained from Southern California Gas Company records, resolved by ZIP code and by customer class (residential, commercial, industrial). Consumption was aggregated to basin totals and to CLARS station footprints to evaluate co-variation with retrieved methane.

3 Results and Discussion

3.1 A Stable Emission Ratio over 15 Years

Figure 1 summarizes the observing geometry and the core result. CLARS samples 33 reflection points across the basin (Figure 1a), with the densest coverage over the San Gabriel Valley and eastern basin where landfills cluster. The monthly ΔXCH₄/ΔXCO₂ ratio (Figure 1b) exhibits a pronounced and repeatable seasonal cycle but no significant long-term trend: a deseasonalized linear

fit yields $-0.005 \pm 0.006 \text{ yr}^{-1}$ ($p = 0.84$) over 2011–2025. The excess correlation between ΔXCH_4 and ΔXCO_2 (Figure 1c) is strong ($R = 0.93$ at the observation level; slope $\approx 5.1 \text{ ppb ppm}^{-1}$), consistent with earlier CLARS analyses (Wong et al., 2015; Zeng et al., 2023). The stability of the ratio across 15 years, despite California climate legislation (e.g., SB 1383, SB 1371) targeting methane, indicates that the methane-to- CO_2 emission balance of the basin has not measurably shifted.

3.2 Seasonal and Diurnal Structure

The emission ratio peaks in winter and early spring and reaches a minimum in summer (Figure 2a). Because basin CO_2 emissions have weak seasonality, this cycle is driven primarily by methane: a shallow winter boundary layer concentrates surface emissions, heating demand raises natural-gas throughput, and summer mixing and biospheric uptake dilute the signal. Seasonal emission maps (Figure 2b) show the highest methane over the eastern and San Fernando Valley sectors in all seasons. The diurnal composite (Figure 2c) reveals a morning rise to a mid-day plateau, with the highest ratios in winter (DJF) throughout the day, consistent with a persistent fugitive source modulated by boundary-layer evolution.

3.3 Persistence of the Spatial Pattern

Station-level methane emissions are derived only for the subset of targets that can be matched to a collocated CO_2 inventory grid cell and that carry a continuous record; of the 33 reflection points (Figure 1a), 9 satisfy both criteria (at least eight years of quality-screened retrievals within the inventory domain) and enter the persistence analysis, while the remaining targets are used for the basin-mean quantities. This is why Figures 3 and 4 show 9 stations rather than 33. To test whether the spatial distribution of methane has changed, we normalize each year’s station emissions by the basin mean, isolating the relative pattern from the basin-wide magnitude (which tracks the declining CO_2 inventory). The station $\times$ year “barcode” (Figure 3a) shows near-constant horizontal banding: stations that are hotspots remain hotspots throughout 2011–2025, and the lowest-emitting sites remain lowest. Per-station trends in relative emission (Figure 3b) are small ($< \sim 1\%$ of the basin mean per year), with most confidence intervals spanning zero. The relative pattern of the retrieved methane field is therefore stationary, with its maxima co-located with landfills and the eastern industrial corridor (Figure 1a). We treat this as supporting rather than primary evidence, for the reason given next.

We caution that the CLARS slant-column geometry complicates a purely spatial reading of these maps. Each target enhancement integrates absorption along the entire grazing path from Mt. Wilson to the reflection point, so more distant targets sample not only their own footprint but also the intervening basin air; the maps are thus path-integrated rather than point measurements. Because this viewing geometry is fixed from year to year, part of the apparent interannual persistence could reflect the invariant sampling footprint rather than genuinely stationary emissions. We regard the persistence as a robust statement about the retrieved field, but note that disentangling the true surface-emission pattern from the fixed-geometry fingerprint would require multi-angle or trajectory-resolved sampling beyond the scope of this study.

