

Assessment of atmospheric methane locational concentration in Rivers State, Nigeria, using Sentinel-5 precursor (TROPOMI) data

Évaluation de la concentration localisée de méthane atmosphérique dans l'État de Rivers, au Nigéria, à l'aide des données du précurseur Sentinel-5 (TROPOMI)

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ABSTRACT: Atmospheric methane (CH₄) impact climate change. Monitoring its levels and emission sources is vital. Rivers State, Nigeria, emits CH₄ from oil, gas, and wetlands. The datasets and observations originating from the Sentinel-5 Precursor (S5P) satellite, specifically those gathered by the Tropospheric Monitoring Instrument (TROPOMI), studies CH₄ concentration over Rivers State, Nigeria, from 2020 to 2024. Methane data analyzed for maps & time series. Avg. methane concentrations. in Rivers State, Nigeria was 1909 ppb, exceeding global avg. of 1866 ppb but lower than US oil & gas-rich regions at 2000 ppb. CH₄ levels vary spatially in Rivers State, with higher concentrations near oil & gas infra, industry, urban areas, & wetlands. Hotspots align with emission sources. S5P/TROPOMI data assists CH₄ monitoring in data-limited regions & identifies emission reduction needs & research areas in Rivers State, providing insights for climate change actions in the Niger Delta.

KEY WORDS: Methane (CH₄), Rivers State, Nigeria, Sentinel-5 Precursor (S5P), TROPOMI, Greenhouse Gas.

RÉSUMÉ : Le méthane (CH₄) dans l'air impacte le climat. Il faut surveiller ses niveaux et ses sources. Rivers, Nigéria, émet du CH₄ du pétrole, du gaz et des zones humides. Les données de Sentinel-5 Precursor (S5P), TROPOMI, analysent la concentration de CH₄ à Rivers, Nigéria, jusque 2024. La concentration moyenne était de 1 909 ppb, dépassant la moyenne mondiale de 1 866 ppb, mais inférieure aux régions américaines riches en énergie (2 000 ppb). Les niveaux varient localement, plus élevés près des infrastructures, industries et zones urbaines. Les points chauds correspondent aux sources d'émission. Les données S5P/TROPOMI aident à la surveillance du CH₄ dans les régions où les données sont limitées et identifient les besoins de réduction des émissions et les domaines de recherche dans l'État de Rivers, fournissant des informations sur les actions de lutte contre le changement climatique dans le delta du Niger.

MOTS CLÉS : Méthane (CH₄), État de Rivers, Nigéria, précurseur Sentinel-5 (S5P), TROPOMI, gaz à effet de serre.

1. Introduction

Methane (CH₄) stands as the second most significant human-induced greenhouse gas, surpassed only by carbon dioxide (CO₂). Its capacity to warm the planet, typically referred to as its global warming potential, is estimated to be approximately 25 times that of CO₂ when assessed over a 100-year period (IPCC, 2014). The atmospheric abundance of this gas has notably increased by more than twofold since the pre-industrial era. This substantial rise is attributed to a combination of human-derived activities, such as the extraction and utilization of fossil fuels, various agricultural practices, and waste management strategies, alongside inherent natural phenomena, predominantly those associated with wetland ecosystems (Saunois et al., 2020). Despite its shorter atmospheric lifetime compared to CO₂, the high warming potential of CH₄ makes controlling its emissions a critical strategy for near-term climate change mitigation (Saunois et al., 2020).

Accurate measurement and monitoring of atmospheric CH₄ concentrations are essential for understanding the global methane budget, identifying major emission sources and hotspots, quantifying emission rates, and verifying the effectiveness of emission reduction policies. Traditionally, CH₄ concentrations are measured through ground-based monitoring networks and atmospheric sampling campaigns. However, these methods are often spatially sparse and costly, particularly in developing regions (Turner et al., 2015).

Satellite remote sensing has emerged as a powerful tool for monitoring atmospheric composition on a global scale, offering broad spatial coverage and relatively high temporal resolution. Several satellite missions have instruments capable of measuring atmospheric CH₄ columns, including SCIAMACHY on Envisat, TANSO-FTS on GOSAT, and OCO-2/3. The Sentinel-5 Precursor (S5P) mission, inaugurated in 2017 as an integral component of the European Copernicus program, is equipped with the Tropospheric Monitoring Instrument (TROPOMI). This advanced instrument facilitates daily, global observation of a multitude of atmospheric trace gases, notably methane (CH₄). A defining characteristic of TROPOMI is its exceptional spatial resolution, which substantially surpasses that achieved by preceding satellite endeavors (Veefkind et al., 2012). This capability makes S5P/TROPOMI particularly valuable for regional-scale studies and the identification of localized emission sources.

Nigeria holds a prominent position among Africa's leading economies, concurrently serving as a primary global producer of hydrocarbons. A substantial proportion of these resource extraction activities is predominantly situated within the Niger Delta region. This region is also characterized by extensive mangrove swamps and freshwater wetlands. Oil and gas production activities, including extraction, processing, and transportation, are known sources of fugitive CH₄ emissions through leaks, venting, and flaring (Ismaila & Ite, 2017). Wetlands are natural sources of CH₄, with emission rates influenced by factors such as temperature, vegetation, and water level (Walter & Heimann, 2000). Furthermore, growing populations in urban centers contribute to emissions from waste management and potentially energy consumption. Rivers State, a key state within the Niger Delta, encompasses a significant portion of Nigeria's oil and gas infrastructure, major urban centers like Port Harcourt, and extensive wetland ecosystems.

