AN IMPROVED RESEARCH AND STAKEHOLDER TOOL FOR MONITORING TOTAL METHANE EMISSIONS

Summary of a research paper by Lucas A. Estrada, et al. "Integrated Methane Inversion (IMI) 2.0: An improved research and stakeholder tool for monitoring total methane emissions with high resolution worldwide using TROPOMI satellite observations." Geoscientific Model Development, vol. 18, p. 3311–3330. June 2025.

Summary

Satellite observations of atmospheric methane concentrations are a powerful resource for quantifying methane emissions globally. The Integrated Methane Inversion (IMI) is an open-source cloud computing tool for inferring emissions by relating satellite observations to emissions using inverse modeling, a process that, until recently, has required a high level of scientific and technical expertise and large computational resources. Improvements in version 2.0 of the IMI offer significantly enhanced performance and greater usability for researchers and non-experts, enabling a wider range of stakeholders to use satellite data from the Tropospheric Monitoring Instrument (TROPOMI) to estimate sector-level methane emissions around the world at resolutions up to 25 square kilometers. Continued development of IMI and other tools to estimate and monitor global methane emission sources is critical for developing effective methane mitigation strategies.

Lucas Estrada is a doctoral student in the research group of Daniel Jacob, Vasco McCoy Family Professor of Atmospheric Chemistry and Environmental Engineering at Harvard University. Several of Estrada's co-authors are members of the group, as well. Professor Jacob's group has collaborated closely with the Harvard Initiative on Reducing Global Methane Emissions; see related research briefs here.

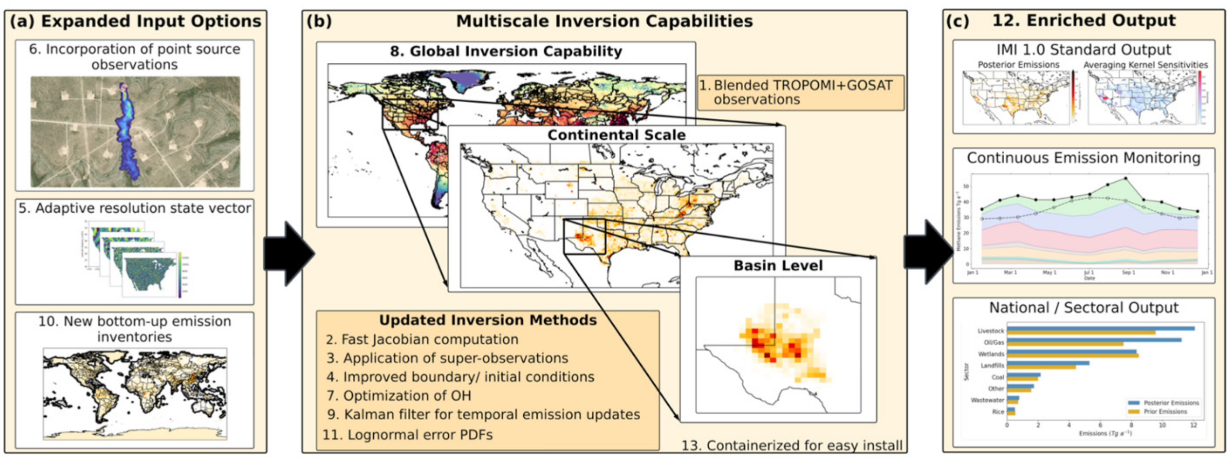
Background & Context

Methane, a short-lived but powerful greenhouse gas, is drawing increased interest from policymakers as a pollutant that offers significant near-term climate change mitigation opportunities. More than 150 countries have joined the Global Methane Pledge, committing to collectively reduce global methane emissions 30% by 2030 (Global Methane Pledge, 2023). Nonetheless, atmospheric concentrations of methane have continued to rise rapidly (at a rate of 0.8 % per year for 2020–2022 (Thoning et al., 2022)). The ability to quantify and monitor methane emissions from different sources and sectors with high spatial and temporal resolution is crucial for understanding methane trends and developing mitigation strategies to achieve policy goals.

