Analysis of Methane Emissions in Alaska Permafrost Areas Using Sentinel-5P Data

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Abstract: Methane (CH_4) is a potent greenhouse gas with significant implications for climate change, especially in Arctic permafrost regions where thawing may release large quantities of stored methane. This study investigates the spatiotemporal variations of methane concentrations over Alaska's permafrost regions from 2019 to 2023 using Sentinel-5P satellite data. Monthly averages were derived, and statistical analyses, including seasonal decomposition and autocorrelation, were performed to reveal trends, seasonality, and the underlying dynamics. Our findings suggest an increasing methane concentration trend with distinct seasonal variations, highlighting the role of permafrost regions in the global methane cycle.

Keywords: Autocorrelation, Anthropogenic, Time series analysis

I Introduction

Methane is number two in list as the most important anthropogenic greenhouse gas after carbon dioxide, with a global warming potential significantly higher over short timescales. About 16% of the radiative force from all well-mixed greenhouse gases comes from methane. Current estimates of the strength of the global methane source (1) converge at $550–900 \bullet \mathrm{Tg} \bullet \mathrm{yr}^{-1}$, with high-latitude wetlands in the Arctic tundra contributing $25 \bullet \pm \bullet 14 \bullet \mathrm{Tg} \bullet \mathrm{yr}^{-1}$. The most significant source of uncertainty in the global methane budget calculation is these wetlands and other inland waters, which together constitute a globally relevant methane source. The lack of flux observation sites and short time series, the high spatial heterogeneity of landscapes affected by permafrost (2), the strong temporal dynamics of methane emissions, and the intricate controls on methane production, transport, and oxidation are some of the factors contributing to this uncertainty.

Methane emissions are expected to rise in response to permafrost degradation, as warming in the Arctic region is at least twice as fast as the global average. Thawing is already causing more methane to be released from permafrost areas. There are currently no discernible changes in methane emissions from high-latitude wetlands for the recent past in air observations, inversion, or biospheric models, save from a few indirect signs of increased carbon loss. Furthermore, it is yet unknown if the two opposing processes of methane oxidation and generation are equally impacted by rising temperatures. Arctic permafrost areas, such as those in Alaska, represent a critical frontier for understanding methane emissions due to the thawing of organic matter trapped in frozen soils. Monitoring these emissions is essential for predicting climate feedback loops.

This study employs Sentinel-5P data to analyze methane emissions in Alaska permafrost regions from 2019 to 2023. By leveraging satellite-based measurements, we aim to:

- Quantify the temporal variations in methane concentrations,
- Explore seasonal trends and correlations,
- Identify potential drivers of methane emissions.

II Materials and methods

II.a Study Area

The study centers on Alaska's permafrost regions, defined by the geographical bounds of $[-163.0°, 66.0°]$ to $[-141.0°, 69.0°]$. This region encompasses extensive permafrost landscapes that are particularly vulnerable to rising global temperatures. Permafrost in these areas contains significant stores of organic carbon, which can decompose upon thawing, releasing methane (CH_4) into the atmosphere.

The geographical boundaries selected for this study ensure the inclusion of diverse permafrost ecosystems, ranging from continuous to discontinuous zones. These areas are of critical importance for understanding the feedback mechanisms between permafrost thaw and climate change. The analysis leverages Sentinel-5P satellite data to monitor methane concentrations, providing detailed spatiotemporal insights.

The chosen bounds also align with the region's significant contribution to Arctic carbon fluxes. By focusing on these coordinates, the study captures the dynamics of methane emissions influenced by permafrost degradation. This approach highlights the region's role in the global greenhouse gas budget. Such investigations are vital for predicting and mitigating the climate impacts of Arctic permafrost changes.

II.b Data Source

Methane data were sourced from the Sentinel-5P TROPOspheric Monitoring Instrument (TROPOMI), specifically the CH_4_column_volume_mixing_ratio_dry_air product. Data spanning from January 1, 2019, to December 31, 2023, were used.

II.c Data Processing

The following steps were implemented: Data Filtering: Sentinel-5P data were filtered for the specified ROI and timeframe using Google Earth Engine (GEE). Monthly Aggregation: Monthly average methane concentrations were computed for each year. Statistical Analysis: Mean and standard deviation were calculated, and the temporal data were decomposed into trend, seasonal, and residual components using seasonal decomposition.

III Analytical Methods

The following steps were implemented: Seasonal Decomposition: Employed to isolate the trend, seasonality, and residuals in methane emissions. Autocorrelation Analysis: Used to detect patterns and correlations over time lags. Seasonal Comparisons: Methane concentrations were compared across years to evaluate interannual variations.

