E3S Web of Conferences **709**, 02003 (2026) https://doi.org/10.1051/e3sconf/202670902003
ICERE 2026

Feasibility of Detecting Low-Level Methane Emissions from Abandoned Oil Wells Using a Multi-Band, Multi-Pass Satellite Approach

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Abstract. In this study, we develop a multi-band, multi-path (MBMP) model using shortwave infrared (SWIR) data to quantify point-source methane emissions from abandoned oil wells. Atmospheric methane concentrations reached about 1,942 ppb in 2025, more than doubling since pre-industrial times. As the second most important greenhouse gas after CO_2, methane emissions from both natural and fossil fuel–related sources contribute significantly to climate change. The greenhouse effect of atmospheric methane (CH_4) is approximately 25–28 times greater than that of carbon dioxide (CO_2). Even small emissions from abandoned oil wells, if left unmanaged, can contribute to long-term global warming. In Japan, we found that backfilling (plugging) old wells is highly effective in reducing greenhouse gas emissions. The abandoned oil wells represent a minor but ongoing source of methane, emitting approximately 200 m^3/day. Even assuming a cost of 50 million JPY per well, the cost to reduce one ton of CO_2 is approximately 3,500 JPY (25 USD). This is a lower cost compared to other greenhouse gas reduction methods. Based on the field measurements and model estimates, methane emissions were estimated at 7,300 t-CO2e per year. This represents a significant proportion compared to the total emissions of 47,400 t-CO_2 reported in Akita Prefecture for the 2019 fiscal year. This study presents a comprehensive satellite-based methodology for monitoring methane leakage from abandoned oil wells using time-series observations from the ESA Sentinel-2 satellite and develops a MBMP model based on these observations. The study aims to conduct the first quantitative evaluation of small amount of methane emissions from abandoned oil wells in Japan by integrating high-resolution satellite data with in situ field survey measurements obtained at the former Kurokawa oil field in Akita Prefecture.

1 Introduction

Atmospheric methane (CH_4) has a greenhouse effect approximately 25–28 times stronger than that of carbon dioxide (CO_2). If not properly managed, even small methane emissions

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from abandoned oil wells can contribute to long-term global warming. As the number of decommissioned wells increases, this issue highlights the need for continued management beyond the end of production in the petroleum industry. Methane (CH_4) has a greenhouse effect 25–28 times greater than CO_2, making even small emissions from abandoned oil wells climatically significant. Methane has a shorter atmospheric lifetime than CO_2. While CO_2 can remain in the atmosphere for several centuries or longer, methane is largely decomposed within approximately a decade. Consequently, the relative impact of methane varies depending on whether short-term, immediate effects after emission or long-term climate impacts are emphasized. Although CO_2 is heavier than CH_4 and has a greater impact on a mass basis, methane absorbs much more infrared radiation per unit mass, making it a more effective greenhouse gas [1-4].

We accompanied the former safety manager of the Kurokawa oil field on volunteer safety inspections and surveyed 17 of the 20 accessible wells. In Japan, small but persistent methane emissions continue from depleted oil fields and former natural gas extraction sites. These emissions highlight the environmental significance of abandoned production infrastructure and the need for effective post-closure management. Given methane's high global warming potential, mitigation measures are urgently required. Effective approaches include leak prevention, recovery and utilization of emitted gas, and the application of methane dehydration technologies [5-6].

Satellite-based remote sensing has become an essential tool for monitoring methane emissions at multiple spatial scales. Observations from instruments such as NASA JPL's EMIT, ESA's Sentinel-2 (SWIR) and Sentinel-5P TROPOMI, GOSAT, and commercial high-resolution sensors (e.g., MethaneSAT and GHGSat) allow for the detection of atmospheric methane enhancements at regional to facility levels. When combined with meteorological information, column-averaged methane measurements can be used to identify emission plumes, attribute sources to individual wells or well clusters, and estimate emission rates. Quantitative methods, including the Integrated Mass Enhancement (IME) approach and cross-sectional flux calculations, enable the translation of observed enhancements into methane flux estimates, providing robust assessments of leakage magnitude [5-8].