Given the combination of these potentially significant CH₄ sources, Rivers State is likely an area with elevated atmospheric CH₄ concentrations. However, detailed, high-resolution CH₄ monitoring data specifically for this region, particularly derived from satellite platforms like S5P, is limited in published literature. Understanding the spatial distribution and temporal dynamics of

CH₄ in this complex environment is crucial for assessing the regional contribution to climate change, identifying major emission culprits, and informing targeted mitigation strategies.

The present investigation endeavors to bridge an existing lacuna in scholarly understanding by employing satellite observations from the Sentinel-5 Precursor/TROPOMI instrument. Its aim is to undertake a detailed spatio-temporal analysis of atmospheric methane concentrations within Rivers State, Nigeria. The specific objectives are to:

1. undertake an analysis of the geographical distribution of atmospheric methane abundance across the entirety of Rivers State.
2. Identify potential CH₄ hotspots within Rivers State.
3. Relate the observed spatial patterns and hotspots to potential anthropogenic and natural emission sources in the region.

By achieving these objectives, this research provide foundational data and analysis for understanding regional CH₄ dynamics in a critical environmental setting and contribute to the broader efforts of monitoring and mitigating greenhouse gas emissions in Nigeria and the wider Niger Delta.

1.1. Literature Review

Methane (CH₄) is a critical component of the Earth's atmosphere and a primary driver of radiative forcing after carbon dioxide (IPCC, 2014). Its concentration has risen sharply, particularly in recent decades, prompting increased scientific focus on understanding its sources and sinks (Saunio et al., 2020). Globally, the origins of methane can be broadly classified into two principal categories: anthropogenic and natural. Human-induced contributions primarily involve the fossil fuel industry, which releases methane during the extraction, refinement, and conveyance of petroleum, natural gas, and coal. Other significant anthropogenic sources include agricultural practices (such as enteric fermentation in livestock, the management of animal waste, and rice cultivation), waste management systems (including landfills and wastewater treatment processes), and the combustion of biomass (Saunio et al., 2020). Natural sources are dominated by wetlands, but also include geological seeps, termites, and wildfires (Kirschke et al., 2013). Quantifying the contribution of each source type remains a significant challenge in understanding the global methane budget.

The Niger Delta region of Nigeria is recognized as a major source of atmospheric trace gases, including CH₄, largely due to its extensive oil and gas operations and abundant wetlands (Ismaila & Ite, 2017; UNEP, 2011). Nigeria is one of the world's largest gas flarers, a process that often leads to incomplete combustion and significant methane emissions through associated venting and leaks (Ite & Ibok, 2013). While flaring technology aims to combust methane, inefficiencies, and associated infrastructure leaks contribute substantially to the regional CH₄ burden (Miller et al., 2013). Additionally, the pervasive network of pipelines, wellheads, and processing plants across the delta represents numerous potential points for fugitive emissions (UNEP, 2011). Simultaneously, the vast mangrove and freshwater swamp forests of the Niger Delta provide ideal conditions for methanogenesis, making them significant natural emitters (Walter & Heimann, 2000). Urbanization and agriculture are also growing contributors to CH₄ emissions in the region (NPC, 2019).

Ground-based monitoring of atmospheric composition in the Niger Delta is sparse due to logistical challenges, cost, and security concerns (Ite & Ibok, 2013). Consequently, satellite remote sensing offers a spatially comprehensive and cost-effective alternative for assessing atmospheric CH₄

levels in this region. Early satellite missions like SCIAMACHY provided global CH₄ column data but at coarse spatial resolution (usually > 30 km x 60 km), limiting their utility for identifying localized sources (Frankenberg et al., 2005). The GOSAT satellite offered significantly improved data quality and sensitivity but still with limited spatial coverage (point measurements with ~10 km footprint) and long revisit times (Crisp et al., 2017).

The Sentinel-5 Precursor (S5P) initiative, furnished with the TROPOMI instrument, constitutes a substantial progression in space-borne atmospheric observation (Veefkind et al., 2012). This particular instrument ascertains the solar irradiance reflected by the Earth's atmosphere and its terrestrial surface across the ultraviolet-visible (UV-VIS), Near Infrared (NIR), and Short-wave Infrared (SWIR) regions of the electromagnetic spectrum. CH₄ column amounts are retrieved primarily from measurements in the SWIR range (Butz et al., 2010; Hu et al., 2018). A key feature of TROPOMI is its high spatial resolution (up to 7 km x 5.5 km initially, later improved) and daily global coverage (Veefkind et al., 2012). This resolution allows for the detection of anomalies in CH₄ concentrations potentially linked to specific industrial facilities, urban areas, or large wetland complexes (Jacob et al., 2022; Schneising et al., 2020).