IV Results

The image illustrates the seasonal decomposition of methane (CH_4) concentrations over Alaska's permafrost regions from 2019 to 2023, using an additive model. It comprises four panels:

IV.a Observed Methane Concentration:

The top panel displays the original time series data, showing monthly mean methane concentrations. A noticeable upward trend and seasonal variations are evident.

IV.b Trend Component:

The second panel isolates the long-term trend, highlighting a gradual increase in methane levels over the years, indicative of persistent emissions possibly linked to permafrost thaw.

IV.c Seasonal Component:

The third panel captures the recurring seasonal pattern, with methane levels fluctuating annually, likely driven by temperature changes and thaw-freeze cycles in the permafrost.

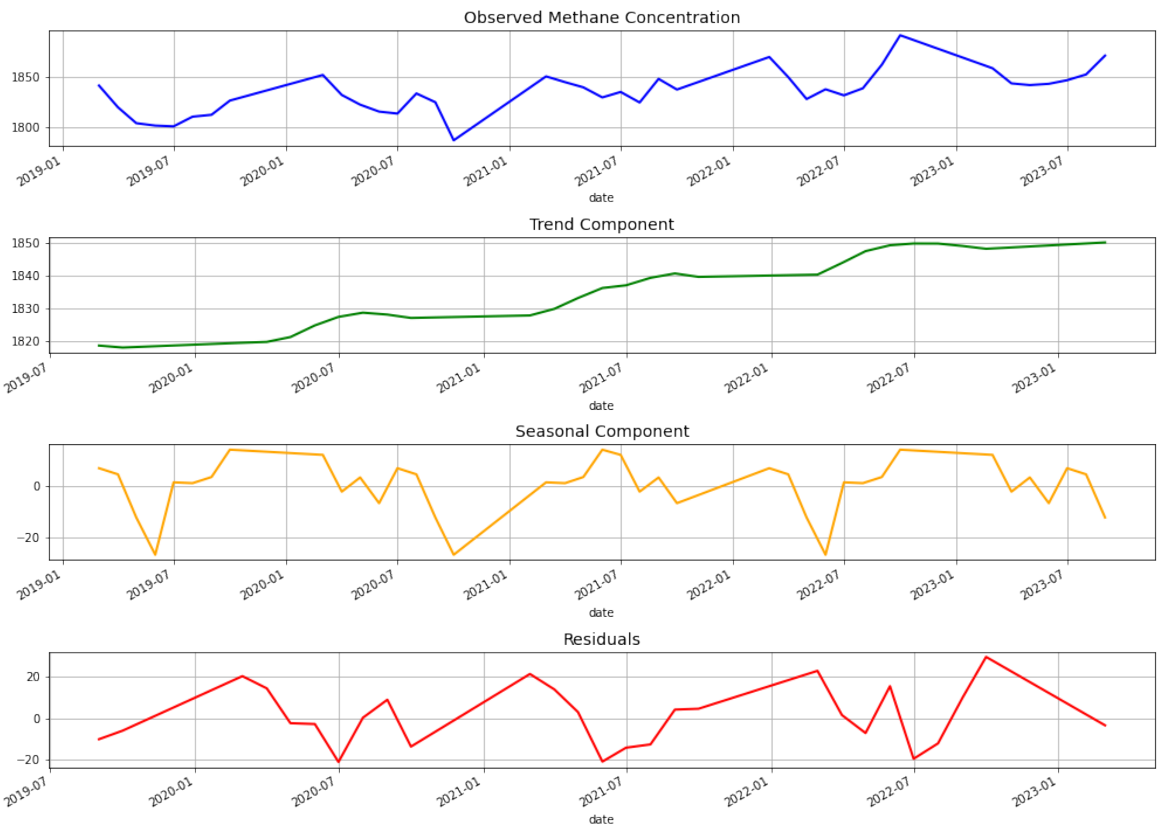

Figure 1: **Technology-enabled SRL facilitating motivational factors for learning excellence**

IV.d Residuals:

The bottom panel represents the irregular variations or unexplained deviations from the observed data, showing noise or anomalies not accounted for by the trend or seasonality. This decomposition provides insights into methane emission dynamics, separating the contributions of trend, seasonality, and residual variability, essential for understanding the underlying processes in Arctic permafrost regions.

V Discussion

a.Trends in Methane Concentrations The decomposition analysis revealed a consistent upward trend in methane concentrations across the study period (2019–2023). The observed trend aligns with increasing temperatures and permafrost thawing in the region, potentially releasing methane from organic matter decomposition.

V.a Seasonal Variations

Seasonal decomposition highlighted significant methane peaks during late summer and early fall (August–September). This is likely driven by: Increased microbial activity during thawing seasons. Wetland emissions amplified by warmer temperatures.

V.b Autocorrelation Analysis

Autocorrelation plots indicated moderate lagged correlations, suggesting that methane concentrations are influenced by persistent seasonal and environmental factors. The peaks at lags corresponding to 12 months reinforce the annual cyclicality of emissions.

