Reviewer -1

Response to Reviewer-1

The manuscript "Emissions of Methane from Coal, Thermal power plants and Wetlands and its Implications on Atmospheric Methane across the South Asian Region" investigates the spatial and temporal dynamics of atmospheric methane (CH_4) concentrations over the South Asia region from 2009 to 2022, utilizing data from the Greenhouse gases Observing SATellite (GOSAT) and the TROPOspheric Monitoring Instrument onboard the Sentinel-5 Precursor (S5P/TROPOMI). The analysis identifies specific sources contributing to this increase, notably the Mundra thermal power station and Mundra ultra mega power plant, exhibiting higher rates of increase in XCH_4 compared to other natural and anthropogenic sources. The study also highlights the significant methane emissions from the Sundarbans natural wetland, competing with coal sites in terms of emission rates, thus emphasizing its importance as an equivalent anthropogenic source. Furthermore, the investigation delves into the distribution of CH_4 emissions across 15 Indian Agroclimatic zones; and employs bottom-up anthropogenic CH_4 emissions data to map against XCH_4 concentrations, revealing a high correlation in the Indo Gangetic Plains (IGP) region, thereby identifying key anthropogenic CH_4 hotspots. Overall, the manuscript provides crucial insights into the impact of both natural and anthropogenic sources on XCH_4 concentrations over the Indian region, quantifying spatio-temporal changes at each study site. The findings hold significance for understanding and addressing the complex dynamics of atmospheric methane, a potent climate change agent.

Reply: Thank you for the overall feedback on the present work. We thank you for the constructive comments. In the revised work, we have addressed all the suggested comments point-by-point carefully.

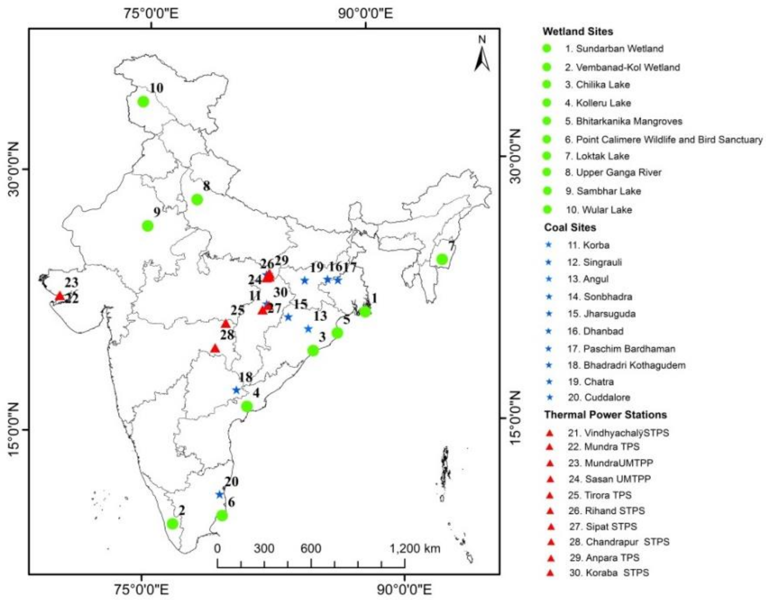
1. Atmospheric methane (CH_4) is one of the high-potential greenhouse gases (GHG) that regulates the chemical reactions in the free troposphere and stratosphere.
   Comment: Here, 'regulates' does not seem appropriate.

   Reply: Thank you for the suggestion. We have modified the sentence as below and the same has been updated in the revised manuscript.

   Atmospheric methane (CH_4) is one of the high-potential greenhouse gases (GHG) and plays a vital role in the chemistry of the atmosphere. In the troposphere CH_4 oxidation is due to hydroxyl radical (OH) and results in the production of carbon monoxide, CO_2 and ozone in the presence of increased amounts of oxides of nitrogen where as in the stratosphere, oxidation of CH_4 is by OH radical, atomic oxygen and chlorine (Nair & Kavitha, 2020).

2. Comment: Could figures 1a, 1b, and 1c be merged into a single figure where all the sources are indicated with different shapes/colors? Three heterogenic CH_4 source regions. Comment: Are the entities depicted in the figure referred to as heterogenic source regions or individual sources? Coal fields and thermal power plants are primarily situated within the same region.

   Reply: As suggested, Figure 1a, 1b and 1c are merged into single figure as shown below. The entities depicted in the figure are individual sources. The figure 1 below shows the top 10 wetlands (circle) which is natural sources of CH_4. The top 10 coal mine locations (star symbol), top 10 thermal power plants (triangle) are anthropogenic sources of CH_4. The same has been updated in the revised manuscript.



3. The Ministry of Environment, Forests and Climate Change (MoEF&CC), Government of India, has identified 75 Ramsar Wetland sites in India as of November 2022. These sites span a total area of 13,35,530 ha. Based on the high total geographical area coverage (Table 1), the top 10 places were determined for the current investigation. The size varies from 423000 ha (Sundarbans Wetland, West Bengal) to 18900 ha (Wular Lake, Jammu and Kashmir). Comment: Reference for the aforementioned statement.