Research employing S5P/TROPOMI data has effectively pinpointed methane (CH₄) plumes and elevated concentrations linked to hydrocarbon extraction and processing operations across diverse global locales, including the Permian Basin in the United States (Chen et al., 2022), regions of intense coal extraction in China (Sadavarte et al., 2021), and pipeline integrity breaches in Russia (Venting et al., 2021). Furthermore, TROPOMI observations have proven instrumental in examining CH₄ emissions emanating from major urban centers (Lorente et al., 2021) and natural wetland ecosystems (Zhang et al., 2021). Nonetheless, despite several global or pan-African investigations encompassing Nigeria within their geographical purview, a dedicated, high-resolution analysis of CH₄ concentrations specifically targeting Rivers State, leveraging the advanced observational capabilities of S5P/TROPOMI, has yet to be extensively published. Such a concentrated investigation is imperative for furnishing practical intelligence to regional stakeholders.

Comprehending the spatial and temporal distribution of CH₄ across Rivers State necessitates accounting for the complex interaction of diverse emission categories within the inherent spatial resolution of TROPOMI. Differentiating between anthropogenic and natural sources, relying exclusively upon atmospheric concentration data from TROPOMI, presents a significant challenge and frequently mandates the integration of supplementary datasets or sophisticated atmospheric transport models (Jacob et al., 2022). Nevertheless, pinpointing persistent regions of heightened concentrations offers vital intelligence concerning where substantial emission fluxes are potentially originating. This investigation, therefore, harnesses the advanced capabilities of S5P/TROPOMI to deliver an unprecedented high-resolution depiction of CH₄ spatial distribution and temporal variability across Rivers State, thereby establishing a foundational dataset for subsequent, more exhaustive source apportionment investigations and precise emission quantification endeavors..

2. Study area

This study's spatial extent is confined to Rivers State, which lies within the eastern sector of Nigeria's Niger Delta region. The territory's approximate Universal Transverse Mercator (UTM) coordinates (Zone 32N_WGS 84) range from 477,432m to 634,925m for Northings and 210,590m to 344,489m for Eastings. (For a visual representation, consult Figures 1 and 2).

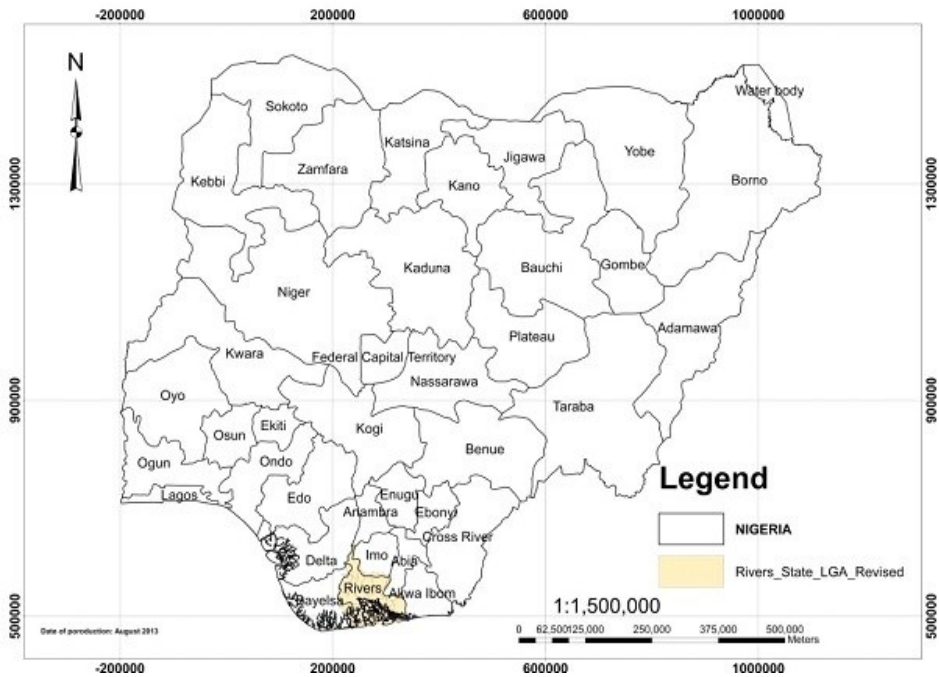


Figure 1 Geographic of Nigeria and the study area, Rivers State. Sources: Rivers State Government, 2025