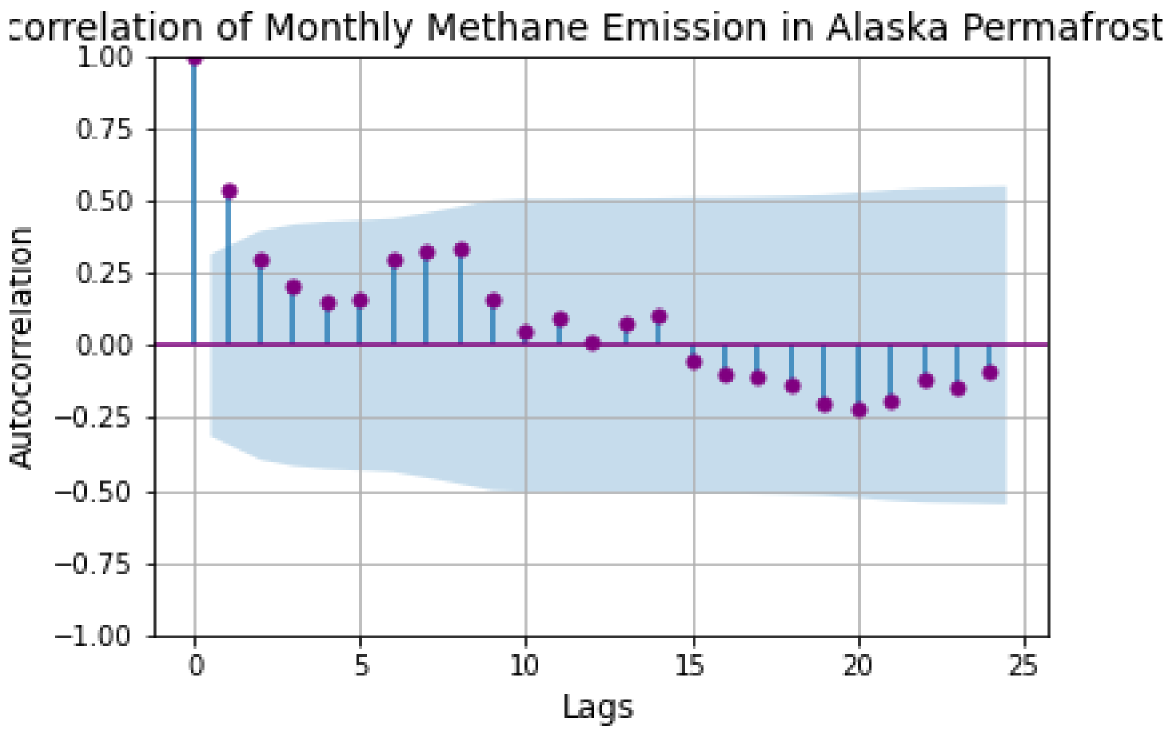

Figure 2: **The image presents the autocorrelation function (ACF) plot of monthly methane emissions in Alaska's permafrost regions from 2019 to 2023.**

V.c Key features include:

Lags on the X-axis: Represent the time intervals (in months) at which the correlation of the methane time series is analyzed with itself. Autocorrelation on the Y-axis: Indicates the strength of correlation between the time series values at different lags. Significance Boundaries: The shaded blue region represents the 95% confidence interval. Points falling outside this interval indicate statistically significant autocorrelation. The ACF reveals notable positive autocorrelations at shorter lags (e.g., up to 6 months), which gradually diminish as the lag increases, suggesting a seasonal pattern. Negative correlations are observed at longer lags, hinting at periodic oscillations in methane levels. This analysis supports the presence of regular seasonal fluctuations and potential trends in methane emissions linked to natural cycles in permafrost dynamics.

V.d Interannual Variations

Seasonal plots by year showed year-to-year variability in methane emissions. While seasonal patterns remained consistent, the magnitude of emissions increased, particularly during warmer months, reflecting potential intensification of thawing and emissions over time.

V.e Implications

Our findings underscore the importance of monitoring methane emissions in permafrost regions. The observed trends and seasonal dynamics emphasize the need for: a.Enhanced Monitoring: High-resolution, year-round satellite measurements to track permafrost methane dynamics. b.Climate Modeling: Integration of permafrost methane feedbacks into global climate models. c.Mitigation Efforts: Strategies to reduce anthropogenic warming and limit permafrost degradation.

VI Conclusion

This study provides a comprehensive analysis of methane emissions over Alaska's permafrost regions using Sentinel-5P data(3). The identified trends and seasonal patterns highlight the critical role of permafrost areas in the global methane budget. Continued observation and analysis are crucial for understanding and mitigating the impacts of climate change.

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