The deployment of satellite-based methane monitoring for abandoned oil wells provides multiple methodological and regulatory advantages. Repeated synoptic coverage enables comprehensive screening of extensive well inventories, while the identification of high-emitting ("super-emitter") sites supports targeted ground and airborne verification campaigns. In addition, satellite-derived methane observations contribute to regulatory compliance and can be incorporated into emission inventories to reduce uncertainties in national greenhouse gas accounting. Despite existing limitations related to detection sensitivity, cloud interference, and wind field uncertainty, satellite monitoring constitutes a rapidly evolving and cost-effective complement to traditional in situ approaches [9-13].

This article presents a comprehensive satellite-based methodology for monitoring methane leakage from abandoned oil wells using time-series observations from the ESA Sentinel-2 satellite and develops a multi-band, multi-pass model based on these observations, highlighting key methodologies and their strengths, limitations, and future potential for global methane mitigation. GOSAT observations enable analysis of global methane distributions, seasonal variability, and anthropogenic emission patterns, while the high-resolution capabilities of GOSAT-GW allow detection of emission sources at sub-3 km spatial scales. These datasets contribute to improved estimates of methane absorption and emissions and to a better understanding of emission source dynamics. ESA's Sentinel-5P satellite measures atmospheric methane using the TROPOMI instrument, providing global observations at 7 km resolution that support the identification of emission sources and emission rate estimation [13-15]. However, while such satellite data are effective for monitoring global methane emissions, they are generally insufficient for detecting small

https://doi.org/10.1051/e3sconf/202670902003

amount, localized methane releases into the atmosphere, such as those considered in the field of this study [6].

2 Methodology

2.1 The study area and field observations

As shown in Figure 1, the Kurokawa oil field is located in the Kanasashi–Kurokawa area in the northern part of Akita City, Akita Prefecture, Japan. The field was developed by Nippon Oil Co., Ltd. in 1912 and reached its peak production in 1914, with annual output exceeding 150,000 kL (approximately 940,000 barrels), making it one of Japan's major oil fields at the time. Production continued steadily until the early Showa period, after which it gradually declined. From the 1960s onward, operations shifted primarily to natural gas production and supply; however, the operator later declared bankruptcy due to financial difficulties. In September 2018, the site was officially abandoned, leaving 21 wells discharging crude oil and natural gas [5].

Owing to concerns about river contamination and other environmental impacts caused by crude oil leakage, both the national government and the local municipality have undertaken systematic well-sealing efforts. However, based on Akita City's experience in 2021, the cost of sealing a single well is approximately 50 million yen, excluding additional expenses such as access road construction, representing a substantial financial burden. Preliminary surveys indicate that approximately 20 abandoned wells collectively emit about 10,000 tons of CO_2-equivalent methane annually [5-6].

In Japan, well sealing has not been implemented primarily as a measure for greenhouse gas (GHG) mitigation. Consequently, unless crude oil leakage incidents occur, GHG emissions from inactive wells are generally left unmonitored, a situation similar to that reported for the United States by the Interstate Oil and Gas Compact Commission (IOGCC) (Interstate Oil and Gas Compact Commission, 2021) [5-6].