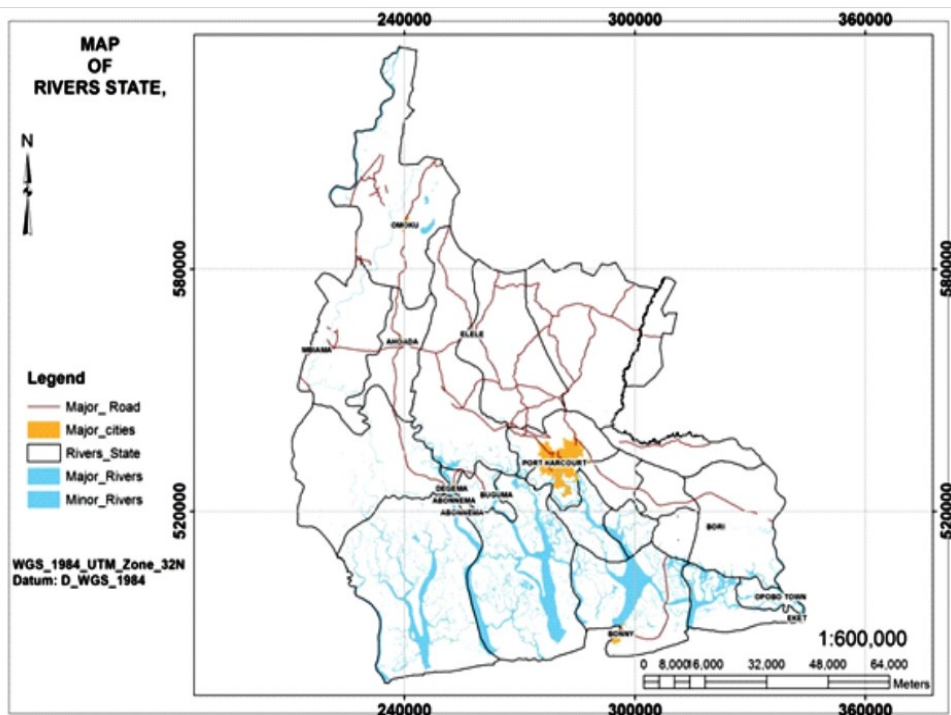


Figure 2 Rivers State Map. Source: Office of Surveyor General, Rivers State, 2025.

The state has a humid tropical climate with significant rainfall and is characterized by a diverse landscape including coastal sands, mangrove swamps, freshwater swamps, and tropical

rainforests. Rivers State is the center of Nigeria's petroleum industry, hosting numerous oil and gas fields, refineries, petrochemical plants, and export terminals, particularly around Port Harcourt and the coastal areas. It is also densely populated, with Port Harcourt serving as a major urban and industrial hub. The confluence of these factors – extensive oil and gas operations, vast wetlands, and a significant urban population – makes Rivers State a critically important region for assessing atmospheric CH₄ concentrations.

3. Methods

3.1. Data Source

This investigation employed Level 2 atmospheric methane (CH₄) columnar data, which were acquired from the Tropospheric Monitoring Instrument (TROPOMI) aboard the Sentinel-5 Precursor (S5P) satellite. Specifically, the L2_CH4 data product was utilized, furnishing measurements of the total column-averaged dry air mole fraction of methane (XCH₄), expressed in parts per billion (ppb). The S5P/TROPOMI platform delivers daily, near-global coverage, providing an initial nadir ground pixel resolution of approximately 7 km by 5.5 km. This represents a notable improvement in spatial resolution when contrasted with predecessor missions, such as SCIAMACHY.

Data were acquired annually for the period spanning from January 1, 2020 to December 31, 2024. Data files were accessed directly from cloud-based platforms Google Earth Engine (GEE) which provide access to the S5P dataset with pre-processing capabilities.

3.2. Data Processing

Sentinel-5 Precursor is a satellite mission designed to monitor atmospheric trace gases, including methane, using the Tropospheric Monitoring Instrument (TROPOMI).

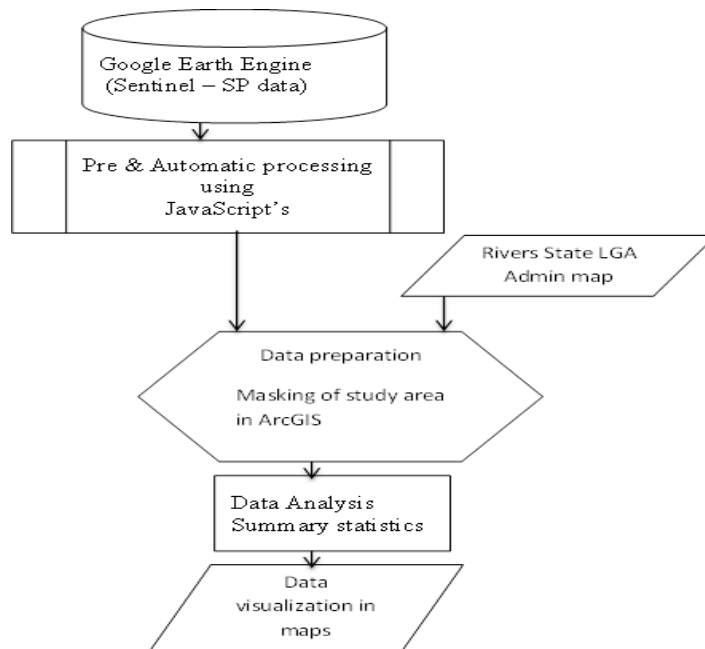


Figure 3 Methodology flowchart of Methane characterisation in Rivers State, Source: Author 2025.

TROPOMI provides high-resolution (3.5 km x 7 km) global daily measurements of methane concentrations. In this study, Sentinel-5 Precursor (resolution (3.5 km) annual data from January 2020 to December 2024 were used to estimate methane concentrations in Rivers State, Nigeria. Processing was performed using Google Earth Engine scripting.