3.4 Source Attribution via Natural-Gas Co-variance

Basin methane co-varies with total natural-gas consumption, both peaking each winter (Figure 4a; Pearson $r = 0.64$, $p < 0.001$). Much of this is the shared seasonal cycle; after removing the monthly climatology, the de-seasonalized CH_4 and natural-gas anomalies remain positively but more weakly

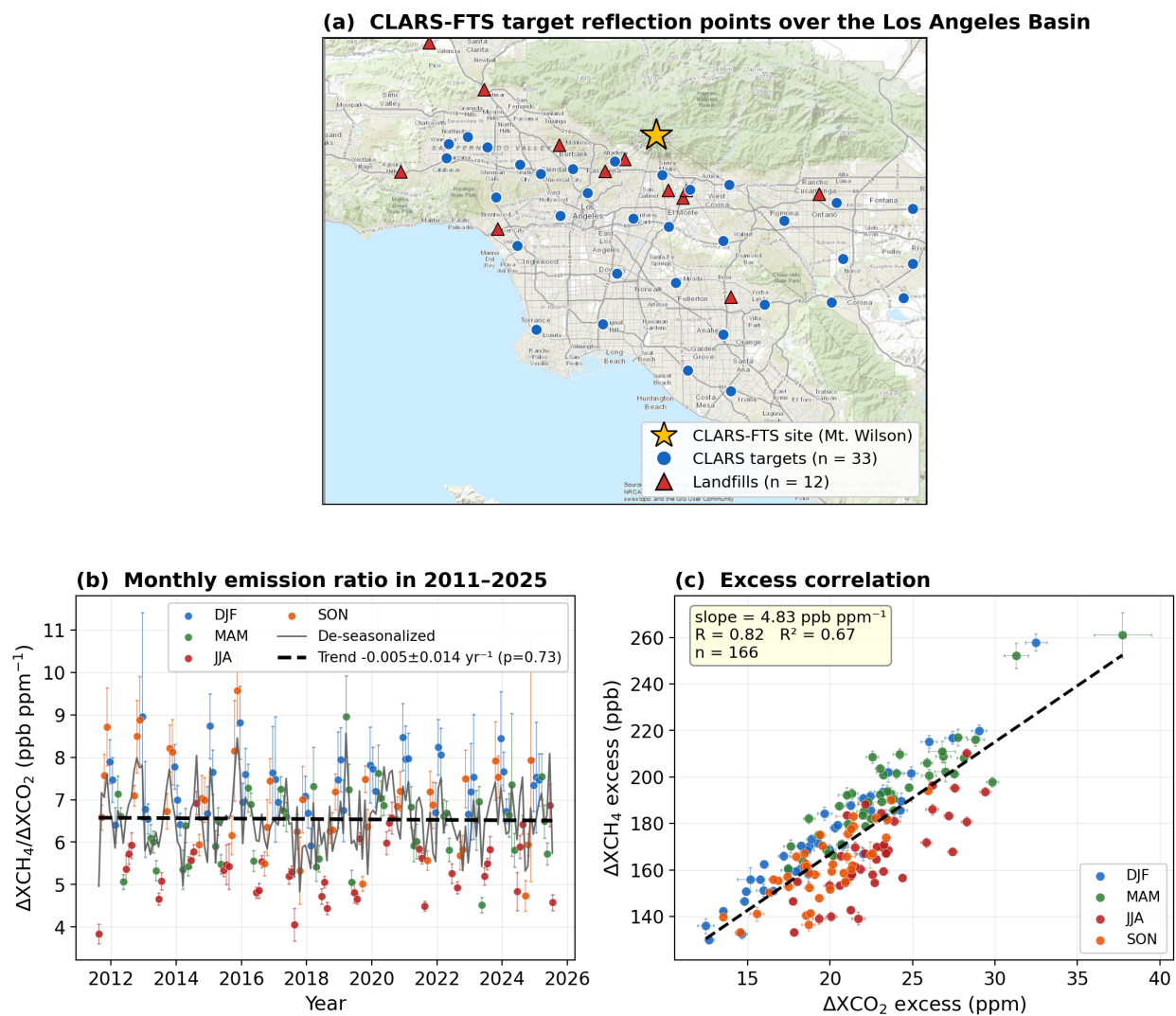


Figure 1: (a) The 33 CLARS-FTS target reflection points (blue) and the Mt. Wilson observing site (star) over the LA Basin; red triangles mark LA County landfills. (b) Monthly $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ emission ratio (2011–2025), colored by season, with the deseasonalized trend (dashed). (c) Excess correlation between monthly-mean ΔXCH_4 and ΔXCO_2 .