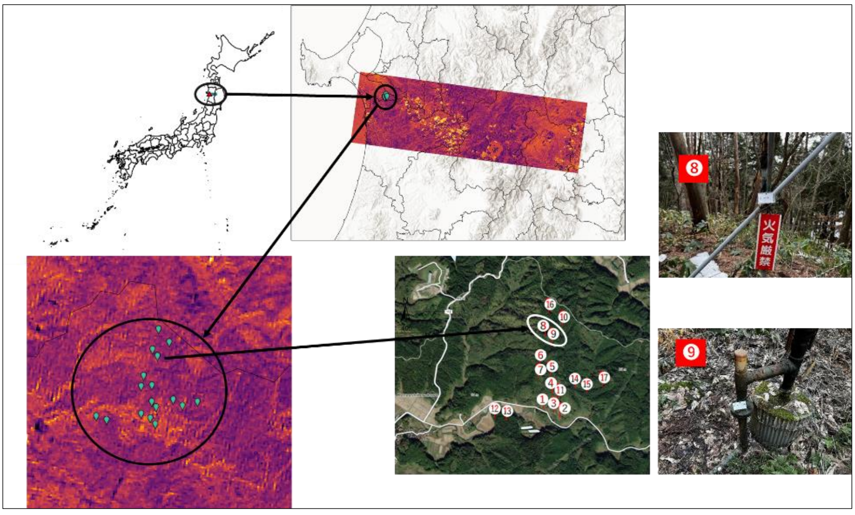

Fig. 1. The study area and the field survey site (The abandoned oil well of the Kurokawa Mine). The study site is located within a densely forested mountainous region on the outskirts of Akita City, Akita Prefecture, in northwestern main-land of Japan. The satellite image depicts methane emissions

estimated using a model based on time-series Sentinel-2 observations. The abandoned oil wells represent a minor but ongoing source of methane, emitting approximately 200 m³/day.

Our research team accompanied the former safety manager of the Kurokawa oil field on volunteer safety inspections and surveyed 17 of the 20 accessible wells. To safely investigate gas leakage, we used an infrared camera to visualize the gas. Based on calculations from this data, the total emissions from the Kurokawa oil field were estimated to be approximately 1,100 cubic meters per day (see Figure 1).

The satellite-based methane index (SMI) provides a remote sensing approach for detecting and monitoring atmospheric methane by exploiting its characteristic absorption features in the near-infrared (NIR) and shortwave infrared (SWIR) regions, particularly near 3.3 μm and 7.6 μm. The SMI enhances methane-related signals by comparing radiance in methane-sensitive bands with that in adjacent reference bands minimally affected by methane absorption. This ratio-based formulation reduces background variability, including surface reflectance and atmospheric scattering, thereby improving the detectability of methane plumes [6, 11-15].

Satellite instruments such as Sentinel-5P/TROPOMI and GHGSat apply this principle to detect methane emissions from a wide range of sources, enabling large-scale monitoring of greenhouse gas emissions. However, detecting small methane releases on the order of 200 $m^3\ day^{-1}$ from abandoned oil fields remains extremely challenging, particularly in densely forested mountainous regions near Akita City, where complex surface and terrain conditions further limit detection capability, even with high-resolution satellite observations [6,8,13].

2.2 The optimal season for satellite-based observation of atmospheric methane emissions

The study area, Akita City, is located in northern Japan and is covered by snow during winter. During this season, deciduous forests are leafless and coniferous forests show minimal photosynthetic activity. Therefore, surface changes can be effectively extracted by applying inter-band differencing to wintertime satellite time-series data.

Figure 2 shows the monthly standard deviation of methane emissions derived from ground-based observations in 2021 and 2022. As can be seen in Fig. 2, the standard deviation is lowest during winter (December, January, and February). This indicates that wintertime observations are least influenced by methane emissions from rice paddies, livestock, and vegetation, enabling more accurate estimation of methane emissions from abandoned oil wells.

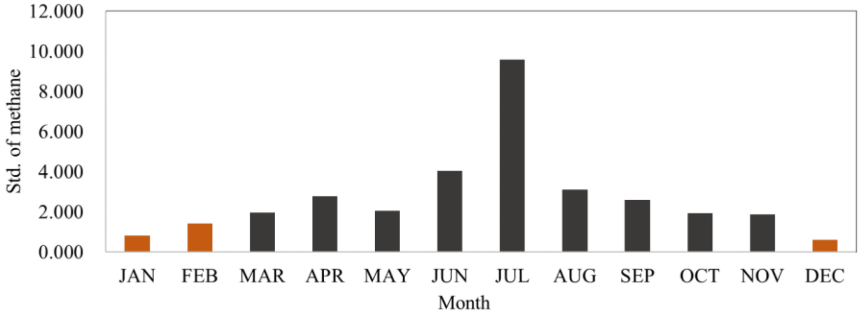

Fig. 2. Monthly Variation Chart of the Standard Deviation (Std.) of Methane Concentrations (2021–2022 average) in Akita City. The monthly variation in the standard deviation of methane concentrations in Akita City (2021–2022 average) shows that variability is lowest in December and January, making this period ideal for stable background methane observations [5].

