SATELLITE QUANTIFICATION OF METHANE EMISSIONS FROM SOUTH AMERICAN COUNTRIES: A HIGH-RESOLUTION INVERSION OF TROPOMI AND GOSAT OBSERVATIONS

Summary of a research paper *by Sarah E. Hancock, et al. "Satellite quantification of methane emissions from South American countries: a high-resolution inversion of TROPOMI and GOSAT observations." Atmospheric Chemistry and Physics, vol. 25. January 2025.*

Summary

This study uses satellite observations of atmospheric methane concentrations from 2021 to quantify methane emissions from South America at the country and sector level, finding substantially higher anthropogenic methane emissions than reported in country submissions to the United Nations Framework Convention on Climate Change (UNFCCC). The authors perform a high-spatial-resolution (up to 25 km x 25 km) inversion of satellite observations, using an atmospheric transport model and prior "bottom-up" estimates of methane emissions to relate atmospheric observations to emissions. The authors' best posterior estimate for total anthropogenic methane emissions over the continent is 48 Tg a^{-1}, which is 55% higher than prior estimates from UNFCCC reports and global emission inventories. Seven countries account for 93% of this total: Brazil alone, at 19 Tg a^{-1}, accounts for 40%, followed by Argentina (9.2 Tg a^{-1}), Venezuela (7.0 Tg a^{-1}), Colombia (5.0 Tg a^{-1}), Peru (2.4 Tg a^{-1}), Bolivia (0.96 Tg a^{-1}), and Paraguay (0.93 Tg a^{-1}). At the sector level, livestock is the largest contributor to anthropogenic emissions (mainly through enteric fermentation), both for South America as a whole (65%) and in all countries except Venezuela and Peru, where oil and gas operations and landfills, respectively, are the dominant sources. Livestock is also the sector that shows the largest difference between this study's top-down estimates using satellite observations and prior estimates. Wetlands are the main source of natural methane emissions in South America; results for wetlands in this study are largely consistent with prior estimates in the case of the Amazon, but lower and higher, respectively, than prior estimates for the Pantanal and Paraná regions.

Background and Context

Atmospheric concentrations of methane (CH_4), a short-lived but potent greenhouse gas, have nearly tripled since pre-industrial times, resulting in an emission-based radiative forcing of 1.21 W m^{-2} compared to 2.16 W m^{-2} for carbon dioxide (CO_2) (Naik *et al*., 2021). Anthropogenic sources of methane emissions include oil and gas operations, coal, livestock, rice cultivation, landfills, and wastewater treatment; natural sources include wetlands, fires, termites, and geological seeps. South America is estimated to account for 14% of global anthropogenic methane emissions with Brazil ranking as the world's third-largest emitter at the country level (Worden *et al*., 2022). Emissions sources in South America — primarily livestock and wetlands — are also believed to play a significant role in rapidly rising levels of atmospheric methane (Y. Zhang *et al.*, 2021, Qu *et al.*, 2024). There are large uncertainties around these contributions, however, and around the bottom-up calculations most governments use to develop methane emission inventories for submission to the UNFCCC, which typically apply generic emission factors to measures of sector-level activity that are often poorly quantified.

Inverse analysis of satellite observations of atmospheric methane concentrations, using an atmospheric transport model and a bottom-up, prior estimate of emissions allows for more reliable quantification of methane emissions. Previous analyses using data from the Greenhouse Gases Observing Satellite (GOSAT, 2009-present) (Parker *et al.*, 2020a) to infer the distribution of methane emissions globally and regionally, have identified significant discrepancies between top-down emissions estimates using satellite observations and bottom-up inventories. However, GOSAT observations are sparse which limits researchers' ability to separate emissions by sector and country. The TROPOspheric Monitoring Instrument (TROPOMI) (2018–present), by contrast, provides global continuous daily mapping of atmospheric methane at much higher spatial resolution (Lorente *et al.*, 2023). Use of TROPOMI data to develop more accurate estimates of methane emissions by region and sector has recently been demonstrated for the United States (Nesser *et al.*, 2024), the Middle East and North Africa (Chen *et al.*, 2023), China (Chen *et al.*, 2022, Liang *et al.*, 2023), and Venezuela (Nathan *et al.*, 2023). This study completes a similar analysis for South America.

