Reporting of Gridded (0.1°X0.1°) Methane Emission Data for India to Redefine Global Climate Studies

Mishra et al., ESSD, 2025

Detailed Response to Anonymous Referee #1

We sincerely thank the reviewer for their valuable comments and constructive suggestions, which have significantly contributed to enhancing the clarity and overall quality of the manuscript. The reviewer's comments are presented below in black, followed by our detailed responses in blue.

RC1: 'Comment on essd-2025-65', Anonymous Referee #1, 09 Oct 2025

The manuscript, "Reporting of Gridded (0.1°×0.1°) Methane Emission Data for India to Redefine Global Climate Studies" by Mishra et al., addresses the important and timely topic of quantifying and spatially representing methane (CH_4) emissions across India. Methane plays a significant role as a climate forcing gas, and there are large uncertainties in regional CH_4 budgets, especially in developing countries. Thus, this study is highly relevant for improving emission inventories and supporting the Global Methane Pledge and the Global Greenhouse Gas Watch (G3W) frameworks. The authors attempted to present a comprehensive, 0.1°×0.1° gridded inventory for 2023 that incorporates both anthropogenic and natural sources, as outlined in IPCC guidelines. However, despite the significance of the topic, the manuscript, in its current form, requires substantial revision to improve methodological transparency, contextual integration, and scientific robustness.

Major comments:

The main concern is the limited transparency of the methodology used to derive the 0.1°×0.1° gridded emissions. Although equations (1–15) outline a general framework, the description lacks sufficient detail to understand how the spatial allocation of emissions was implemented. It is unclear which proxy datasets were used to distribute emissions geographically, how high-resolution input data were obtained for different source sectors, and if region-specific adjustments or scaling procedures were applied. To ensure reproducibility and allow for a meaningful evaluation of the results, the manuscript must provide a thorough description of the data sources, spatial disaggregation methods, emission factors, and activity data used for each category (e.g., livestock, rice paddies, fossil fuels, waste management).

The methodology for uncertainty quantification is unclear and needs substantial improvement. Figure 5, which shows sector-wise uncertainty estimates, is difficult to interpret. The reported total uncertainty of ±59% is unusually large compared to other inventories and requires justification. The authors should clearly describe their approach to uncertainty estimation and specify how they defined, combined, and propagated uncertainties in emission factors and activity data across sectors. They should also provide details on assumed distributions and aggregation procedures to ensure reproducibility. Figure 5 should be revised and accompanied by a concise discussion that identifies the major contributors to the total uncertainty and explains why it is so high compared to other studies.

This study attempted to present a valuable dataset that could help fill a significant gap in methane emission information for India. The inclusion of 25 source categories, as well as the effort to quantify emissions from natural sources such as wetlands and termites, demonstrates the study's comprehensive scope and is commendable. However, the methodology is described only superficially, making it difficult to assess the reproducibility and robustness of the results. The comparison with previous studies is limited and omits several key references, which weakens the scientific context and credibility of the analysis. Furthermore, Figure 4, intended to support the intercomparison, is confusing because it includes unrealistically low total estimates derived from studies considering only a limited subset of emission sectors. A clearer, more balanced comparison that includes comprehensive inventories would significantly strengthen the manuscript.

Section 3.3 largely overlaps with the introduction and does not offer new insights. The intercomparison should focus on a quantitative evaluation against prior bottom-up and top-down estimates. Several key studies are missing from the literature review and CH_4 budget comparison, including (Miller et al. 2019; Ganesan et al. 2017; Chandra et al. 2021), as well as the updated Global Methane Budget (Saunois et al. 2024).

In conclusion, while this paper tries to address a critical gap in regional methane emission data, the methodological details, intercomparison rigor, and literature integration must be substantially improved. With clearer explanations of the gridding approach and inclusion of the missing references, as well as stronger data analysis, the manuscript could become a valuable contribution to CH_4 emission research and policymaking. At this stage, the recommendation is a major revision.

Minor comments:

1. Fig. 1b: The labels on the y-axis are not clearly defined.
2. Fig. 2: The axis and color bar labels should be enlarged.
3. Lines 277-278: " The methane footprint of Indians is found to be 27 kg and the per square km area is attributed to 11.6 tonnes." This sentence is confusing and should be revised.
4. Fig. 4: Why are some estimations so low? Apparently, some of the works considered here include only separate categories and do not provide good total estimations.