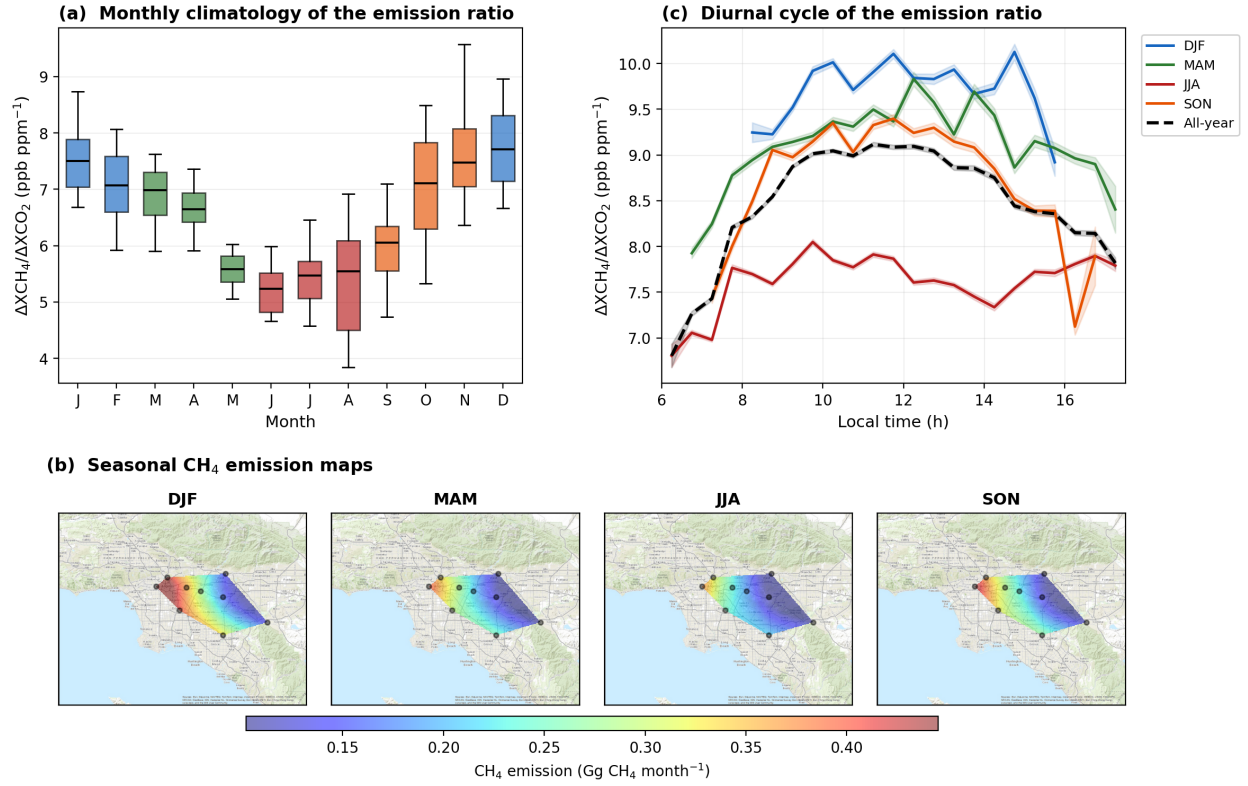


Figure 2: (a) Monthly climatology of the $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ ratio (box plots). (b) Seasonal CH₄ emission maps (DJF/MAM/JJA/SON) on a common color scale. (c) Diurnal cycle of the emission ratio by season; shading is ± 1 standard error.