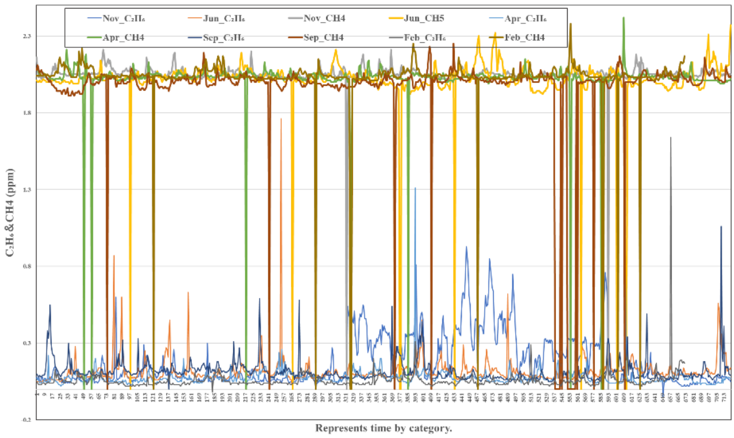

Fig. 3. Hourly variations in methane and other hydrocarbons (ethane, etc.) observed in Akita City [5]. Short-term spikes and apparent outliers reflect instrumental noise and detection-limit effects inherent to high-resolution field measurements and were retained without filtering.

Methane (CH_4) has both biogenic and fossil fuel origins. However, ethane (C_2H_6) is rarely present in biogenic emissions, including those from wetlands, rice paddies, ruminants, and landfills. Accordingly, ethane serves as a tracer for greenhouse gas emissions from fossil fuel sources, including natural gas. The ratio of atmospheric methane to ethane concentrations (CH_4/ C_2H_6) enables a quantitative differentiation between predominantly biogenic and fossil fuel–dominated sources. Ethane is commonly co-emitted with methane from fossil fuels, including natural gas. Therefore, the presence of atmospheric ethane suggests that the detected methane is highly likely to originate from fossil fuel sources.

As shown in Figure 3, stability of methane concentrations (upper set of curves): Regardless of season (February, April, June, September, and November), methane concentrations remain nearly constant at around 2.0 (estimated unit: ppm), indicating a highly stable baseline. This level is consistent with background methane concentrations in the Northern Hemisphere, which are generally reported to be approximately 1.9–2.0 ppm.

Low-level variability of ethane concentrations (lower set of curves): Compared with methane, ethane concentrations are substantially lower, varying within a range of approximately 0.0–0.5. Although temporary spikes are observed in certain months—particularly in April (ethane; light blue line)—overall ethane concentrations remain low and relatively stable [5-6].

2.3 Satellite-Based Multi-Bands Multi-Pass Methane Detection

Physical retrieval algorithms employ radiative transfer models to derive methane column concentrations (mol/m²) from SWIR spectral observations [3-6]. Shortwave infrared (SWIR) spectral bands are widely used for atmospheric methane (CH_4) detection because the lower absorption coefficients in this region reduce saturation effects and improve sensitivity to near-surface methane concentrations. The Sentinel-2 Multispectral Instrument (MSI) includes two SWIR bands, B11 (1560–1660 nm) and B12 (2090–2290 nm), which sample methane absorption features. As illustrated in Figure 4, atmospheric methane exhibits distinct absorption characteristics at specific wavelength ranges within the SWIR regions [6-9].

In this study, atmospheric methane concentrations were derived using a satellite-based Multi-Bands Multi-Pass Methane Detection (MBMP). The method exploits Top of Atmospheric (TOA) reflectance from Sentinel 2 SWIR spectral bands sensitive to methane absorption, typically cantered at approximately 1600-1800 nm and 2100-2500 nm. Nevertheless, as shown in Figure 4, the central wavelengths of the Sentinel-2 SWIR bands, at 1610 nm and 2190 nm respectively, do not precisely coincide with the specific absorption features of methane [3-6, 12].