The data were pre-processed to remove cloud-contaminated pixels and ensure the quality of the measurements (see Fig 3). The methane concentrations were then averaged over the study period to obtain a representative value for the region. The spatial distribution of methane emissions was assessed using the averaged methane concentrations and the geographic coordinates of the study area. The filtered data were clipped to the geographical boundary of Rivers State, Nigeria. This involves masking the data using a vector shapefile of the state boundary. The irregularly spaced S5P pixels (swaths) were reprojected to a common coordinate system (WGS84_UTM_ZONE 32N) and spatially aggregated onto a regular grid. The annual average CH₄ concentration maps visualised. During the study period (2020 - 2024), a long-term average map was created and converted into vector format for hotspot analysis. The hotspots map was generated using the Getis-Ord Gi* statistic tool in ArcGIS 10.8. This analytical methodology is employed to discern statistically significant spatial concentrations, specifically identifying areas of elevated values (hotspots) and regions of attenuated values (coldspots). The dataset is subsequently stratified into seven distinct categories based on key statistical indicators, including z-scores, p-values, and a confidence level bin (e.g., a Gi*_Bin index) assigned to each spatial feature. These classifications are delineated at standard confidence thresholds of 99%, 95%, and 90% for both coldspot and hotspot phenomena, with a 0% categorization denoting statistical insignificance.

4. Results and discussion

4.1. Spatial Analysis: Average CH₄ Maps

Annual average CH₄ concentration maps were generated to visualize the general spatial distribution across Rivers State for 2020,2021,2022,2023 and 2024(see figure 4-8).

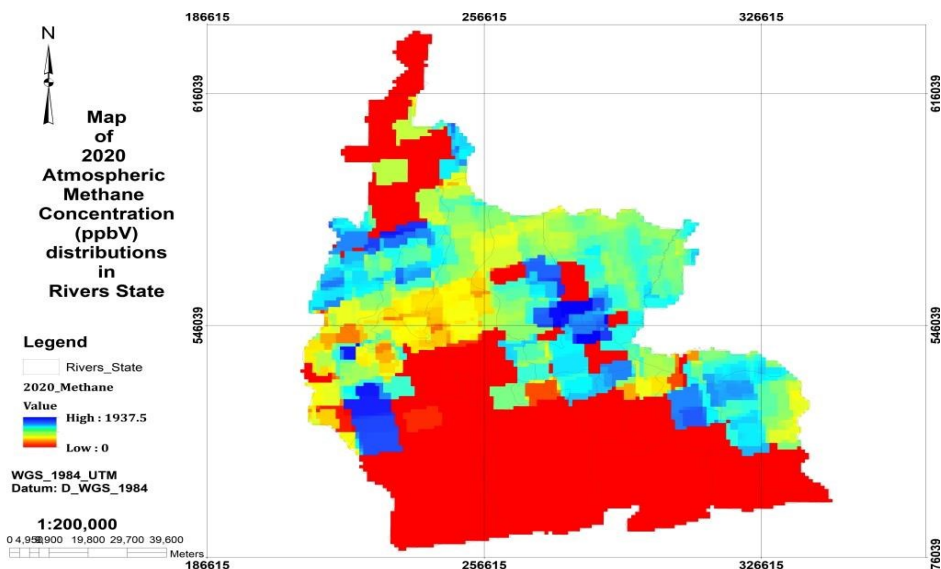


Figure 4 Map of 2020 Methane distributions in Rivers State. Source: Author 2025.

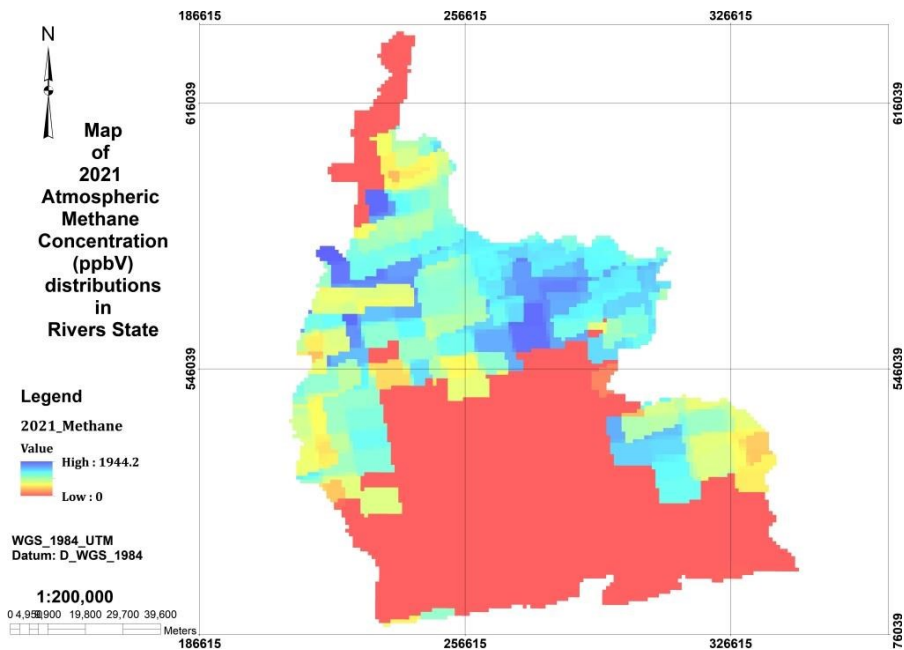


Figure 5 Map of 2021 Methane distributions in Rivers State. Source: Author 2025.