Data and Methods

The inversion uses TROPOMI and GOSAT observations from 2021 to infer methane emissions from different sources and countries in South America at up to 25 km x 25 km resolution. For prior estimates of emissions, the authors use national inventories reported by individual countries to the UNFCCC, gridded using the Emissions Database for Global Atmospheric Research (EDGARv7) for the livestock, waste, and rice sectors and the UNFCCC-based Global Fuel Exploitation Inventory (GFEIv2) for fossil fuel emissions. Prior estimates for wetlands from two emission inventories with different magnitudes and spatial distributions (WetCHARTs and LPJ-MERRA2) are used to account for the high uncertainty in wetland emissions.

Posterior estimates were obtained analytically through Bayesian synthesis of prior emissions estimates with the TROPOMI and GOSAT observations. A blended TROPOMI+GOSAT product was used to correct spatially variable biases and artifacts in the TROPOMI data using information from GOSAT (Balasus *et al.*, 2023). Although TROPOMI observations are much denser than GOSAT, GOSAT provides unique coverage over the Amazon where TROPOMI data are sparse. The inversion used variable resolution, applying a Gaussian mixture model (GMM) to enforce higher resolution in regions with both high emissions and high observation density. To provide a conservative uncertainty estimate, the authors generate a 54-member ensemble of sensitivity inversions by varying key parameters in the inversion analysis and identify their "best" posterior estimate as the median of the inversion ensemble.

Results and Discussion

Table 1 compares prior emission estimates for South America from UNFCCC reports and global inventories to the posterior estimates developed in this study using the methods described above. For the continent as a whole, including anthropogenic and natural sources, the analysis yields a best posterior estimate of 121 (109–137) Tg a^{-1}, where the parentheses indicate the range from the inversion ensemble. This represents a significant increase from the prior total of 96 Tg a^{-1} shown in Table 1. Anthropogenic emissions, which total 31 Tg a^{-1} in prior estimates and 48 (41–56) Tg a^{-1} in the posterior analysis, account for most of the difference. Compared to prior estimates, this study also finds higher emissions for all source sectors, with oil/gas showing the largest increase over previous estimates (158%).

Table 1: Methane Emissions in South America (Tg a^{-1})

	Prior[a]	Posterior[b]
Total	96	121 (109–137)
Anthropogenic (UNFCCC)	31	48 (41–56)
Livestock	21	31 (27–37)
Waste[c]	5.7	7.8 (6.5–9.5)
Rice	0.68	0.86 (0.74–1.4)
Oil/Gas	2.4	6.2 (5.2–7.9)
Coal	0.40	0.59 (0.42–1.4)
Other[d]	1.0	1.3 (1.1–1.5)
Natural	56–74	74 (68–83)
Open Fires	2.4	2.6 (2.4–3.0)
Wetlands	52–68[e]	67 (62–75)
Seeps	0.09	0.22 (0.17–0.30)
Termites	2.6	3.8 (3.2–5.1)

[a] *Prior emission estimates used in the inversion. Livestock, waste, and rice emissions are from national reports to the UNFCCC for 2004 to 2020. Oil/gas and coal are from GFEIv2 (Scarpelli et al., 2022). Wetland and open fire are for 2021 (inversion year).*

[b] *Median best estimates from the inversion of TROPOMI and GOSAT data for 2021, and ranges from the inversion ensemble.*

