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The Distribution Characteristics and Influencing Factors of Near-Surface Atmospheric Methane in China Based on Remote Sensing Data: A Review

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Abstract: With the advancement of urbanization and industrialization, methane emissions from human activities have been on the rise, playing a critical role in global warming. As a potent greenhouse gas, the impact of methane on climate change has attracted increasing attention, particularly in China, a major global emitter of methane. Studying its distribution and influencing factors in the near-surface atmosphere is of great importance. This paper aims to explore the distribution patterns and key drivers of methane in China's near-surface atmosphere. By reviewing relevant literature and analyzing remote sensing data, it examines the variation patterns of methane concentrations in different regions of China and their main influencing factors. The research data comes from the AIRS (Atmospheric Infrared Sounder) satellite remote sensing dataset, which spans methane concentration data from 2002 to 2020, focusing on seasonal variations and regional differences. The results show that regions like Inner Mongolia, Heilongjiang, Qinghai, and Gansu exhibit higher methane concentrations, which are mainly influenced by human factors such as wetland distribution, agricultural activities (e.g., rice paddies), and mining activities. Moreover, methane concentrations peak in autumn and winter, closely related to seasonal agricultural activities and heating demands. The study highlights the vital role of methane emission control in mitigating climate change and suggests strengthening the monitoring and management of methane emission sources to help achieve China's carbon neutrality goals.

Keywords: Near-Surface Atmospheric Methane, Remote Sensing Monitoring, Greenhouse Gas, Methane Emission, Emission Factors

1. Introduction

As urbanization and industrialization continue to advance, the influence of human activities on the natural environment is becoming increasingly significant. The emission of substantial amounts of anthropogenic greenhouse gases into the atmosphere is driving the acceleration of global warming. Methane (CH_4), as the second-largest greenhouse gas, has a high global warming potential and a relatively short lifespan. Existing research indicates that the increase of CH_4 concentration in the atmosphere is largely driven by increasing human emissions[1]. Due to its efficient absorption of infrared radiation, CH_4 has a global warming potential 34 times greater than that of carbon dioxide over a 100-year period [2]. Therefore, controlling methane emissions is more efficient in slowing

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down global warming than controlling carbon dioxide emissions [3]. China is a big man-made CH_4 emitter in the world, and it is also located in the high CH_4 concentration area.In view of the current severe status of CH_4 emission, China has clearly incorporated CH_4 emission reduction plan into the Tenth Five-Year Plan and the long-term development plan for 2035 for the first time, and actively achieved peak carbon dioxide emissions and carbon neutrality goals [4]. The data sources used in the existing research are limited, with relatively few ground-based observation datasets and short time series. As such, it is necessary to combine more satellite data and ground data to analyze the distribution characteristics and variation laws of methane concentration more comprehensively. At the same time, the gas-phase chemical reactions related to CH_4 are not complete, and the process of methane transport to stratosphere is not considered completely among the existing studies. This paper seeks to use remote sensing data to observe the distribution of methane near the surface of China and its influencing factors, so as to contribute to a better understanding of methane emissions and their role in improving air quality and addressing global warming.

2. Application of Remote Sensing Data in Atmospheric Methane Monitoring

The satellite remote sensing, owing to its advantages of rapid observation, low cost, and extensive synchronous monitoring capabilities, has emerged as a critical tool for the continuous monitoring of atmospheric CH_4 concentrations on a global scale [5]. Despite its lower precision in comparison to ground-based monitoring, satellite remote sensing inversion products have been extensively utilized in the research of global atmospheric methane concentrations, as well as their temporal and spatial evolution, and source-sink dynamics. And major remote sensing data sources include Aqua/AIRS, GOSAT-1/TANSO-FTS, and Sentinel-5P/TROPOMI, each with its own strengths. For instance, AIRS provides high temporal and spatial resolution data ($1°\times1°$ spatial resolution and monthly temporal resolution), thus making it particularly useful for analyzing global methane concentration trends, while GOSAT and Sentinel-5P offer higher precision in methane monitoring. The selection of data sources is determined by the specific research objectives, as different satellites differ in terms of spatial and temporal resolution, as well as observation coverage.

The AIRS remote sensing data used in this study is from the Atmospheric Infrared Sounder (AIRS) on the EOS/Aqua satellite, which provides methane concentration data across wavelengths from 3.74μm to 15.4μm, with a spatial resolution of $1°\times1°$ and a temporal resolution of one month [6]. The data selected spans around 17 years, from December 2002 to February 2020, covering 206 months of methane concentration data based on the V6 version of the AIRS3STM standard product [7]. Given that atmospheric CH_4 is affected by factors distant from the ground in the troposphere, and that vertical atmospheric mixing does not fully represent the CH_4 concentration characteristics near the surface, the study aims to analyze the temporal and spatial variations of CH_4 concentrations in China by integrating data from both the lower and middle troposphere. Considering that AIRS exhibits peak sensitivity to CH_4 at the 500hPa level, inversion data from the 500hPa layer will be utilized to represent the middle troposphere, while data from the 850hPa layer will be used for the lower troposphere [7].