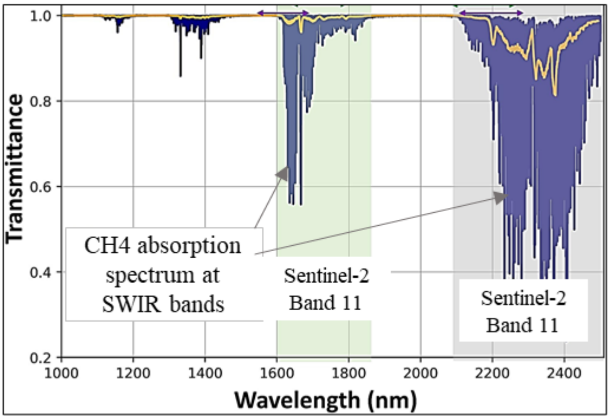

Fig. 4. The methane transmittance spectrum (dark blue) in the 1000–2500 nm wavelength range (SWIR) is shown together with the spectral sensitivities of Sentinel-2A SWIR bands B11 (1568–1659 nm) and B12 (2114–2289 nm), which are impacted by the presence of atmospheric methane [8].

To overcome this issue, this research investigated a retrieval method for methane emissions by leveraging multi-band and multi-pass data from the Sentinel-2 SWIR bands. The Multi-Band Multi-Pass (MBMP) methane detection method is a satellite-based remote sensing approach for detecting and quantifying large, anomalous methane point sources. The method utilizes multispectral observations from the Sentinel-2 satellite, with a particular focus on the shortwave infrared (SWIR) bands. The method leverages the high spatial resolution (20 meters) and frequent revisit rates (every 2-5 days) of the European Space Agency's (ESA) Sentinel-2 mission [12].

Multi-Band Approach: The "multi-band" aspect involves combining data from both bands 11 and 12. Band 12 is significantly more sensitive to methane than band 11.

Multi-Pass Approach: The “multi-pass” approach compares an observation containing a potential methane plume with a reference image of the same area acquired on a different day without a plume. This comparison reduces background effects caused by surface albedo variations.

Methane Column Retrieval: Information from two spectral bands acquired at different times is combined to retrieve methane column enhancements, enabling the localization and quantification of emission sources.

The MBMP method can detect methane point sources with emission rates of approximately 3t / h under favourable, quasi-homogeneous surface conditions. Compared with other approaches, MBMP is robust and well suited for high-frequency monitoring of strong, localized emissions. The method uses the 20 m spatial resolution of Sentinel-2 SWIR bands, enabling finer spatial mapping than coarser-resolution methane sensors such as TROPOMI. The MBMP method is generally considered the most successful among retrieval methods for Sentinel-2 because combining both spectral and temporal data significantly reduces false positives and improves precision. The method is frequently applied to monitor "super-emitters" in the oil and gas industry, such as well-pads and compressor stations. Its high revisit rate (every 2–5 days) enables frequent monitoring of these high-priority sites.

The calculation formula for the Multi-Band Multi-Pass (MBMP) method focuses on isolating methane column enhancements $\Delta\Omega_{MBMP}^{t}$ by combining r Top-of-Atmosphere (TOA) reflectance of spectral band differences with temporal reference subtraction. The methane column enhancement is obtained by subtracting the non-plume reference retrieval from the active-plume retrieval [12]:

$$\Delta\Omega_{MBMP}^{t} = \frac{\delta_{12}^{t}B_{12}^{t} - \delta_{11}^{t}B_{11}^{t}}{\delta_{11}^{t}B_{11}^{t}} - \frac{\delta_{12}^{t-1}B_{12}^{t-1} - \delta_{11}^{t-1}B_{11}^{t-1}}{\delta_{11}^{t-1}B_{11}^{t-1}}\ , \qquad (1)$$