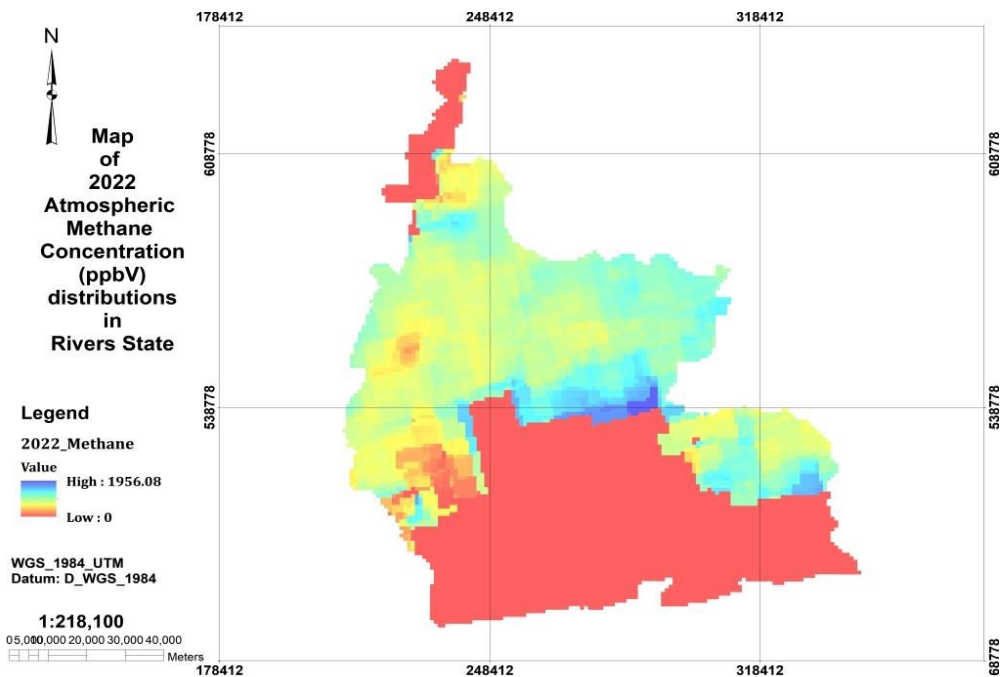


Figure 6 Map of 2022 Methane distributions in Rivers State. Source: Author 2025

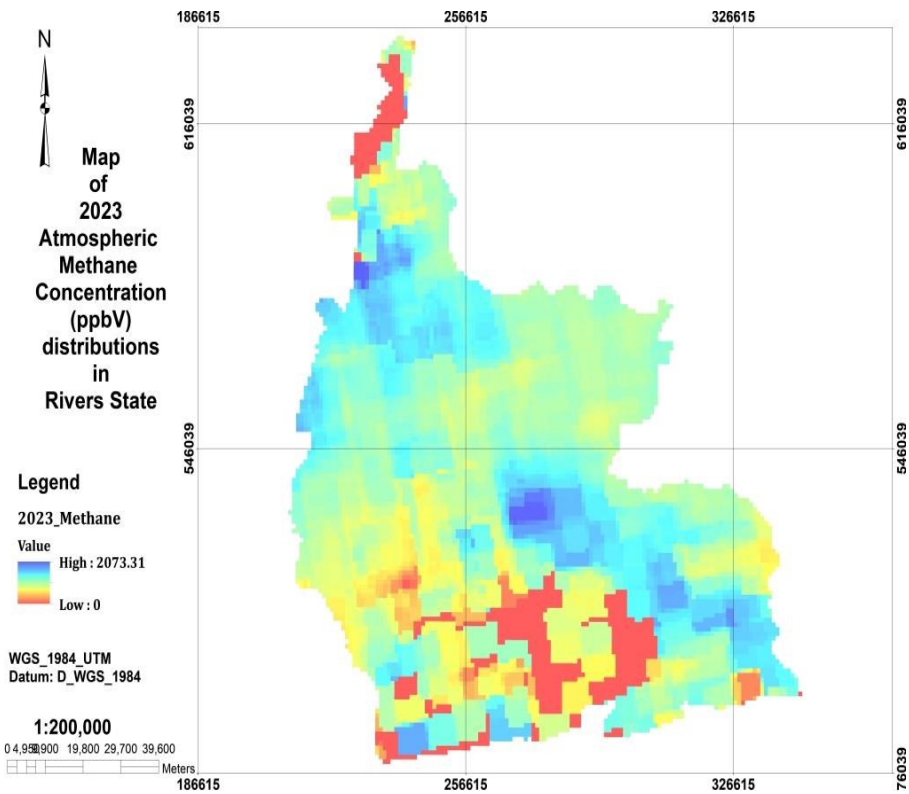


Figure 7 Map of 2023 Methane distributions in Rivers State, Source: Author 2025.