[c] *Including landfills and wastewater treatment.*

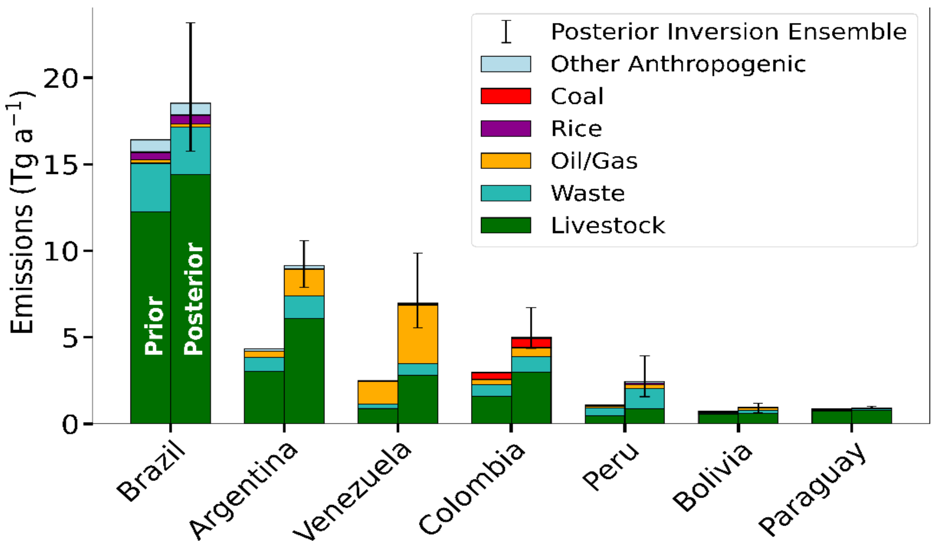
[d] *Including industry, stationary combustion, mobile combustion, aircraft, composting, and field burning of agricultural residues. Taken from EDGARv7.*

[e] *Prior estimates for the inversion are taken either from the mean of the high-performing subset of the WetCHARTs ensemble (52 Tg a^{-1}) or from LPJ-MERRA2 (68 Tg a^{-1}).*

Because wetlands are by far the largest source of methane emissions in South America, the study includes a closer examination of emission estimates over key wetland regions — the Amazon Basin, the Bolivian Amazon, the Pantanal, and the Paraná. Comparing against two existing wetlands inventories, WetCHARTs and LPJ, the authors find their results are roughly consistent with prior estimates for the Amazon, but lower for the Panatanal, a large, seasonally flooded tropical grassland area located below the Amazon Basin, and higher for the Paraná River region in northern Argentina. Other work has suggested that prior inventories underestimate the extent of wetlands in the Paraná (Parker *et al.* 2020b), which would help explain this result.

Figure 1 shows results by source sector and country for each of the top seven methane emitting countries in South America, comparing the posterior, top-down estimates from this study to prior, bottom-up estimates, as reported to the UNFCCC. In all cases, the posterior estimate is higher than the prior estimate although the magnitude of the discrepancy varies. The gap between posterior and prior emission estimates is largest for Argentina, Venezuela, Colombia, and Peru and noticeably less pronounced for Brazil, Bolivia, and Paraguay (in each of the latter countries, the low end of the range of results from the inversion ensemble overlaps with prior estimates).

Figure 1: Anthropogenic Emissions by Country



The full study details several noteworthy findings at the sector level:

- Livestock is by far the dominant source of anthropogenic methane emissions in South America overall, and in all major South American countries excepting Venezuela and Peru. Even countries with complex Tier 2 reporting methods report livestock emissions much lower than this study's posterior estimates, with particularly large discrepancies evident in the estimates for Argentina, Venezuela, Colombia, and Peru. These differences may stem from underestimations in Tier 2 reporting methods or from the inability of bottom-up approaches to capture spatial and temporal variability in emission factors. They may also be the result of uncertainty in the inversion arising from aggregation error or the prior spatial distribution of emissions that determines how posterior emission estimates are attributed to each sector.

- Waste (landfills and wastewater) is the second-largest source of anthropogenic emissions after livestock. Results from this study suggest that the contribution from waste is higher than previously reported to the UNFCCC for all South American countries except Brazil. The discrepancy is especially large for Peru (+150% in the top-down estimate relative to the prior estimate) and Argentina (+59%).

- For oil and gas, the continent's third-largest anthropogenic source sector, the authors compare posterior estimates of methane intensity (defined as the amount of methane emitted per unit of natural gas production) to methane intensities inferred from other inversion analyses of TROPOMI data, including that of Shen *et al.* (2023) for individual countries worldwide and Nathan *et al.* (2023) for Venezuela. Results for Venezuela, Peru, and Colombia are comparable to those from the previous studies, but Argentina's intensity in this study is higher (5.9%) than the 1.5% intensity inferred from Shen *et al*. (2023), potentially due to recent expansion of oil and gas operations in Argentina's Neuquén basin. This study finds methane intensities for all countries except Venezuela to be comparable to the global average of 2.4% inferred by Shen *et al*. (2023) and much higher than the industry target of 0.2% (OGCI, 2022), indicating a large potential to reduce emissions. Venezuela's estimated methane intensity, at 33%, is by far the highest of any country in South America; this may be due to leakage from abandoned infrastructure as the country's oil production has declined (Nathan *et al*., 2023).