This component differentiates methane by comparing a sensitive band (Band 12) to a less sensitive band (Band 11) within the same image. Where, $\Delta\Omega_{MBMP}^{t}$ is the Multi-Band Single-Pass retrieval on the day a plume is suspected. With δ^{t}_{12}, δ^{t}_{11}, δ^{t-1}_{12}, δ^{t-1}_{11} is normalization coefficients of the corresponding bands and times. Theses normalization calibrates band 12 relative to band 11 before computing methane-related contrast. These coefficients are depending on scene brightness/albedo and observation geometry and must be estimated per image. Throughout this paper, methane detection using the $\Delta\Omega_{MBMP}^{t}$ method is based on a threshold applied to the inverse of Eq. (1), where a decrease in B12 reflectance indicates methane.

3 Results

Various techniques exist for retrieving methane column concentrations from satellite data, including physical models, matched filters, band ratios (BR), regression analysis, AI, and hybrid approaches. These methods have been applied to varying extents in the literature [11-15]. In this study, we develop a multi-band, multi-path model using shortwave infrared (SWIR) data to quantify point-source methane emissions from abandoned oil wells. Following the methodology described above, low-level atmospheric methane emissions were identified using wintertime Sentinel-2 imagery. TOA reflectance data from SWIR Bands 11 and 12, acquired on 6 January, 11 January, and 15 February 2025, were processed using the retrieval algorithm defined in Eq. (1). This process involved: i) converting DN to TOA reflectance using radiometric coefficients; ii) computing normalization coefficients between Sentinel-2 Bands 11 and 12 via regression; and iii) calculating methane detection values. By subtracting data from different passes, systematic errors consistent across acquisitions were suppressed, effectively isolating the methane enhancement signal.

Figure 5 presents a notable example of a methane point source detected by Sentinel-2A over an abandoned oil well in Akita on 15 February 2025. The plume, advected by wind, was identified using a multi-band multi-pass approach applied to reflectance data from 15 February and 11 January 2025. An enlarged view of the point source is shown in Figure 6. Although the methane absorption signal is weak and the detected enhancement appears spatially discontinuous, the absence of other emission sources during this period allows the detected plume to be attributed to the abandoned oil well with high confidence.

Assuming uncorrelated and normally distributed instrumental noise, we estimated the single-pixel retrieval precision as the standard deviation of non-plume methane values over the entire scene. As shown in Figure 5 and 6, the MBMP retrieval yielded a much clearer methane plume, allowing the extent of the plume to be detected with substantially higher precision. This improvement is achieved by computing a band ratio using radiance values from methane-sensitive bands (SWIRs at time (t)) and reference bands (SWIRs at time (t-1)), which allows methane plumes to be effectively distinguished from background surface reflectance. In principle, combining Sentinel-2 data with this customized band-ratio processing enables the detection and quantification of relatively large methane plumes. In this study, we specifically calculated multi-pass band ratios using wintertime data to maintain sensitivity to atmospheric absorption features, as this season corresponds to the lowest variability in background noise (or retrieval anomalies).

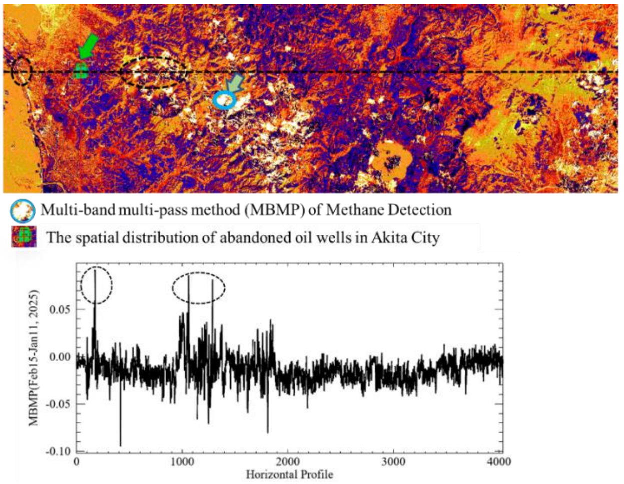

Fig. 5. Methane estimation results based on a multi-band, multi-pass (MBMP) approach.