References:

Chandra, N., P. K. Patra, J. S. H. Bisht, and A. Ito. 2021. “Emissions from the Oil and Gas Sectors, Coal Mining and Ruminant Farming Drive Methane Growth over the Past Three Decades.” *Journal of The*. https://www.jstage.jst.go.jp/article/jmsj/99/2/99_2021-015/_article/-char/ja/.

Ganesan, Anita L., Matt Rigby, Mark F. Lunt, Robert J. Parker, Hartmut Boesch, N. Goulding, Taku Umezawa, et al. 2017. “Atmospheric Observations Show Accurate Reporting and Little Growth in India’s Methane Emissions.” *Nature Communications* 8 (1): 836.

Miller, Scot M., Anna M. Michalak, Robert G. Detmers, Otto P. Hasekamp, Lori M. P. Bruhwiler, and Stefan Schwietzke. 2019. “China’s Coal Mine Methane Regulations Have Not Curbed Growing Emissions.” *Nature Communications* 10 (1): 1–8.

Saunois, Marielle, Adrien Martinez, Benjamin Poulter, Zhen Zhang, Peter Raymond, Pierre Regnier, Joseph G. Canadell, et al. 2024. “Global Methane Budget 2000–2020.” https://doi.org/10.5194/essd-2024-115.

Response

Major Comments

Thank you very much for your thorough review and acknowledging our efforts to bridge the research gap on methane emissions in India. We are also thankful for your valuable comments, which will strengthen the manuscript.

The methodology adopted for emission estimation is prescribed by the IPCC defined generalised approach, which is widely being adopted by researchers around the globe, where the country-specific sectoral emission factors and activity data are vital and key challenge. . The specific sources of the activity data and emission factors are well documented and reported in tabular form in the supplementary data file. The link to the sources and references to the literature are also provided for ease of access to the dataset. Additionally, the detailed spatial allocation of emissions is described in the supplementary file (line no. 262-318). However, an elaborated description of the emission distribution is provided below for a better enhance the clarity in data integration and scientific understanding and has also been updated in the supplementary data file.

GIS-based Spatial allocation of emission:

Livestock: The livestock population was taken from the 20th livestock census-2019, which provides the district-level livestock population for 10 distinct livestock species. Then the population was upscaled to village level using proxies like rural population and availability of agricultural land. In the absence of population census data for 2023, the village-level population from the 2011 census data has been considered and extrapolated for the base year 2023. We have accessed the agricultural land from the

ESRI-land Use land cover (LULC) map of India. The agricultural land was then imported to the ArcGIS software to scale up to the village level. The higher the rural population and agricultural area in a village, the higher the livestock population as villages with larger rural populations and greater agricultural areas generally tend to have higher livestock populations, considering the fact that farming communities largely rely on livestock for agriculture, income, and household needs. Later, the category-wise livestock population is distributed over the village shapefile. The village level species-specific emission is calculated and distributed accordingly with precise political boundary data which accounts nearly 0.63 million spatial emission datasets. The village-level emission file is imported into the GIS environment using ArcGIS tools, and a new 0.1° ×0.1° gridded map is created based on weighted village-wise livestock contributions within each grid cell, followed by spatial distribution of methane emission. Both datasets were then intersected with each other and checked for duplicate entries and multiple overlaps through frequency analysis. Finally, the per-grid emission were obtained and plotted.

Agricultural Field: In case of major crop like rice and sugarcane, the CH_4 emission were calculated on the basis of each crop's cropping area in the districts and the water regime present there. The cropping area and irrigated land data were been retrieved from the Dept. of Agriculture and Farmers Welfare, Govt. of India. District-wise cropping area of rice and sugarcane were extracted from the ESRI-agricultural land shape files in GIS environment individually and allocated to village level based on spatial interaction. This was extrapolated to 0.1° x 0.1° grids, and run for frequency check and area re-calculation. On the basis of the per-grid cropping area, the emission is redistributed at fine resolution.