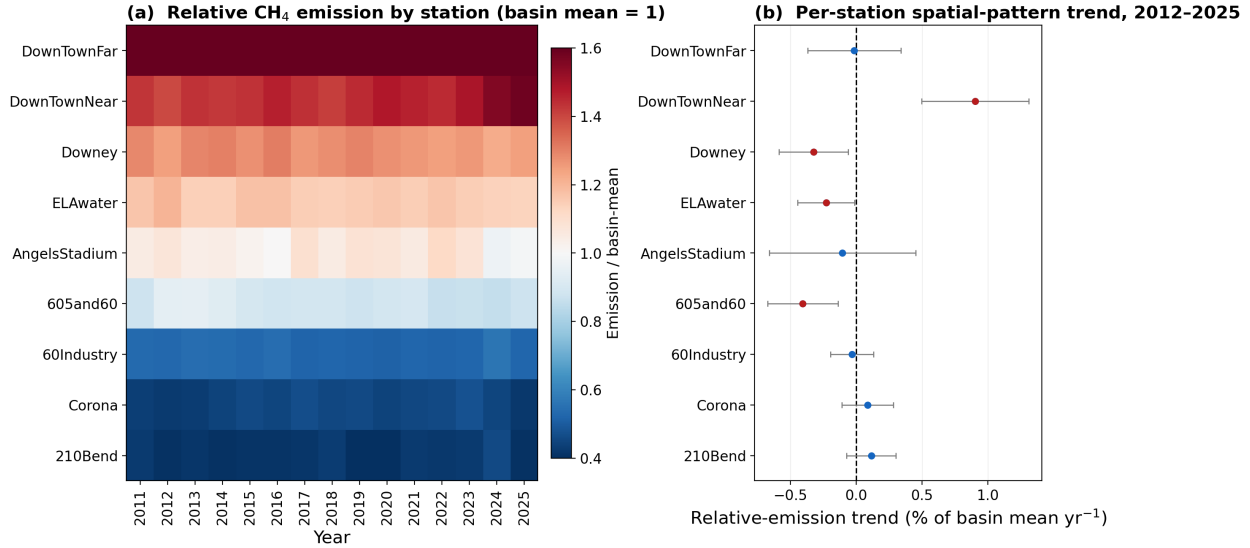


Figure 3: (a) Relative annual-mean CH_4 emission by station (basin mean = 1); horizontal banding indicates a fixed spatial pattern. (b) Per-station linear trend in relative emission (2012–2025) with 95% confidence intervals (grey whiskers). Dot color encodes statistical significance: red dots mark stations whose confidence interval lies entirely on one side of zero (a statistically significant trend at the 95% level), whereas blue dots mark stations whose confidence interval spans the dashed zero line (no significant trend). Even where significant, the trend magnitudes are small (below about 1% of the basin mean per year), so the relative spatial pattern remains effectively stationary.

correlated ($r = 0.22$, $p = 0.006$), indicating that gas demand explains part of the interannual and month-to-month methane variability beyond the common seasonal forcing. Resolving the correlation by station and sector (Figure 4b) shows that methane correlates most strongly with the residential sector (R^2 up to 0.43) and negligibly with the commercial and industrial sectors, in agreement with He et al. (2019), who reported $R^2 = 0.58$ for the combined residential–commercial signal. The strongest station correlations occur at sites overlooking the eastern industrial corridor (60Industry, Downey). Together with the fixed spatial pattern, this isolates the residential and distribution-level natural-gas system, rather than large industrial point sources, as the dominant fugitive pathway sustaining the basin methane signal.

3.5 Discussion

Three lines of evidence, a flat 15-year ratio (Figure 1), a stationary relative hotspot pattern (Figure 3), and a residential natural-gas signature (Figure 4), converge on a picture of methane sources that are structurally embedded in the urban gas-distribution and waste infrastructure of the basin. The three are not fully independent, since all derive from the same retrieved field, but they have different sensitivities to transport, retrieval bias, and inventory error, so their agreement strengthens confidence that the persistence reflects source behavior rather than measurement artifact. We weight them accordingly below: the ratio trend is the primary result, while the spatial stationarity is supporting evidence subject to the geometric caveat of Section 3.3.

Our findings both extend and refine the decadal picture of Zeng et al. (2023). Whereas that study emphasized that the absolute top-down methane decline (2011–2020) is much smaller than bottom-up inventories predict, our extended record shows that the emission ratio itself carries no

