Global Variability and Trends of Atmospheric Methane: From Satellite Observations to Emission Modelling

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Global Variability and Trends of Atmospheric Methane: From Satellite Observations to Emission Modelling

by

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Certificate

This is to certify that the thesis entitled "**Global Variability and Trends of Atmospheric Methane: From Satellite Observations to Emission Modelling**" being submitted by Ms Deepshikha for the award of the degree of Doctor of Philosophy, is a record of the original bona fide research work carried out by her. She has worked under the joint guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results presented in this thesis have not been submitted in part or whole to any University or Institution for the award of any degree/diploma.

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If I had to sum up this entire journey in one word, it would be ‘perseverance’. Not the shiny, motivational kind, but the messy, stubborn, crying-at-2-a.m.-and-still-opening-the-laptop kind. And perhaps that is the only kind that truly finishes a PhD.

“A done thesis is the best thesis.”



July 2026 Deepshikha

Abstract

Atmospheric methane (CH_4) has grown rapidly since the mid-2000s, yet substantial uncertainty persists in its regional emission trajectories and sectoral attribution. This thesis investigated the spatial and temporal variability of column-averaged methane (XCH_4) using satellite observations, ground-based validation, and chemistry–transport modelling, with the objective of evaluating the consistency of satellite retrievals, characterising long-term methane trends, and assessing the realism of contemporary emission inventories.

A cross-platform analysis of XCH_4 from GOSAT, GOSAT-2, and TROPOMI was first conducted for the period 2019–2023. The three datasets exhibited strong agreement in global means, interhemispheric gradients, seasonal variability, and large-scale spatial patterns. Residual inter-sensor differences were generally small at the global scale but showed coherent regional structures influenced by sampling density, surface reflectance, aerosol loading, and retrieval sensitivity. Based on temporal stability and consistency with TCCON, GOSAT Version 03.05 was selected as the primary dataset for long-term analysis.

Using the GOSAT record, global and regional XCH_4 variability over 2010–2024 was characterised. The global mean methane increased at approximately 8–9 ppb yr^{-1}, with clear acceleration after 2014 and enhanced growth during 2020–2022. A persistent interhemispheric gradient was observed, with higher concentrations in the Northern Hemisphere. Regionally, strong enhancements were identified over South and East Asia, the United States, central Africa, and tropical South America. Seasonal variability was pronounced over monsoon- and wetland-influenced regions, while large-scale growth remained spatially coherent.

The observed trends were then interpreted using MIROC4-ACTM simulations sampled in retrieval space with GOSAT averaging kernels and a priori profiles. While the model reproduced global methane growth and hemispheric gradients with high fidelity, it also showed systematic regional discrepancies. To investigate these, sensitivity experiments were conducted using emission scenarios derived from EDGARv6 and GAINSv4 inventories. The baseline configuration (E1), characterised by strong fossil-fuel growth (570 ± 14 Tg yr^{-1}; growth 3.32 Tg yr^{-1}), resulted in systematic overestimation of atmospheric methane growth across all regions, indicating that the imposed fossil-sector increase exceeded that supported by the observed global growth of ~7–9 ppb yr^{-1}.An alternative configuration (E2), which removed unconventional U.SA's. oil and gas growth and moderated Chinese coal emissions (552 ± 11 Tg yr^{-1}; growth 2.23 Tg yr^{-1}), substantially reduced the global model–satellite bias

but resulted in overall underestimation, indicating that complete suppression of fossil-sector growth was unrealistic. The intermediate configuration (E3), retaining 30% of the unconventional U.S.A's growth while preserving moderated coal emissions in China (555 ± 12 Tg yr^{-1}; growth 2.55 Tg yr^{-1}), provided the best agreement with observations, reducing global ΔXCH_4 by more than 80% relative to E1 and reproducing observed trends with high correlation ($R > 0.8–0.9$).

These results demonstrated that structural differences in fossil-fuel emission trajectories exerted a first-order control on simulated atmospheric methane growth during 2010–2020. In particular, GAINSv4 overestimated the magnitude of unconventional oil and gas emissions in the United States, while EDGARv6 underestimated coal-related emissions in China. Adjustments to fossil-sector growth of 15–18 Tg yr^{-1} were sufficient to produce measurable changes in decadal methane trends at the hemispheric scale, whereas microbial-sector emissions remained comparatively consistent across scenarios.

Overall, this thesis showed that while global methane growth is robustly captured by current models and satellite observations, significant uncertainties remain in the regional allocation and sectoral representation of emissions. The results highlight the importance of combining long-term satellite records with retrieval-space modelling and targeted sensitivity experiments to diagnose structural biases in emission inventories and improve representation of methane sources.