Wetlands: Wetlands consists of Inland wetland, Coastal wetland, and Mangroves. The data are accessed from the Wetlands of India Portal. The wetland maps obtained were georeferenced and digitised using ArcGIS tools, and have been segregated for categories like lake, pond, wetlands and coastal wetlands. Each of the wetlands has been separately layered and processed to generating the gridded map, going through the intersection, frequency and area re-calculations, and the final per-grid area of each wetland type has been prepared. As CH_4 emission from wetland is a temperature-dependent phenomenon, we incorporated the average temperature from the National Centre for Medium Range Weather Forecasting (NCMRWF)for further processing and gridded emission calculation and distribution accordingly.

Point sources: Fossil fuel production and refinery, Thermal power plants, Brick kilns, and Crematorium units are point sources. The data corresponds to the point sources are retrieved from various government reports (Sources mentioned in table S1) and their locations were collected manually from Google maps. The spatial allocation of emissions was based on points extrapolated into grids and mapped. Each grid cell containing relevant units was assigned the corresponding sectoral emission value calculated using the equation. Grids with greater capacities and a higher diversity of emission sources exhibited higher overall emissions.

Waste management: Municipal solid waste burning and landfilling were both considered under waste management. Activity information on per-capital and population density were collected from government agency like Central Pollution Control Board (CPCB). Regions with larger populations tend to generate greater amounts of waste. Variations in waste generation patterns are influenced by lifestyle differences, as urban populations generally produce more waste than their rural counterparts. Thus, urban agglomeration having more than 100000 population were masked out which comes out to be more than 1000 cities. The MSW burning and open dumping is distributed as per the gridded population distributions. The major landfilling site locations were loaded in grids and the emissions were assigned to those particular grids. Similarly, emissions from domestic and industrial wastewater treatment plants were assigned to the locations of Sewage treatment plants and Common Effluent Treatment Plants. The emission distribution was based on the wastewater treatment capacity of that particular plant and assigned to the respective grid.

Biomass Burning: Forest fire and agricultural crop residue burning were considered under this category. NASA-FIIRMS active fire counts (VIIRS) data was used as proxy to spatially allocate emissions. From the ESRI-LULC data, forest area was masked out, and the fire points that overlaid on the forest area were considered as forest fire. The emission is distributed according to the intensity of that fire reported in the fire count data. Likewise, the fire points present in the agricultural area are regarded as the crop residue burning events. The emission distribution also follows the similar procedure. After identification of forest fire and crop residue burning, the data was intersected with the gridded mapper-grid emission was achieved.

Residential & Commercial Cooking: Cooking activities were distributed on the basis of population residing in rural, urban and slums. Urban slum clusters were identified from each state and the emission is calculated and distributed accordingly. Major slum areas identified manually and from state reports and then georeferenced and digitised in ArcGIS for further processing. The slum locations were then intersected with the gridded map, and after post-processing, the slum population per grid was calculated. The emission is then distributed accordingly. The data for hotel and restaurants are taken from the medium, small and micro enterprises, and the locations are loaded in the gridded map to assign the emission. Street vendors were distributed in the urban agglomeration, i.e., which cities having higher population and higher street vendors are assigned with higher emission polygons. The gridded emissions are distributed on the major and minor road networks running through the cities and people residing in it.

Transport sector: This is one of the major sectors in which the emission distribution was tedious. The road network of 6.6 million kilometres was accessed from the OpenStreetMap and loaded into ArcGIS interface. National Highways (NH), State

Highways (SH), Major Roads, and Minor Roads were segregated with their individual type total road length. Additionally, the vehicle density in the NH and SH were calculated from the vehicles crossing toll plazas. Heavy vehicle mobility is carefully distributed over the NH & SH, complying with the interstate vehicle movement. The emissions from the transport sector were distributed on the basis of the number of registered vehicles present in the states distributed across the road networks present in that state. Since the heavy commercial vehicular activities are usually high in activity areas like Point of interest (POIs) like mining areas, Industries, etc, higher vehicular weightages were given to the POIs for better representation of the emission scenarios complying with the real-life scenarios. NH & SH road networks, major roads, minor roads, residential roads and points of interest were overlaid the grids and emissions were assigned to the grids that intersected, where the grid containing the higher proxy data were assigned with higher emissions.

Termites: Lastly, the termite sector was distributed on the forest area and the termite biomass present per square meter of forest land. The forest region was mapped from the ESRI-LULC data and then different forest types were segregated according to the species present. The file was intersected with the grids, and the grid containing the forest area was recalculated post-processing. The emissions were then distributed according to the forest area present in that particular grid.