Conclusion

South America is a heterogenous continent where a complex range of factors drives natural and anthropogenic methane emissions. Future work would benefit from partnering with local experts to make stronger connections between top-down estimates and bottom-up emissions data in specific countries. Top-down estimates using satellite observations can improve understanding of methane emissions, but attribution to sectors is dependent on prior bottom-up estimates to characterize the distribution of emissions sources; country-specific information can improve these prior estimates and thus the inversion results. Further, in-situ measurements of atmospheric methane are valuable for validating satellite observations, but these kinds of measurements are currently available primarily for the Northern Hemisphere. The credibility of future emission estimates derived from inversion analysis would be greatly enhanced by comprehensive and systematic in-situ methane observations across South America.

Reference to Full Paper

A more detailed account of the research on which this brief is based may be found in: Sarah E. Hancock, Daniel J. Jacob, Zichong Chen, Hannah Nesser, Aaron Davitt, Daniel J. Varon, Melissa P. Sulprizio, Nicholas Balasus, Lucas A. Estrada, María Cazorla, Laura Dawidowski, Sebastián Diez, James D. East, Elise Penn, Cynthia A. Randles, John Worden, Ilse Aben, Robert J. Parker, Joannes D. Maasakkers. "Satellite quantification of methane emissions from South American countries: a high-resolution inversion of TROPOMI and GOSAT observations." *Atmospheric Chemistry and Physics,* vol. 25. January 2025. https://doi.org/10.5194/acp-25-797-2025.

References

Balasus, N., Jacob, D. J., Lorente, A., Maasakkers, J. D., Parker, R. J., Boesch, H., Chen, Z., Kelp, M. M., Nesser, H., and Varon, D. J.: A blended TROPOMI+GOSAT satellite data product for atmospheric methane using machine learning to correct retrieval biases, Atmospheric Measurement Techniques, 16, 3787–3807, https://doi.org/10.5194/amt-16-3787-2023, 2023.

Chen, Z., Jacob, D., Nesser, H., Sulprizio, M., Lorente, A., Varon, D., Lu, X., Shen, L., Qu, Z., Penn, E., and Yu, X.: Methane emissions from China: a high-resolution inversion of TROPOMI satellite observations, Atmospheric Chemistry and Physics Discussions, 1–31, https://doi.org/10.5194/acp-2022-303, 2022.

Chen, Z., Jacob, D. J., Gautam, R., Omara, M., Stavins, R. N., Stowe, R. C., Nesser, H. O., Sulprizio, M. P., Lorente, A., Varon, D. J., Lu, X., Shen, L., Qu, Z., Pendergrass, D. C., and Hancock, S.: Satellite quantification of methane emissions and oil/gas methane intensities from individual countries in the Middle East and North Africa: implications for climate action, EGUsphere, 1–42, https://doi.org/10.5194/egusphere-2022-1504, 2023.

Liang, R., Zhang, Y., Chen, W., Zhang, P., Liu, J., Chen, C., Mao, H., Shen, G., Qu, Z., Chen, Z., Zhou, M., Wang, P., Parker, R. J., Boesch, H., Lorente, A., Maasakkers, J. D., and Aben, I.: East Asian methane emissions inferred from high-resolution inversions of GOSAT and TROPOMI observations: a comparative and evaluative analysis, Atmospheric Chemistry and Physics, 23, 8039–8057, https://doi.org/10.5194/acp-23-8039-2023, 2023.

Naik, V., Szopa, S., Adhikary, B., Artaxo, P., Berntsen, T., Collins, W. D., Fuzzi, S., Gallardo, L., Kiendler Scharr, A., Klimont, Z., Liao, H., Unger, N., and Zanis, P.: Short-Lived Climate Forcers, in: Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 817–922, https://doi.org/10.1017/9781009157896.008, 2021.

Nathan, B., Maasakkers, J. D., Naus, S., Gautam, R., Omara, M., Varon, D. J., Sulprizio, M. P., Lorente, A., Borsdorff, T., Parker, R. J., and Aben, I.: Assessing methane emissions from collapsing Venezuelan oil production using TROPOMI, EGUsphere, 1–27, https://doi.org/10.5194/egusphere-2023-2887, 2023.