   Reply: The reference for the aforementioned statements are given below:

   - https://indianwetlands.in/wetlands-overview/indias-wetlands-of-international-importance/
   - PIB Press Release on World Wetlands Day dated 26th August, 2022.

   The same has been updated in the revised manuscript.

4. In the present study, the atmospheric CH_4 was obtained from 2009 to 2020…. Comment: As previously stated and indicated in Figure 2, data up to 2022 was utilized for the current study.

   Reply: Thank you for the suggestion. For studying the natural sources (wetlands) and anthropogenic sources (coal and thermal power plants) of CH_4, the XCH_4 concentration was taken for the period 2009 to 2022 is shown in figure 5. To maintain the uniformity in the datasets, we have updated the figure 5 with 2021 and 2022 years as shown below.

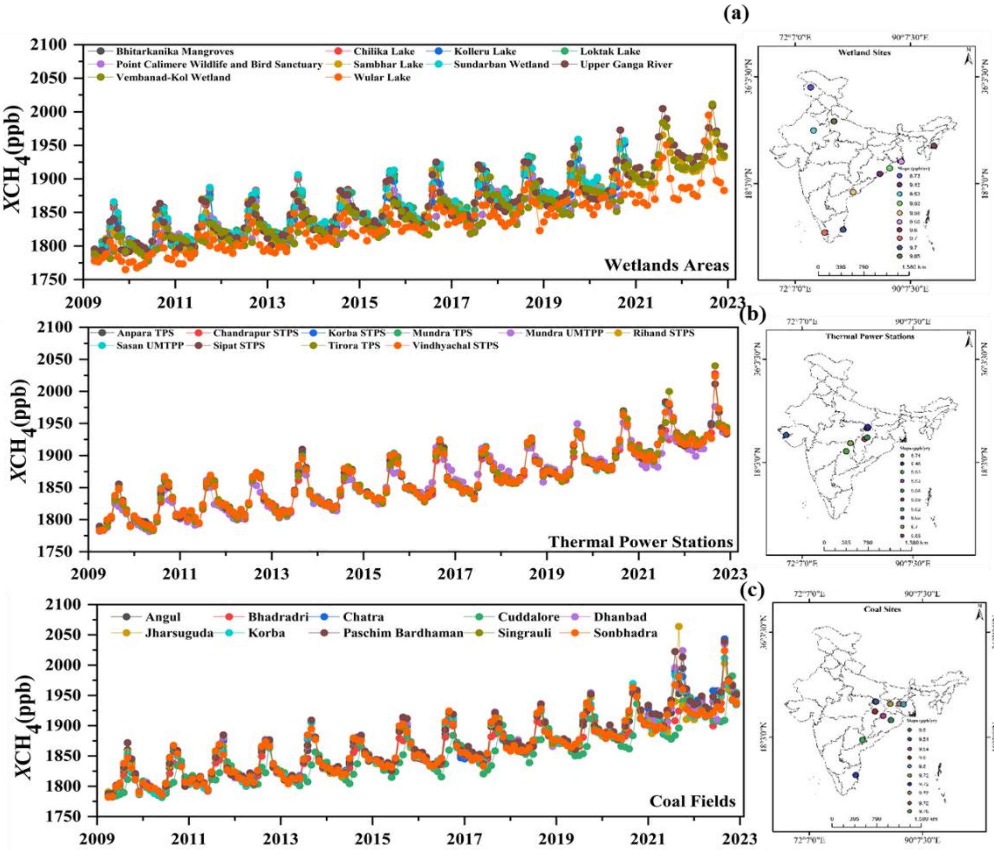


Figure 5. Monthly time series of XCH_4 over the a) wetlands, b) thermal power stations, and c) coal fields: sources of emissions, along with the overall growth rate at the respective site.

5. Comment: There is no mention of gridding of level 2 data, if any has been applied. Have all the datasets been gridded to the same resolution?

Reply: We have re-gridded the data to the same resolution

6. Comment: In Figure 3, regarding the TROPOMI data from 2019 to 2022, is it averaged over this period or does it represent all the observations? There are data gaps in Tropomi, which are assumed to occur during the monsoon season. However, these gaps are absent in GOSAT. Are you employing any data-filling method for the GOSAT data?

Reply: Figure 3c shows the averaged TROPOMI data from 2019 to 2022. As you pointed there are data gaps observed both in TROPOMI and GOSAT. The spatiotemporal variability of XCH_4 as discussed in figure 5 has few data gaps in the daily data during monsoon season which is due to the influence of cloud cover and sensor observation mode. However over the study locations a good number of representative XCH_4 data was observed in each month. Therefore we could analyse space time variability of XCH_4 over the study sites.

7. Figures 5a-c shows the monthly time series of XCH_4 over the specific sources of CH_4 dotted in the Indian region during 2009 to 2020. Comment: dotted?