Uncertainty estimations:

The uncertainty in the estimation is calculated using both the linear error propagation method and the Monte Carlo simulation method. We have updated the text to present a detailed methodology for uncertainty estimation in the supplementary file as well.

The Linear Error Propagation Method is a first-order analytical technique recommended by the IPCC for estimating uncertainties in emission inventories. It assumes that total emissions are derived from the product of activity data and emission factors, each associated with inherent uncertainty due to data variability or measurement limitations. These uncertainties are combined mathematically through a root-sum-of-squares approach, which assumes independence between variables and linear relationships among them. The resulting value represents the combined relative uncertainty of the emission estimate. However, it does not account for non-linear behaviours, and thus may underestimate uncertainty in complex cases. So, IPCC prescribed a Monte Carlo simulation Method to address the non-normal distributions and asymmetry in the dataset. In the Monte Carlo Simulation (MCS) approach, uncertainties associated with source-specific activity data and emission factors are characterized through appropriate probability distribution functions, such as Normal, Log-Normal, Student's t, Triangular, or Uniform distributions, depending on the statistical nature of the input data. The method involves repeatedly drawing random samples from these distributions and computing emission estimates for each iteration. This iterative process, typically performed 100,000 times, produces a probabilistic distribution of emission outcomes.

From this distribution, key statistical parameters namely, the mean, standard deviation, and the 95% confidence interval, are computed to quantify the overall uncertainty associated with each emission sector.

Most of the previous studies haven't reported the sector-wise uncertainties for India specifically and global studies like Saunois et al. (2025) have reported the uncertainty of ~45% for Southeast Asia as a whole. This is the mean uncertainty calculated for all other nations in Southeast Asia, including India, where the uncertainty associated with large country like India is unclear. Solazzo et al. (2021) presented the sectoral uncertainties of CH_4 in the EDGAR estimation for India. The reported uncertainties in the Energy: fuel consumption sector were found to be 223%, followed by Oil & Gas (139%), Waste (107%), Solid fuels (57%), Industrial processes and product use (42%), and Agriculture (42%). However, the uncertainty reported here is improved with the use of regional activity data, large proxy data and regional scale sectoral emission factors. The uncertainty shoots up with the inclusion of natural sources like emissions from Wetlands (Inland wetland, Coastal wetland & Mangroves) and Termites. It is observed that uncertainty associate with small sectors like Coal mining, forest fire is high as compared to major sectors like Livestock and paddy field. Besides these sectors, the overall anthropogenic emission uncertainty is found to be ~44%, improving the reliability of developed present inventory and robustness of the emission dataset. The higher uncertainty for various sources, including natural sources, is due to the paucity of updated technological emission factors. With higher emissions and higher uncertainty of the wetland sector, it alone drives the uncertainty upward. Similarly, major sectors like Paddy and sugarcane fields and fossil fuel activity contribute more to the overall higher uncertainty. The semi-log plot of sectoral uncertainty depicts the sector-specific methane emissions and the associated uncertainty in the estimation. The grey bar shows the emission in Terra gram (Tg), and the line depicts the uncertainty values in percentage (%).

We have presented the comparison with previous studies, which provide detailed sector-specific emission estimates for India. We acknowledge our limitations in incorporating recent literature in this study area. We must thank the reviewer for the suggested couple of important articles. We have now included them in the literature review and in the intercomparison section. There are limited studies of comprehensive multi-sectoral emission estimation for India, such as EDGAR and Garg et al., which are discussed in detail. We have revised section 3.3, the intercomparison section, with quantitative emission data in this revision. Figure 4 illustrates the comparison of sectoral emissions with previous studies. Some of the studies only consider a single sector, resulting in a low total column and creating ambiguity. We have modified the plot and removed the total column for ease of understanding.

Response to Minor comments:

1. Fig. 1b: The labels on the y-axis are defined in the lower right-hand side corner. For ease of understanding, we have modified the plot and mentioned in the bottom.

2. Fig. 2: The axis and color bar labels are enlarged for clear visibility
3. Lines 277-278: This sentence is revised to “The per-capita methane footprint of Indians is found to be 27 kg, and the per square km area CH4 burden is 11.6 tonnes.”.
4. We have removed the total column from Fig. 4 to remove the ambiguity.

Thank you very much for the critical review. We have incorporated all the suggested changes from the reviewer in this current revision to strengthen the article and for ease of understanding.