सार

वायुमंडलीय मीथेन (CH_4) में 2000 के दशक के मध्य से तीव्र वृद्धि देखी गई है, किंतु इसके क्षेत्रीय उत्सर्जन प्रवृत्तियों और क्षेत्र-विशिष्ट स्रोतों के निर्धारण में अभी भी पर्याप्त अनिश्चितताएँ बनी हुई हैं। इस शोध प्रबंध में उपग्रह अवलोकनों, भू-आधारित सत्यापन तथा रसायन-परिवहन मॉडलिंग के माध्यम से स्तंभ-औसत मीथेन (XCH_4) की स्थानिक एवं कालिक परिवर्तनशीलता का अध्ययन किया गया। इसका उद्देश्य उपग्रह रिट्रीवल्स की संगति का मूल्यांकन करना, दीर्घकालिक मीथेन प्रवृत्तियों का विश्लेषण करना तथा समकालीन उत्सर्जन सूचियों (inventories) की यथार्थता का परीक्षण करना था।सबसे पहले, 2019–2023 अवधि के लिए GOSAT, GOSAT-2 तथा TROPOMI से प्राप्त XCH_4 डेटा का तुलनात्मक विश्लेषण किया गया। इन तीनों डेटासेट्स में वैश्विक औसत, अंतर-गोलार्धीय प्रवणता, मौसमी परिवर्तनशीलता तथा बड़े पैमाने के स्थानिक पैटर्न में उच्च स्तर की संगति पाई गई। यद्यपि वैश्विक स्तर पर अंतर अपेक्षाकृत कम थे, कुछ क्षेत्रों में सुसंगत भिन्नताएँ देखी गईं, जो सैंपलिंग घनत्व, सतही परावर्तन, एरोसोल लोडिंग तथा रिट्रीवल संवेदनशीलता से प्रभावित थीं। समयिक स्थिरता और TCCON के साथ बेहतर संगति के आधार पर GOSAT Version 03.05 को दीर्घकालिक विश्लेषण हेतु प्राथमिक डेटासेट के रूप में चयनित किया गया।

इसके पश्चात GOSAT डेटा का उपयोग करते हुए 2010–2024 अवधि में वैश्विक एवं क्षेत्रीय XCH_4 प्रवृत्तियों का अध्ययन किया गया। वैश्विक औसत मीथेन में लगभग 8–9 ppb प्रति वर्ष की वृद्धि पाई गई, जिसमें 2014 के बाद स्पष्ट तीव्रता और 2020–2022 के दौरान उच्च वृद्धि देखी गई। एक स्थायी अंतर-गोलार्धीय प्रवणता भी पाई गई, जिसमें उत्तरी गोलार्ध में मीथेन सांद्रता अधिक रही। क्षेत्रीय स्तर पर दक्षिण एवं पूर्व एशिया, संयुक्त राज्य अमेरिका, मध्य अफ्रीका तथा उष्णकटिबंधीय दक्षिण अमेरिका में उच्च XCH_4 मान पाए गए। मौसमी परिवर्तनशीलता मानसून और आर्द्रभूमि-प्रभावित क्षेत्रों में अधिक स्पष्ट थी, जबकि बड़े पैमाने पर वृद्धि स्थानिक रूप से संगत रही।प्रेक्षित प्रवृत्तियों की व्याख्या MIROC4-ACTM मॉडल के माध्यम से की गई, जिसमें GOSAT के averaging kernels तथा a priori प्रोफाइल का उपयोग करते हुए मॉडल को रिट्रीवल स्पेस में सैंपल किया गया।

यद्यपि मॉडल ने वैश्विक स्तर पर मीथेन वृद्धि और गोलार्धीय प्रवृत्तियों को अच्छी तरह पुनरुत्पादित किया, क्षेत्रीय स्तर पर व्यवस्थित अंतर देखे गए। इनका विश्लेषण करने के लिए EDGARv6 तथा GAINSv4 आधारित उत्सर्जन परिदृश्यों का उपयोग करते हुए संवेदनशीलता प्रयोग किए गए। आधारभूत परिदृश्य (E1), जिसमें उच्च जीवाश्म ईंधन वृद्धि (570 ± 14 Tg yr^{-1}; वृद्धि 3.32 Tg yr^{-1}) शामिल थी, ने सभी क्षेत्रों में मीथेन वृद्धि का अधिक आकलन किया, जिससे यह संकेत मिला कि जीवाश्म-क्षेत्रीय वृद्धि वास्तविक