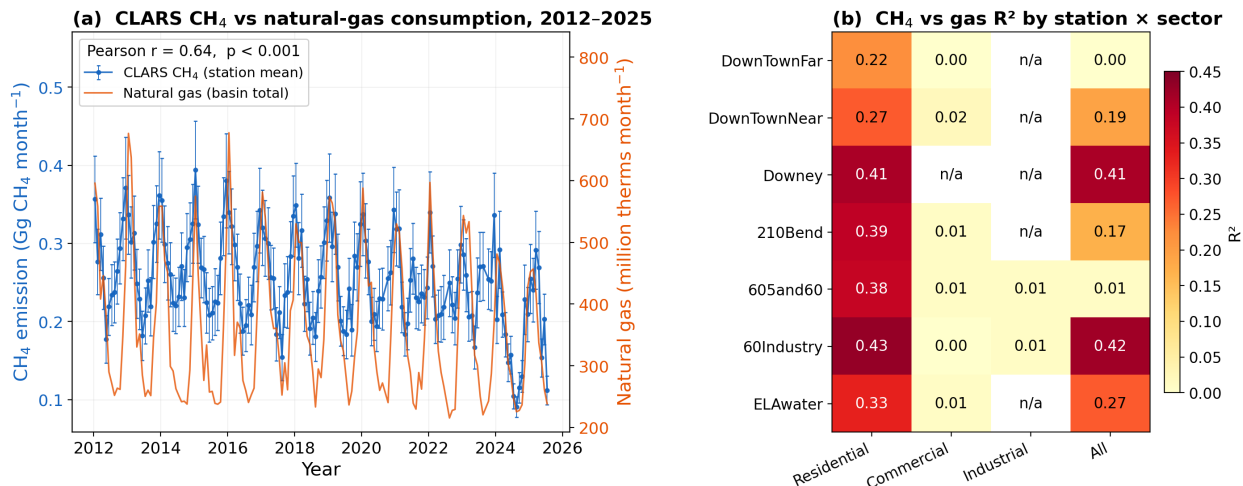


Figure 4: (a) Basin-mean CLARS CH₄ (blue, ± 1 SE) and total natural-gas consumption (orange), 2012–2025 (Pearson $r = 0.64$, $p < 0.001$). (b) Correlation (R^2) between station-level CH₄ and natural-gas consumption by sector.

significant trend through 2025. It is important to state precisely what this does and does not imply. A flat ratio is not evidence that absolute methane emissions were constant: the CLARS ΔXCH_4 signal does decline over the record, but ΔXCO_2 declines by a comparable relative amount, so the two changes largely cancel in the ratio. Consistently, the inventory-scaled emissions of Equation 3 also decline, driven by the falling CO₂ inventory used in the tracer–tracer conversion, including the sharp 2020 COVID-19 reduction. The correct reading is therefore relative rather than absolute: methane has fallen no faster than the CO₂-correlated activity of the basin, so there is no observational signature of methane-specific abatement over and above the general decline in fossil energy use. This distinction matters for policy evaluation, because a decrease in absolute emissions that simply tracks declining CO₂ activity should not be counted as successful methane mitigation. It also motivates our emphasis on the ratio rather than on the derived emissions: the ratio isolates precisely the quantity that methane-targeted regulation is designed to move, and it does so without depending on an inventory.

The dominance of the residential sector in the natural-gas correlation (Figure 4b; Figure S3) is consistent with the leakage-rate framework of He et al. (2019), who attributed roughly 1.4% of residential and commercial gas consumption to fugitive loss, and with ethane-based loss-rate estimates of 2.5–6% for the South Coast Air Basin (Wunch et al., 2016). The weak commercial and negligible industrial correlations argue against large industrial point sources as the primary driver of the basin-wide seasonal signal, instead implicating distributed, beyond-the-meter losses across the residential distribution network. The co-location of the fixed hotspots with LA County landfills (Figure 1a) further indicates a substantial, persistent biogenic contribution superimposed on the gas-distribution signal, consistent with prior source-attribution work in the basin (Hopkins et al., 2016; Townsend-Small et al., 2012).

Several limitations temper these conclusions. First, although GFIT3 treats aerosol scattering explicitly, residual scattering that is not fully accounted for can bias retrieved XCH_4 and XCO_2 and, because the two bands respond differently to aerosol, could in principle alias into the $\Delta XCH_4/\Delta XCO_2$ slope. We mitigate this with the O₂-ratio and continuum screening (Section 2.1), and the stability of the slope across 15 years of varying aerosol loading argues against a large time-

varying scattering artifact, but a residual constant bias in the absolute slope cannot be excluded from the CLARS data alone. Second, the in-basin and background views are not comparable partial columns (Section 2.2): the long grazing basin path double-weights the boundary layer relative to the near-vertical Spectralon path. To test both issues we compare CLARS against the Total Carbon Column Observing Network (TCCON) site in Pasadena (Wunch et al., 2011), whose near-vertical solar columns are far better defined and much less sensitive to aerosols. Over the overlapping 2012–2025 period, CLARS-FTS and TCCON XCH_4 are positively correlated ($r = 0.55$; Figure S5a), and both records exhibit consistent positive long-term trends, with CLARS higher and slightly steeper as expected for an in-basin, boundary-layer-weighted view relative to a free-tropospheric vertical column (Figure S5b). This agreement supports the fidelity of the CLARS methane retrieval; full quantitative closure of the absolute $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ slope additionally requires the corresponding XCO_2 comparison, which we leave to dedicated future work. We therefore report the ratio trend and spatial persistence as robust while not claiming closure of the absolute slope here.