3. The Distribution Characteristics of Atmospheric Methane in China

3.1. The Spatial Distribution Characteristics of Methane Concentration

The spatial distribution of CH_4 concentration is affected by a combination of natural environmental factors and human activities. Different regions, due to variations in climate, geographical features, land use patterns, and other factors, show distinct high and low value areas. Understanding these distribution characteristics helps reveal the sources of methane emissions and their potential impact on climate change.

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3.1.1. High-Value Areas of Methane

The high-value areas of CH_4 concentration are mainly distributed in regions such as Inner Mongolia, Heilongjiang, Gansu, Qinghai, Xinjiang, and Sichuan. And these areas generally exhibit higher CH_4 concentrations, with annual average concentrations from 1779.80 to 1928.53 ppb, an average value of about 1852.35 ppb, and a standard deviation of 19.65 ppb. The CH_4 concentrations in Inner Mongolia, Heilongjiang, Gansu, Qinghai, Xinjiang, and Sichuan generally exceed 1900 ppb, with an average value of about 1900~1950 ppd, mainly influenced by agricultural activities, coal mining, and oil and natural gas extraction [7].

In Heilongjiang (1846.53±8.99 ppb), the anaerobic environment in rice paddy fields promotes methane production. The flooded paddy fields create an anaerobic environment that provides ideal conditions for methanogenic bacteria, thus intensifying methane emissions. Research indicates that methane in paddy soil is primarily released into the atmosphere through plant tissue transport, liquid-phase diffusion, and the ascent of gas bubbles, with plant tissue transport accounting for 55% to 73% of the emissions. Meanwhile, Heilongjiang, rich in resources, also experiences methane leakage during oil and natural gas extraction. In addition, the permafrost in Heilongjiang releases more methane as temperatures rise [8,9]. Methane leakage from coal mining activities in Inner Mongolia (1830~1870 ppb) and Shanxi (1860~1890 ppb) is also a significant factor contributing to the elevated concentration. In Inner Mongolia, the extensive wetlands and abundant coal resources together drive high methane concentrations, primarily through the decomposition of organic matter in wetlands and methane leakage from coal mining activities. Besides, the Sanjiangyuan Wetland Reserve in Qinghai (1829.07±14.32 ppb), with its vast wetland area, is also a region with higher methane concentrations. In Xinjiang (1835~1875 ppb)and Sichuan (1828~1870 ppb), high methane concentrations are not only related to oil and natural gas extraction but also greatly influenced by the development of animal husbandry. Sichuan is rich in natural gas resources and has a developed livestock industry [10], with methane emissions from enteric fermentation of livestock and manure management being an important source. Special topographical conditions in Sichuan also promote the accumulation of polluted air masses, further exacerbating the rise in methane concentrations.

3.1.2. Low-Value Areas of Methane

Low-value areas of CH_4 concentration are mainly concentrated in regions such as the Qinghai-Tibet Plateau, Tarim Basin, Greater Khingan Range, and Changbai Mountains, with an average methane concentration of less than 1850 ppb. The formation of low concentrations is primarily associated with unique natural environments and limited human activities [11]. The high altitude and cold climate of the Qinghai-Tibet Plateau significantly restrict biological activity, thus reducing methane production. The permafrost in this region acts as a natural barrier, effectively trapping methane and limiting its release into the atmosphere. And the strong winds and atmospheric circulation of the Qinghai-Tibet Plateau aid in dispersing and diluting methane, preventing its buildup.

In the Tarim Basin, the arid climate and low vegetation cover severely limit methane production and release. The region’s unique geological and hydrological conditions mean that methane is primarily found underground and is difficult to release into the atmosphere. Although methane concentrations in these areas have increased in recent years due to rising temperatures, the growth rate remains relatively small. On the Qinghai-Tibet Plateau, the high altitude and cold climate significantly restrict biological activity, thereby reducing methane production. Additionally, strong winds and atmospheric circulation effectively disperse methane, preventing its accumulation at high concentrations. Furthermore, the plateau’s extensive permafrost serves as a crucial methane sink, trapping it underground and limiting its release into the atmosphere. Meanwhile, in the Tarim Basin and Qinghai-Tibet Plateau, although CH_4 concentrations have risen in recent years, the growth rate

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on the Qinghai-Tibet Plateau is even higher, averaging around 8~10 ppb per year. This may be attributed to rising temperatures, which enhance methane emissions from biological sources and thawing permafrost while simultaneously weakening the permafrost's role as a carbon sink.