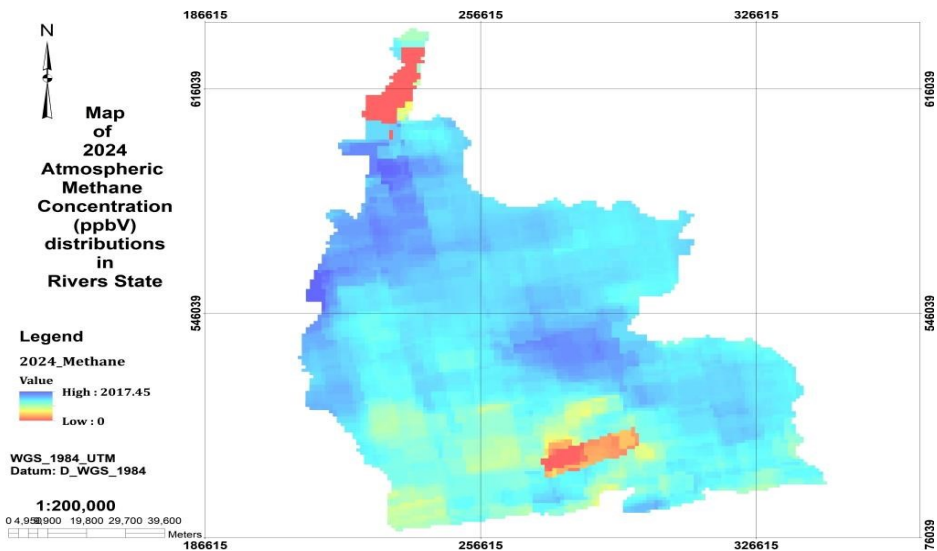


Figure 8 Map of 2024 Methane distributions in Rivers State. Source: Author 2025.

The average methane concentration in Rivers State, Nigeria, was estimated to be 1909 ± 130 ppb (parts per billion) for the study period. This value is higher than the global average methane concentration of 1866 ppb (WMO, 2019) but lower than the average methane concentration in the oil and gas-rich regions of the United States (2000 ppb) (Conley et al., 2016).

Table 1 Summary statistics value of methane in Rivers State.

	Min	Max	mean	Global mean
Methane value	00.00	2017	1909	1866

Analysis of atmospheric methane levels in Rivers State, Nigeria, revealed a pronounced spatial correlation, with the highest concentrations observed in geographical proximity to prominent hydrocarbon extraction and processing facilities. These areas notably encompassed the urban center of Port Harcourt, alongside the local government areas of Eleme, Obio/Akpor, Ahoada, and Ogba/Egbema (cf. Figure 4-8). This observed distribution strongly suggests that the petroleum and natural gas industry represents a principal source of methane emissions within the region.

4.2. Hotspot Identification

Potential areas with consistently high concentrations of CH4 were pinpointed by visually inspecting average maps and determining grid cell values that were significantly above the state-wide average. These areas, identified as hotspots, were found to be correlated with known geographical features and infrastructure layers (such as locations of oil fields, refineries, major cities, and extensive wetlands) sourced from publicly available data (OpenStreetMap). Hotspot regions include Port Harcourt city, Eleme local Government area (LGA), Obio/Akpor LGA, Ahoada LGA, and Ogba/Egbema/Ndoni LGA Please refer to Figure 9 for a visual representation. The interpretation of the spatial patterns focused on relating elevated concentrations and variability to known CH4 sources present in Rivers State

4.3. Discussion

The observed mean atmospheric methane concentration in Rivers State, Nigeria, corroborates findings from earlier investigations that have reported elevated levels in hydrocarbon-producing regions (Conley et al., 2016; Zavala-Araiza et al., 2015). Furthermore, the spatial distribution of methane emissions lends substantial support to the proposition that the petroleum and natural gas industry constitutes a primary source of these emissions within the locality.

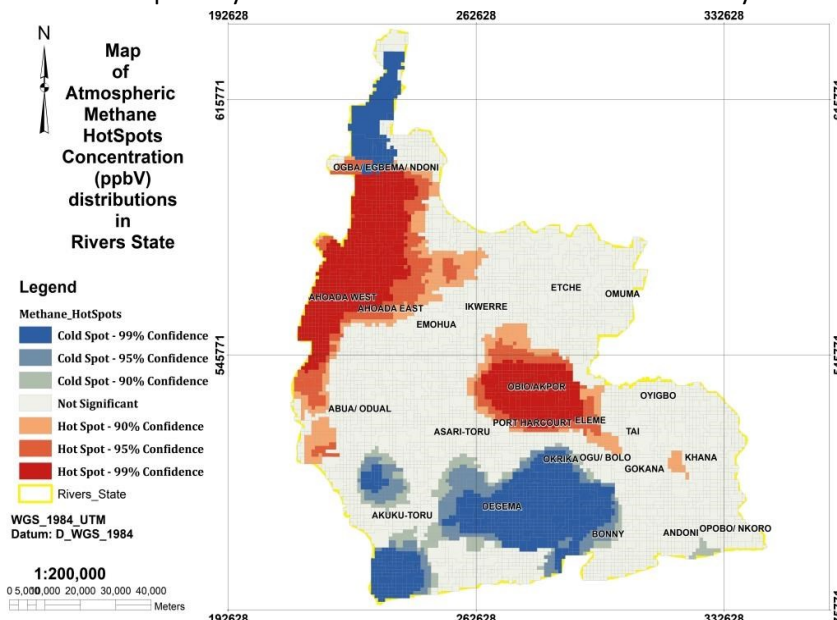


Figure 9 Map of 2024 Methane distributions in Rivers State Source: Author 2025.