Additional limitations concern the derived emissions and maps. The methane emissions in Equation 3 inherit uncertainty from the CO_2 inventory, dominated by the biospheric correction to ΔXCO_2 (Section 2.3) and the GRACED-based extrapolation of ODIAC for 2024–2025 (Text S2); these affect absolute magnitudes but not the ratio-based trend, which is independent of the inventory. The spatial maps rest on only 9 collocated stations and a fixed slant-column geometry, so the persistence they show is a robust property of the retrieved field but may partly encode the invariant viewing footprint (Section 3.3). Finally, the tracer–tracer method assumes co-located CH_4 and CO_2 sources well mixed within the boundary layer; localized super-emitters decoupled from CO_2 (e.g., a single venting landfill) would not be captured by the ratio and warrant complementary point-source observations such as those from imaging spectrometers (Duren et al., 2019).

From a monitoring and policy standpoint, the column emission ratio offers a practical, inventory-independent indicator of urban methane that is robust to meteorological variability and can be sustained at low cost from a fixed vantage. Its 15-year stability implies that, to date, methane-targeted regulation in California has not produced a detectable reduction in the basin’s top-down methane-to- CO_2 balance. As CO_2 emissions continue to fall under decarbonization, the relative importance of methane to the basin’s greenhouse forcing will grow, reinforcing the case for mitigation aimed specifically at the residential gas-distribution network and landfills rather than at CO_2 -correlated activity alone.

4 Conclusions

Fifteen years of CLARS-FTS observations show that the column $\Delta\text{XCH}_4/\Delta\text{XCO}_2$ emission ratio over Los Angeles has not significantly changed ($-0.005 \pm 0.006 \text{ yr}^{-1}$, $p = 0.84$), that the relative spatial pattern of methane in the retrieved field is essentially stationary, and that methane co-varies most strongly with residential natural-gas consumption. Because the basin CH_4 and CO_2 signals declined together over the period, the stable ratio should be read as an absence of methane-specific abatement rather than as an absence of change in methane itself. That is the quantity methane-targeted regulation is designed to move, and it has not moved. We therefore recommend the self-normalizing, inventory-independent column ratio as a robust metric for long-term urban methane monitoring, and note that the results underscore the need for targeted, sector-specific mitigation of fugitive natural-gas and landfill emissions.

Open Research

CLARS-FTS retrievals were produced with the GFIT3 algorithm (Zeng et al., 2021); NOAA/Mt. Wilson Observatory flask data are available from the NOAA Global Monitoring Laboratory. The ODIAC fossil-fuel CO₂ inventory (Oda and Maksyutov, 2011) is distributed by the National Institute for Environmental Studies, and the GRACED near-real-time inventory (Dou et al., 2022). Monthly natural-gas consumption records were provided by Southern California Gas Company under a data-use agreement and are proprietary; they cannot be redistributed by the authors and may be requested directly from Southern California Gas Company.

Acknowledgments

We thank the CLARS-FTS operations team at JPL. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Author contributions: Conceptualization: J.Y., C.P., Y.L.Y., C.F.; Methodology: J.Y., X.S., E.Q., Z.C.Z., T.P.; Investigation: J.Y., X.S., E.Q.; Visualization: J.Y., E.Q.; Funding acquisition: Y.L.Y.; Project administration: J.Y.; Supervision: J.Y., C.P., Y.L.Y., C.F.; Writing – original draft: J.Y., X.S., E.Q.; Writing – review and editing: Z.C.Z., T.P., Y.L., C.P., C.F.