Satellite measurements of methane concentrations in the atmosphere have greatly improved prospects for accurate emissions monitoring by enabling researchers to blend bottom-up estimation methods (typically, applying emission factors to different methane-generating processes and sources) and top-down methods that infer emissions by combining observations of atmospheric methane concentrations with atmospheric transport models. Data from TROPOMI, which was launched aboard the European Space Agency's Sentinel-5 Precursor low-Earth orbiting satellite in October 2017, currently provide the most spatially dense resource for worldwide mapping of atmospheric methane concentrations and have already been used in a number of studies to develop global and regional emissions estimates.

Initially released in 2022, the IMI (https://carboninversion.com/, last access: 25 February 2025) is specifically designed to enable optimized estimation of methane emissions at up to 25 km² resolution using TROPOMI satellite observations. Featuring a user-friendly interface, an open-source code base, and operability on the Amazon Web Services (AWS) cloud, which avoids the need for local computing resources, the IMI provides a transparent and accessible tool for assessing the contribution of different methane sources and for developing actionable and effective policy interventions. The recent release of version 2.0 enhances IMI's overall flexibility for use in a wide range of scientific and stakeholder applications.

Figure 1



Key changes in version 2.0 include:

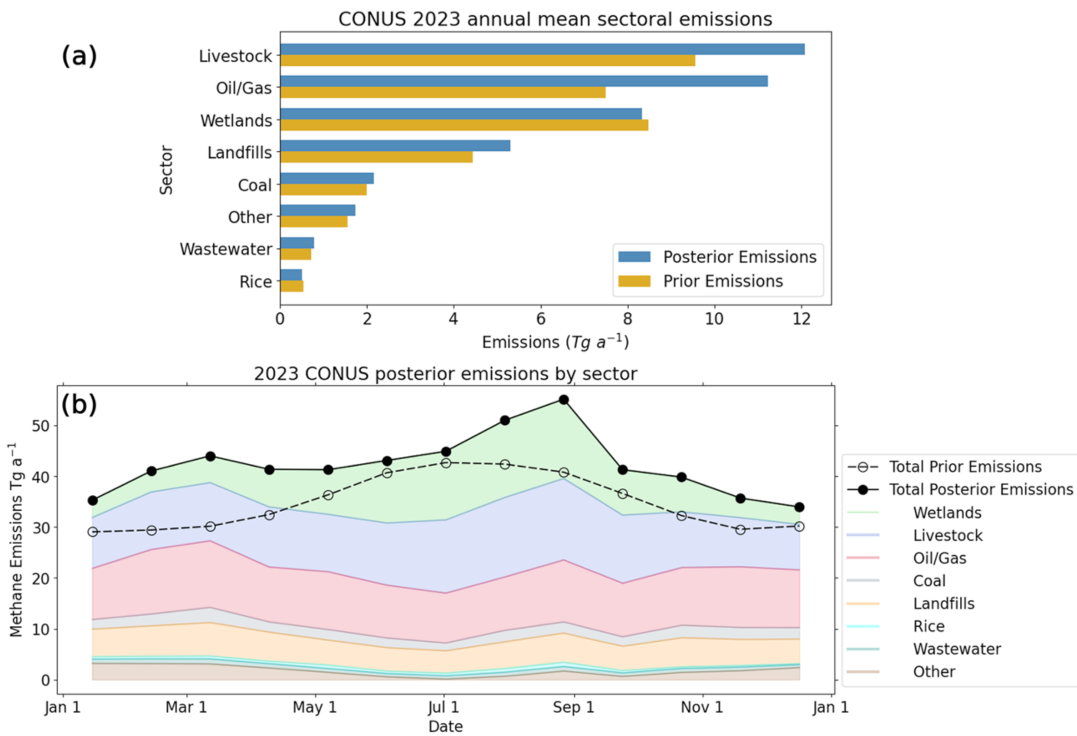
- **Blended TROPOMI+GOSAT dataset compatibility** to improve the quality of observations used by the IMI and remove retrieval artifacts.
- **Speedup of Jacobian matrix construction,** which enhances computational performance several fold and significantly reduces CPU time and cost.
- **Superobservations** to reduce storage size and computational time, while also providing better characterization of observational error correlations.
- **Optimization of boundary conditions** to remove systematic biases from the model background.
- **Adaptive, information-based spatial resolution** that reduces computational cost by using a clustering algorithm that maintains high resolution in areas of high emissions and dense observations while smoothing the solution in areas with weak emissions or insufficient observations.