This comprehensive assessment of atmospheric methane concentrations in Rivers State, Nigeria, utilizing Sentinel-5 Precursor satellite data, offers critical intelligence for policymakers and relevant stakeholders. By pinpointing areas of particularly high methane concentration, precisely targeted mitigation strategies can be devised and implemented to effectively reduce emissions originating from the hydrocarbon sector.

5. Conclusion

This investigation systematically examined the atmospheric methane levels within Rivers State, Nigeria, utilizing data acquired from the Sentinel-5 Precursor satellite. The calculated average methane concentration for the region was determined to be 1909 ± 130 ppb. This value, while exceeding the global average, was observed to be lower than typical concentrations found in prominent oil and gas-producing areas within the United States. Furthermore, the observed spatial distribution of methane emissions strongly indicates that the petroleum and natural gas sector represents a substantial contributor to these atmospheric releases within the local environment. Consequently, the outcomes of this investigation can furnish valuable information to guide the development of precise mitigation strategies aimed at curtailing methane discharges from the petroleum and natural gas industry in Rivers State, Nigeria.

5.1 Limitations of the Study

The use of satellite remote sensing, specifically TROPOMI, involves inherent constraints that must be acknowledged when interpreting the results:

Cloud Interference and Data Gaps: Rivers State is located in a tropical rainforest climate characterized by persistent cloud cover and high humidity, particularly during the monsoon season. TROPOMI relies on shortwave infrared (SWIR) measurements; heavy cloud cover leads to significant data gaps or low-quality retrievals, potentially biasing seasonal averages toward the dry season.

Spatial Resolution Constraints: While TROPOMI offers an unprecedented resolution (approx. 5.5×7 km), it remains a "sub-regional" tool. It may struggle to distinguish between closely spaced point sources, such as individual oil flow stations, gas flaring sites, and neighboring municipal landfills or wetlands.

Columnar vs. Surface Concentration: TROPOMI measures the dry-air column-averaged mole fraction of methane. This represents the total methane from the surface to the top of the atmosphere. It does not directly provide the "breathing zone" concentration at ground level without complex vertical profile modeling.

Aerosol Interference: High concentrations of aerosols—common in Rivers State due to gas flaring, soot (black carbon) from illegal refining, and Harmattan dust—can scatter light and introduce uncertainties in the methane retrieval algorithms.

Source Attribution Challenges: Atmospheric methane in the Niger Delta originates from both anthropogenic (oil/gas leaks, agricultural waste, landfills) and natural (mangrove swamps, wetlands) sources. Distinguishing between these sources using TROPOMI data alone is difficult without isotopic analysis or high-resolution dispersion modeling.

5.2. Recommendations for Future Research

To enhance the precision of methane monitoring and move toward actionable mitigation strategies, the following steps are recommended:

Integrated Multi-Sensor Approach: Future studies should combine TROPOMI's wide-area coverage with "target-mode" high-resolution satellites (such as GHGSat, Sentinel-2, or PRISMA). This allows for the "tip-and-cue" method: using TROPOMI to identify hotspots and high-resolution sensors to pinpoint specific leaking infrastructure.

Ground-Truthing and In-Situ Validation: There is a critical need for localized validation. Deploying low-cost Internet of Things (IoT) sensors or mobile methane sniffers at ground level in Port Harcourt and surrounding industrial zones would help correlate TROPOMI's columnar data with surface-level concentrations.

Atmospheric Inverse Modeling: Researchers should employ chemical transport models (e.g., GEOS-Chem or WRF-Chem) to "back-calculate" methane emission rates from the observed concentrations. This would provide quantitative data (kg/hr) rather than just qualitative concentration maps.

Seasonal and Diurnal Analysis: Studies should specifically investigate the correlation between methane spikes and meteorological variables (wind speed, planetary boundary layer height). Comparing data across several years will help distinguish between permanent industrial leaks and seasonal biogenic emissions from wetlands.

Policy Linkage and Emission Inventories: The findings should be used to update the Nigerian National Greenhouse Gas Inventory. Academics should collaborate with the National Environmental Standards and Regulations Enforcement Agency (NESREA) to establish a baseline for the "Methane Emissions Reduction Strategy" in the oil and gas sector.

Source Characterization via Auxiliary Data: To improve source attribution, methane data should be overlaid with thermal anomaly data (for gas flares) and land-use maps (for wetlands and landfills) to better categorize the primary drivers of locational concentrations.

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