वायुमंडलीय वृद्धि (~7–9 ppb yr^{-1}) से अधिक थी।वैकल्पिक परिदृश्य (E2), जिसमें संयुक्त राज्य अमेरिका के अपरंपरागत तेल एवं गैस उत्सर्जन को हटाया गया तथा चीन के कोयला उत्सर्जन को नियंत्रित किया गया (552 ± 11 Tg yr^{-1}; वृद्धि 2.23 Tg yr^{-1}), ने मॉडल–उपग्रह अंतर को काफी हद तक कम किया, किंतु समग्र रूप से कम आकलन किया गया, जिससे यह स्पष्ट हुआ कि जीवाश्म-क्षेत्रीय वृद्धि का पूर्ण निष्कासन यथार्थवादी नहीं है। मध्यवर्ती परिदृश्य (E3), जिसमें अमेरिकी अपरंपरागत वृद्धि का 30% बनाए रखा गया तथा चीन के कोयला उत्सर्जन को नियंत्रित रखा गया (555 ± 12 Tg yr^{-1}; वृद्धि 2.55 Tg yr^{-1}), ने सर्वाधिक उपयुक्त परिणाम दिए, जिसमें वैश्विक ΔXCH_4 में E1 की तुलना में 80% से अधिक कमी आई तथा उच्च सहसंबंध ($R > 0.8–0.9$) के साथ प्रेक्षित प्रवृत्तियों का सफल पुनरुत्पादन हुआ।इन परिणामों से यह स्पष्ट हुआ कि जीवाश्म ईंधन उत्सर्जन प्रवृत्तियों में संरचनात्मक भिन्नताएँ 2010–2020 के दौरान वायुमंडलीय मीथेन वृद्धि को नियंत्रित करने में प्रमुख भूमिका निभाती हैं। विशेष रूप से, GAINSv4 ने संयुक्त राज्य अमेरिका के तेल एवं गैस उत्सर्जनों का अधिक आकलन किया, जबकि EDGARv6 ने चीन के कोयला उत्सर्जनों का कम आकलन किया। लगभग 15–18 Tg yr^{-1} के स्तर पर जीवाश्म उत्सर्जनों में परिवर्तन से गोलार्धीय स्तर पर मीथेन प्रवृत्तियों में महत्वपूर्ण परिवर्तन उत्पन्न हुए, जबकि जैविक स्रोत अपेक्षाकृत स्थिर पाए गए।

समग्र रूप से, इस शोध ने यह प्रदर्शित किया कि वर्तमान उपग्रह अवलोकन और मॉडल वैश्विक मीथेन वृद्धि को सुसंगत रूप से दर्शाते हैं, किंतु क्षेत्रीय उत्सर्जन वितरण और क्षेत्रीय स्रोतों के प्रतिनिधित्व में अभी भी महत्वपूर्ण अनिश्चितताएँ विद्यमान हैं। यह अध्ययन इस बात पर बल देता है कि उपग्रह डेटा, मॉडलिंग तथा संवेदनशीलता विश्लेषण के समेकित उपयोग से उत्सर्जन सूचियों में संरचनात्मक त्रुटियों की पहचान और सुधार संभव है।

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Abbreviations

Abbreviation	Definition
ACTM	Atmospheric Chemistry–Transport Model
AIRS	Atmospheric Infrared Sounder
AK	Averaging kernel
APR	A priori profile
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
BU	Bottom-up (inventory-based) estimate
CA	Central Africa (regional mask)
CEDS	Community Emissions Data System
CH_4	Methane
CO_2	Carbon dioxide
CTM	Chemistry–transport model
DJF	December–January–February
DOFS	Degrees of freedom for signal
E1, E2, E3	MIROC4-ACTM emission experiments used in Objective 1
EDGAR	Emissions Database for Global Atmospheric Research
EDGARv8	Version 8 of the EDGAR emission inventory
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants emission scenario set (GAINS/ECLIPSE)
ERA5	Fifth-generation ECMWF atmospheric reanalysis
FTIR	Fourier Transform Infrared spectroscopy

Abbreviation	Definition
GCP	Global Carbon Project
GHG	Greenhouse gas
GMB	Global Methane Budget
GMST	Global mean surface temperature (often expressed as GSAT in AR6)
GML	NOAA Global Monitoring Laboratory
GOSAT	Greenhouse gases Observing SATellite
GOSAT-2	Second Greenhouse gases Observing SATellite
GSAT	Global Surface Air Temperature
HiR	High-resolution TROPOMI L2 NO_2 product
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JJA	June–July–August
LMDZ	Laboratoire de Météorologie Dynamique Zoom model
MAM	March–April–May
MBL	Marine boundary layer
MIROC	Model for Interdisciplinary Research on Climate
MIROC4-ACTM	MIROC version 4 coupled Atmospheric Chemistry–Transport Model
MRV	Monitoring, Reporting and Verification
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction

Abbreviation	Definition
NIES	National Institute for Environmental Studies (Japan)
NOAA	National Oceanic and Atmospheric Administration
OH	Hydroxyl radical
RCP	Representative Concentration Pathway
RF	Radiative forcing
RMSE	Root-mean-square error
SON	September–October–November
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY
SRON	Netherlands Institute for Space Research (for TROPOMI retrievals, if mentioned)
SWIR	Short-wave infrared
TCCON	Total Carbon Column Observing Network
TES	Tropospheric Emission Spectrometer
TIR	Thermal infrared
Tg	Teragram (10^{12} g)
TM5	Tracer Model version 5
TROPOMI	TROPOspheric Monitoring Instrument
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VCD	Vertical column density
XCH_4	Column-averaged dry-air mole fraction of methane