- **Point source incorporation in the state vector construction** to better integrate data on major point source emissions.
- **Optimization of methane sinks** to better capture the role of sinks in determining atmospheric concentrations (in contrast to IMI 1.0, which optimized only for methane emissions).
- **Global inversion capability** to enable global-level estimation of emissions, albeit at a coarser level than regional estimation, using the same analytical inversion method.
- **Temporal emission updates with a Kalman filter** to enable IMI to conduct successive methane inversions over user-specified time intervals (such as weekly or monthly) using observations for that interval.
- **Updated bottom-up inventories for use as prior estimates,** including more recent emissions data from a variety of sources and the ability for users to add or substitute their own prior emissions estimates.
- **Lognormal error pdfs for heavy-tailed emissions** as an option to better characterize the error distribution of methane emissions.
- **Enriched outputs,** including the addition of tabulated and gridded estimates of posterior emissions by source sector.
- **IMI Docker container,** a lightweight, stand-alone, executable software package that facilities IMI installation on local systems and is capable of supporting scheduled inversion workflows (e.g. weekly or monthly).

Results from an example application of IMI 2.0 to the contiguous United States

To demonstrate these capabilities, the authors conduct an example, out-of-the-box application of IMI 2.0 to quantify methane emissions in the contiguous United States (CONUS) from 1 January 2023 to 31 December 2023. Figure 2 shows the time series of CONUS 28-day emissions and mean annual totals by sector. The annual mean prior emissions estimate is 34 $Tg\,a^{-1}$ and peaks in July. Using IMI 2.0, the authors find annual mean posterior emissions of 42 $Tg\,a^{-1}$ for 2023 with maximum emissions in September. The seasonal offset from July to September is largely driven by wetlands, which may be explained by WetCHARTs' use of air temperature rather than soil temperature to predict wetlands emissions. The same issue is found for boreal wetlands (East et al., 2024). Upward corrections to emissions are largest for livestock as well as for the oil and gas sector but the results are broadly in agreement with the range of emission estimates from other CONUS inverse studies (Lu et al., 2022, 2023; Worden et al., 2022; Shen et al., 2023; Nesser et al., 2024).

Figure 2



Conclusion

While IMI 2.0 introduces major improvements, further development from scientific users will be important to ensure that future versions address remaining limitations. Efforts currently underway include (1) reducing latency to 2–3 days, (2) increasing spatial resolution to 12×12 km^2, (3) integrating methane observations from new satellite instruments (MethaneSAT), (4) directly incorporating information from point source imagers (GHGSat, Carbon Mapper), (5) adding an IMI preview tool to provide guidance on boundary conditions, and (6) extending the IMI to CO_2. These and other enhancements will provide the basis for IMI 3.0.

Reference to full paper

A more detailed, technical description of the improvements included in IMI 2.0 is provided in the full paper on which this brief is based: Lucas A. Estrada, Daniel J. Varon, Melissa Sulprizio, Hannah Nesser, Zichong Chen, Nicholas Balasus, Sarah E. Hancock, Megan He, James D. East, Todd A. Mooring, Alexander Oort Alonso, Joannes D. Maasakkers, Ilse Aben, Sabour Baray,Kevin W. Bowman, John R. Worden, Felipe J. Cardoso-Saldaña, Emily Reidy, and Daniel J. Jacob. “Integrated Methane Inversion (IMI) 2.0: An improved research and stakeholder tool for monitoring total methane emissions with high resolution worldwide using TROPOMI satellite observations.” *Geoscientific Model Development,* vol. 18, p. 3311–3330. June 2025. https://doi.org/10.5194/gmd-18-3311-2025.

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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.