   Reply: Thank you for the comment. Our intended meaning was different sources situated/pointed in the figure. However sentence has been modified now. The figures 5a-c shows the monthly time series of XCH_4 over the specific sources of CH_4 plotted for the Indian Region during 2009 to 2022. This figure is now updated with 2021 and 2022 data and same is reflected in the revised manuscript.

8. The seasonal cycle (peak and trough) of XCH_4 is strongly associated with the vegetation during the active phase of cultivation and reduced photochemical reaction by the hydroxyl radicals, respectively. Comment: could you provide a reference for the statement? Considering wetlands and coal as the largest emitter of CH_4, how is the seasonal cycle associated with this? A seasonal maximum of XCH_4 was observed over Coal and Thermal power plants from September to October and a minimum in pre-monsoon (March-May). Comment: Are you associating this cycle with rice cultivation?

   Reply: Sreenivas et al. (2016) in his studies observed high CH_4 concentrations during post-monsoon which may be associated with Kharif season. Low concentrations of CH_4 are observed during monsoon which is due to reduction in atmospheric hydrocarbons because of the reduced photochemical reactions and significant drop in solar intensity. As you rightly pointed seasonal maximum is also strongly associated with rice cultivation. Kavitha et al. (2016) also reported that different seasonal behaviour with seasonal peak in post-monsoon and low during monsoon in the Southern peninsular regions. These regional variations are to distribution of sources like livestock population, rice cultivation, wetland, biomass burning and oil and gas mining.

9. Comment: There is a typo in Figure 7, indi. Does the spatial distribution represent the mean of all the years?

   Reply: The typo has been corrected in figure 7 (indi to Indian Region).

10. Comment: The descriptions of Figures 7 and 8 do not match their respective figures. Additionally, the description of Figure 8 appears before that of Figure 7.

   Reply: Thank you. The figures numbers were wrongly written in the text of the manuscript. Figure 7 shows the continuous XCH_4 data from S5P/ TROPOMI complementing the GOSAT efforts instead of figure 8 which was written in the manuscript. In section 4.4, significant high emissions of CH_4 as shown in figure 9c, instead of figure 7c which was written in the manuscript. The figures numbers were corrected in the revised manuscript.

11. Significant high emissions of CH_4, as shown in Figure 7c. Comment: Figure 7c is missing.

Reply: The figure in section 4.3 is figure 9c instead of figure 7c and the same has been corrected in the revised manuscript.

Additional Suggestions

1. Emissions from EDGAR only verify the anthropogenic emissions, but there is a significant wetland source situated over India that requires verification with the appropriate inventory.

   Reply: We thank you for the important suggestion. We have implemented the emissions from the natural sources (wetlands) using the inventory "WetCHARTs v1.3.1". This has really helped us to apportion the contribution from the natural and anthropogenic emissions of CH_4. The below figure 8 shows the monthly time series of methane emissions (mg m^{-2} $month^{-1}$) over the wetland sites, inset figure shows the seasonal methane emissions over the wetland sites from 2001 to 2019. As suggested, introduced new figure 8 in the revised manuscript.

2. Additionally, previous studies have demonstrated the limitations of satellite data during the monsoon season and the biases associated with global inventories such as EDGAR, over the Indian region. Therefore, it would be appropriate to study the uncertainty associated with the emissions and XCH_4 from their respective datasets.

   Reply: We agree with you suggestion. Present study included the relevant supporting information attributed to the uncertainties associated with the EDGAR based bottom-up CH_4 emission inventory and biases associated with the XCH_4 retrievals from the Remote Sensing sensors. However, this inventory helps to map the high emission (hotspots) zones of CH_4 and associated activities.

- Uncertainties in the information on source intensity, activity and other statistical data are the key parameters for the uncertainties in the EDGAR emission inventory (Janardanan et al., 2017).
- Bottom up inventory uncertainties range between 20 and 35% for agriculture, waste and fossil fuel sectors; 50% for biomass burning and natural wetland emissions and 100% or higher for natural sources such as geological seeps and inland waters for global methane emissions (Saunois et al.,. 2020).
- Ground based FTIR measurements of XCH_4 by the Total Carbon Column Observing Network (TCCON) are used extensively to validate the GOSAT retrievals. Retrieval bias and precision of column abundance from GOSAT SWIR observations have been estimated as approximately 15-20 ppb and 1% respectively (Morino et al., 2011; Yoshida et al., 2013).
- Methane retrieval from TROPOMI is in overall agreement with correlative ground based from TCCON and Network for Detection of Atmospheric Composition Change (NDACC). The systematic differences of the bias corrected XCH_4 data with respect to TCCON data and NDACC data are on average, -0.26±0.56% and 0.57±0.83% respectively (Song et al., 2023).

3. There are extensive studies of XCH_4 over India from satellites have been conducted by Mottungan et al. However, the authors have not reffered them in their study.

   Reply: We sincerely appreciate the previous works carried out by Mottungan et al., which were missed in our work inadvertently. However, we could read those papers and utilised in the revised work to strengthen the present work.