Nesser, H., Jacob, D. J., Maasakkers, J. D., Lorente, A., Chen, Z., Lu, X., Shen, L., Qu, Z., Sulprizio, M. P., Winter, M., Ma, S., Bloom, A. A., Worden, J. R., Stavins, R. N., and Randles, C. A.: High-resolution US methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills, Atmospheric Chemistry and Physics, 24, 5069–5091, https://doi.org/10.5194/acp-24-5069-2024, 2024.

OGCI: Oil & Gas Climate Initiative Reporting Framework (Version 3.6), OGCI, 2022.

Parker, R. J., Webb, A., Boesch, H., Somkuti, P., Barrio Guillo, R., Di Noia, A., Kalaitzi, N., Anand, J. S., Bergamaschi, P., Chevallier, F., Palmer, P. I., Feng, L., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Kivi, R., Morino, I., Notholt, J., Oh, Y.-S., Ohyama, H., Petri, C., Pollard, D. F., Roehl, C., Sha, M. K., Shiomi, K., Strong, K., Sussmann, R., Té, Y., Velazco, V. A., Warneke, T., Wennberg, P. O., and Wunch, D.: A decade of GOSAT Proxy satellite CH_4 observations, Earth System Science Data, 12, 3383–3412, https://doi.org/10.5194/essd-12-3383-2020, 2020a.

Parker, R. J., Wilson, C., Bloom, A. A., Comyn-Platt, E., Hayman, G., McNorton, J., Boesch, H., and Chipperfield, M. P.: Exploring constraints on a wetland methane emission ensemble (WetCHARTs) using GOSAT observations, Biogeosciences, 17, 5669–5691, https://doi.org/10.5194/bg-17-5669-2020, 2020b.

Qu, Z., Jacob, D. J., Bloom, A. A., Worden, J. R., Parker, R. J., and Boesch, H.: Inverse modeling of 2010–2022 satellite observations shows that inundation of the wet tropics drove the 2020–2022 methane surge, Proceedings of the National Academy of Sciences, 121, e2402730121, https://doi.org/10.1073/pnas.2402730121, 2024.

Shen, L., Jacob, D. J., Gautam, R., Omara, M., Scarpelli, T. R., Lorente, A., Zavala-Araiza, D., Lu, X., Chen, Z., and Lin, J.: National quantifications of methane emissions from fuel exploitation using high resolution inversions of satellite observations, Nat Commun, 14, 4948, https://doi.org/10.1038/s41467-023-40671-6, 2023.

Worden, J. R., Cusworth, D. H., Qu, Z., Yin, Y., Zhang, Y., Bloom, A. A., Ma, S., Byrne, B. K., Scarpelli, T., Maasakkers, J. D., Crisp, D., Duren, R., and Jacob, D. J.: The 2019 methane budget and uncertainties at 1° resolution and each country through Bayesian integration Of GOSAT total column methane data and a priori inventory estimates, Atmospheric Chemistry and Physics, 22, 6811–6841, https://doi.org/10.5194/acp-22-6811-2022, 2022.

Zhang, Y., Jacob, D. J., Lu, X., Maasakkers, J. D., Scarpelli, T. R., Sheng, J.-X., Shen, L., Qu, Z., Sulprizio, M. P., Chang, J., Bloom, A. A., Ma, S., Worden, J., Parker, R. J., and Boesch, H.: Attribution of the accelerating increase in atmospheric methane during 2010–2018 by inverse analysis of GOSAT observations, Atmospheric Chemistry and Physics, 21, 3643–3666, https://doi.org/10.5194/acp-21-3643-2021, 2021.

About the Program

The Harvard Methane Initiative seeks meaningful and sustained progress in reducing global emissions of this very important greenhouse gas — through research and effective engagement with policymakers and key stakeholders. This Initiative is supported by the Salata Institute for Climate and Sustainability at Harvard University. The Harvard Methane Initiative and other Research Clusters supported by the Salata Institute comprise interdisciplinary teams of researchers from across Harvard's schools, whose varied expertise is required to address the complexity of the climate-related problems that they seek to solve. Robert N. Stavins, A.J. Meyer Professor of Energy and Economic Development at Harvard Kennedy School, directs the Harvard Methane Initiative. The findings, views, and conclusions in this publication are those of the authors alone.