References

- Cui, Y. Y. et al. (2015). Top-down estimate of methane emissions in california using a mesoscale inverse modeling technique: The south coast air basin. *Journal of Geophysical Research: Atmospheres*, 120:6698–6711.
- Dou, X. et al. (2022). Near-real-time global gridded daily CO₂ emissions. *The Innovation*, 3(1):100182.
- Duren, R. M. et al. (2019). California’s methane super-emitters. *Nature*, 575:180–184.
- Fu, D. et al. (2014). Near-infrared remote sensing of los angeles trace gas distributions from a mountaintop site. *Atmospheric Measurement Techniques*, 7:713–729.
- He, L. et al. (2019). Atmospheric methane emissions correlate with natural gas consumption from residential and commercial sectors in los angeles. *Geophysical Research Letters*, 46:8563–8571.
- Hopkins, F. M. et al. (2016). Spatial patterns and source attribution of urban methane in the los angeles basin. *Journal of Geophysical Research: Atmospheres*, 121:2490–2507.
- Hsu, Y. K. et al. (2010). Methane emissions inventory verification in southern california. *Atmospheric Environment*, 44:1–7.
- IPCC (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.
- Natraj, V., Shia, R. L., and Yung, Y. L. (2010). On the use of principal component analysis to speed up radiative transfer calculations. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 111(5):810–816.
- Natraj, V., Spurr, R. J., Boesch, H., Jiang, Y., and Yung, Y. L. (2007). Evaluation of errors from neglecting polarization in the forward modeling of O₂ a band measurements from space, with

- relevance to CO₂ column retrieval from polarization-sensitive instruments. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 103(2):245–259.
- Ocko, I. B. et al. (2021). Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. *Environmental Research Letters*, 16:11.
- Oda, T. and Maksyutov, S. (2011). A very high-resolution (1 km x 1 km) global fossil fuel CO₂ emission inventory derived using a point source database and satellite observations of nighttime lights. *Atmospheric Chemistry and Physics*, 11:543–556.
- Plant, G. et al. (2019). Large fugitive methane emissions from urban centers along the u.s. east coast. *Geophysical Research Letters*, 46:8500–8507.
- Rodgers, C. D. (2000). *Inverse Methods for Atmospheric Sounding: Theory and Practice*. World Scientific.
- Saunio, M. et al. (2020). The global methane budget 2000–2017. *Earth System Science Data*, 12:1561–1623.
- Spurr, R. et al. (2013). Linearization of the o-pca radiative-transfer method. *Journal of Quantitative Spectroscopy and Radiative Transfer*.
- Townsend-Small, A. et al. (2012). Isotopic measurements of atmospheric methane in los angeles, california, usa: Influence of “fugitive” fossil fuel emissions. *Journal of Geophysical Research: Atmospheres*, 117:D07308.
- Wennberg, P. O. et al. (2012). On the sources of methane to the los angeles atmosphere. *Environmental Science & Technology*, 46:9282–9289.
- Wong, C. K. et al. (2016). Monthly trends of methane emissions in los angeles from 2011 to 2015 inferred by clars-fts observations. *Atmospheric Chemistry and Physics*, 16:13121–13130.
- Wong, K. W. et al. (2015). Mapping CH₄:CO₂ ratios in los angeles with clars-fts from mount wilson, california. *Atmospheric Chemistry and Physics*, 15:241–252.
- Wunch, D. et al. (2009). Emissions of greenhouse gases from a north american megacity. *Geophysical Research Letters*, 36:L15810.
- Wunch, D. et al. (2011). The total carbon column observing network. *Philosophical Transactions of the Royal Society A*, 369:2087–2112.
- Wunch, D. et al. (2016). Quantifying the loss of processed natural gas within california’s south coast air basin using long-term measurements of ethane and methane. *Atmospheric Chemistry and Physics*, 16:14091–14105.
- Yadav, V. et al. (2019). Spatio-temporally resolved methane fluxes from the los angeles megacity. *Journal of Geophysical Research: Atmospheres*, 124:5117–5130.
- Zeng, Z.-C. et al. (2021). Gfit3: a full-physics retrieval algorithm for remote sensing of greenhouse gases in the presence of aerosols. *Atmospheric Measurement Techniques*, 14:6483–6507.
- Zeng, Z.-C. et al. (2023). Decadal decrease in los angeles methane emissions is much smaller than bottom-up estimates. *Nature Communications*, 14:5353.