3.2. The Temporal and Spatial Variation of Methane Concentration

Methane concentration exhibits a distinct seasonal variation pattern. In particular, methane levels are higher in autumn and winter and lower in spring and summer. According to grid-based statistical results, the seasonal average atmospheric CH_4 concentration in China is ranked as follows: autumn (1863.87±17.68 ppb), summer (1857.53±16.29 ppb), winter (1843.43±26.70 ppb), and spring (1841.09±27.15 ppb). This indicates relatively higher concentrations in summer and autumn, and relatively lower concentrations in winter and spring [12].

The main factors impacting this seasonal variation include temperature, photochemical reactions, and human activities. In summer and autumn, higher temperatures can lead to increased methane emissions from sources such as rice paddies and wetlands. Besides, high temperatures promote methane production by wetland microbes, resulting in relatively high methane concentrations. In particular, methane levels reach their highest in summer in rice-growing regions such as the North China Plain, the middle and lower reaches of the Yangtze River, and the Northeast Plain. The flooded conditions created during rice cultivation promote anaerobic microbial activity, which may further increase methane emissions.

However, in some regions, methane concentrations in winter are higher than in summer, such as in western Inner Mongolia, Qinghai, and Gansu. This is mainly due to coal combustion for heating and livestock farming. During the winter heating season, methane emissions from coal combustion increase. Moreover, lower temperatures reduce the boundary layer height, weakening atmospheric dispersion and leading to higher local methane concentrations. Additionally, methane emissions from livestock, particularly ruminants, during winter feeding contribute significantly to the seasonal increase in methane levels.

The lowest methane concentrations typically occur in July (1820.70±30.31 ppb) and August (1764.91±56.81 ppb), mainly because intense solar radiation in summer enhances the activity of hydroxyl (OH) radicals in the atmosphere, accelerating methane oxidation and shortening its atmospheric lifetime. Moreover, the Taklamakan Desert in Xinjiang and the Qinghai-Tibet Plateau exhibit low methane concentrations in summer, likely due to sparse vegetation and the limited presence of wetlands and farmlands, resulting in lower methane emissions. Variations in methane concentrations across different regions of China are impacted by a combination of geographical factors, climatic conditions, and human activities. The seasonal changes in methane concentration reflect complex source-sink mechanisms, necessitating further integration of observational data and modeling studies to better understand the seasonal differences and driving forces behind methane concentration variations.

4. The Emission Characteristics of Atmospheric Methane in China

4.1. Main Natural Methane Emission Sources

In wetland ecosystem, methanogenic bacteria produce methane by decomposing organic matter in strict anaerobic conditions, through two main pathways: acetic acid-dependent methane generation and hydrogen-dependent methane generation. Acetic acid-dependent methane generation involves acetic acid-reducing bacteria and methanogenic archaea, while hydrogen-dependent CH_4 generation relies on hydrogen and carbon dioxide. These two pathways result in different levels of methane emissions depending on environmental conditions and substrate availability.

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Methane in soil is mainly produced through acetic acid fermentation and H_2/CO_2 reduction. Studies show that methane production through acetic acid fermentation is generally higher than through H_2/CO_2 reduction [13]. Specifically, the dominant pathway for CH_4 production in wetlands depends on the availability of active organic carbon. In wetlands with high levels of active organic carbon, such as marshes, acetic acid fermentation predominates, leading to higher CH_4 emissions. In contrast, in wetlands with lower organic carbon content, methane is primarily produced through H_2/CO_2 reduction, resulting in lower CH_4 emissions. Wetland CH_4 emissions account for about 25% to 40% of global CH_4 emissions and 70% of natural CH_4 emissions [14]. The anaerobic conditions in wetlands provide favorable conditions for CH_4 generation, but the intensity of CH_4 emissions is impacted by various factors. In recent years, warming has caused permafrost to melt, which has led to increased CH_4 release. For example, in Alaska, rising temperatures have increased CH_4 emissions from wetlands by about 30%, and climate models predict that global wetland CH_4 emissions could increase by 15% to 50% by the end of this century [15]. These trends indicate that wetland methane emissions are strongly influenced by climate change and may become an important source of global methane concentration fluctuations in the future. Wetland CH_4 emissions are influenced not only by temperature rise but by organic carbon storage and transformation processes. Warming can alter microbial community structure, further affecting methane production and emissions.