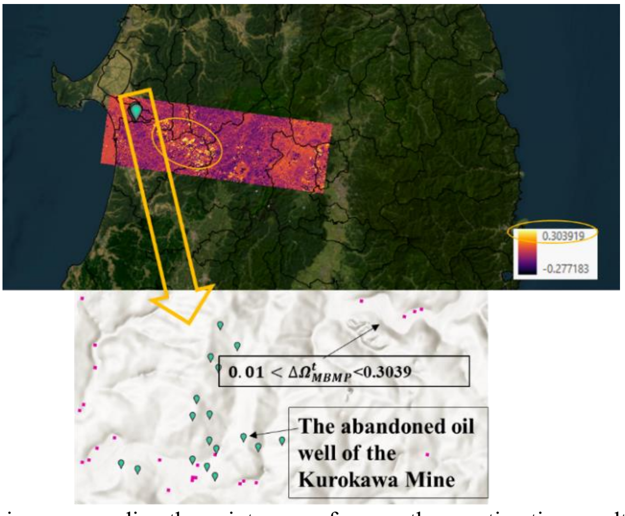

Fig. 6. the enlarged view surrounding the point source from methane estimation results based on a multi-band, multi-pass (MBMP) approach.

4 Discussions

In recent years, methane (CH_4) has attracted increasing attention as a major contributor to global warming. Although its atmospheric abundance is much lower than that of carbon dioxide (CO_2), methane possesses a significantly higher global warming potential (GWP) over short timescales, making it a critical target for climate change mitigation [3-4, 7-10, 14]. However, despite global efforts to reduce emissions over the past decade, atmospheric methane concentrations have recently shown a rapid resurgence. The underlying drivers of this increase are not yet fully understood. Numerous studies have attributed this trend primarily to rising emissions from wetlands, agriculture, and the fossil fuel sector. However, a crucial alternative factor warrants investigation: the potential decline in the atmosphere's oxidative capacity. The primary removal mechanism for atmospheric methane is oxidation by the hydroxyl radical (OH). As the atmosphere's primary oxidant, often termed its "detergent," OH is responsible for approximately 90% of methane removal. Therefore, the atmospheric burden and residence time of methane are highly sensitive to OH concentrations; a decline in OH abundance directly results in a longer atmospheric lifetime for methane [15].

This study estimation small amount of atmospheric methane emission the from abandoned oil well in Akita using multi-band multi-pass Sentinel 2 SWIR band 11 and 12. Sentinel-2 SWIR Bands 11 (approx. 1560–1660 nm) and 12 (approx. 2090–2290 nm) feature a spatial resolution of 20 m. This resolution enables the detailed characterization of the spatial distribution of small methane point sources near the Earth's surface. Band 12 encompasses the methane absorption features in the SWIR region (specifically near 2300 nm), providing high sensitivity to atmospheric methane enhancements. In contrast, Band 11 is utilized as a reference band due to its spectral proximity and lack of significant methane absorption. This combination allows for the normalization of background surface reflectance heterogeneity, thereby isolating the methane signal [9,11,15].

A further advantage of Sentinel-2 is its constellation of two satellites, which achieves a short revisit time of 5 days at the equator. This high temporal resolution allows for the monitoring of temporal dynamics and, under cloud-free conditions, enables the detection of transient or event-driven methane emissions.

However, it has been reported that the detection threshold for Sentinel-2 point source analysis is relatively high, generally restricted to large plumes with emission rates of several tons per hour or more. Consequently, while Sentinel-2 serves as a powerful tool for identifying super-emitters, its sensitivity may be insufficient for characterizing small or low-magnitude releases [3-4, 7-12]. In addition, band difference and ratio methods are susceptible to artifacts arising from surface reflectance characteristics, such as variations in surface albedo, wetlands, water bodies, and cloud shadows. Consequently, surface noise and shading effects can lead to false positives, often necessitating additional corrections and manual verification [9-15].

Acknowledgments

This work was supported by JSPS KAKENHI Project Number 25K03325 “Verification of abandoned oil well plugging effects for carbon offset credits by precise measurement of methane emissions”.

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