4.2. Main Anthropogenic Methane Emission Sources

Based on the investigation and statistics of greenhouse gas emissions from various departments, the main anthropogenic CH_4 sources in China include waste, wastewater, animal intestinal fermentation, manure management, rice fields, biomass burning, coal mining, and oil and gas system leaks [15]. China is the country with the largest coal output in the world. In 2015, the national output reached 3.75 billion tons, accounting for 47.7% of the world's total coal output. Methane is stored in coal seams and surrounding rock layers, and the coal mining process will lead to methane escape and emission from coal seams. And methane emissions from agriculture mainly come from intestinal fermentation and manure management in ruminant livestock. Emissions from rice fields and straw burning are largely due to fermentation in the digestive systems of ruminants and the management of their manure. The mechanism is that methanogens in rumen of ruminants synthesize methane based on hydrogen and carbon dioxide produced by microorganisms, but methane is excreted through belching without being used by animals, and at the same time, feces will be decomposed by microorganisms under anaerobic conditions, thus producing methane. Paddy field emission is one of the main sources of atmospheric methane. As a big rice producer, China contributes a lot to the methane emission from paddy fields. The distribution of rice planting in China gradually decreases from southeast to northwest, and the southern region is a region with large methane emission, with the middle and lower reaches of the Yangtze River, the Pearl River Delta and the Chengdu Plain as the main emission areas. The methane emissions in northern China are mainly concentrated in the Northeast and North China Plain, which align with the country’s rice-growing regions. Emissions from waste treatment primarily stem from the processing of municipal solid waste and wastewater.

5. The Challenges in the Application of Remote Sensing Data

While remote sensing data provides valuable insights into atmospheric methane concentrations, it comes with challenges, including inherent uncertainties and accuracy issues. These uncertainties primarily arise from algorithmic errors during data inversion, as well as environmental factors such as cloud cover and aerosol presence. These factors can skew the data, thus resulting in significant inversion errors. To mitigate these issues, it is essential to integrate more extensive ground station data for calibration and improve the inversion algorithms. This dual approach can enhance the

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reliability of satellite-derived methane concentration estimates. Besides, atmospheric conditions such as cloud cover and aerosols have a notable impact on the quality of remote sensing data. Cloud coverage can block satellite signals, while aerosols can scatter or absorb the radiation, complicating accurate data interpretation. To address these challenges, developing and optimizing algorithms that can better identify and filter out the influences of clouds and aerosols is crucial for improving the precision of atmospheric measurements.

The limitations in spatial and temporal resolution of current satellite platforms pose significant challenges to accurate monitoring. The differences in spatial resolution between satellites can lead to reduced data accuracy, particularly in areas with complex terrain or high methane concentrations, where fine-scale details may be insufficiently captured. To address this issue, data fusion techniques can be employed, integrating datasets with complementary spatial resolutions from multiple satellite platforms. This approach enhances the accuracy and comprehensiveness of methane distribution assessments across diverse geographical regions, thereby enhancing the accuracy and completeness of methane distribution assessments across diverse geographical regions. Besides, existing remote sensing data processing algorithms have inherent limitations that prevent them from fully capturing local atmospheric variations or accurately identifying specific methane emission sources. By locally adjusting and optimizing these algorithms with machine learning techniques, their accuracy and adaptability can be significantly enhanced. In the future, improving remote sensing data quality will require a multifaceted approach. In particular, integrating advanced sensors, artificial intelligence, and interdisciplinary collaboration offers new pathways to overcoming current challenges. With ongoing advances in data processing and algorithm optimization, remote sensing will become an increasingly powerful tool for monitoring atmospheric methane and tackling global environmental challenges.

6. Conclusion

This study provides valuable insights for studying the distribution characteristics and influencing factors of atmospheric methane near the surface of China by using remote sensing data. The results show that the methane concentration is significantly affected by natural and man-made sources, and the main methane emission sources are determined by observing high-concentration methane emissions in areas with a large number of agricultural, mining activities and wetlands. The main methane emission sources are classified and analyzed in this paper. The seasonal variation of methane concentration is studied, which reveals the peak level of methane in autumn and winter affected by agricultural practice and heating demand, and provides ideas for controlling man-made methane emission. However, this study has limitations, such as the need for ground verification. At present, the observation of methane concentration by remote sensing data still depends on the supplement of ground monitoring data. Future research should focus on improving the accuracy and resolution of remote sensing data, and exploring more effective methane emission control strategies to mitigate climate change according to the list of methane emission sources. With the development of urbanization and industrialization in China, it is very important for China to continuously monitor and reduce methane emissions to achieve its climate goals.

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