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QUANTITATIVE STUDY ON METHANE EMISSION IN LIAONING PROVINCE BASED ON GAUSSIAN PLUME MODEL

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Abstract: Methane, a critical greenhouse gas, significantly contributes to climate warming. This study quantifies methane emissions in Liaoning Province, China—a major industrial region—using TROPOMI satellite data and the Gaussian plume model. Filtered satellite observations and ERA5 meteorological parameters were integrated to retrieve emission rates and spatial patterns. Results indicate annual methane emissions of (720 ± 150) Gg yr^{-1}, with coal mining accounting for more than 60%. Seasonal analysis highlights elevated winter emissions linked to heating-related coal use. Satellite-derived emissions exceed EDGARv6.0 estimates by approximately 35%, suggesting underreported industrial sources, particularly mine ventilation leaks. The study demonstrates the effectiveness of combining remote sensing and dispersion modeling for regional methane monitoring. Key recommendations include enhancing emission inventories through high-resolution models and promoting methane recovery technologies in coal and steel sectors. These findings emphasize the need for targeted industrial emission controls to address climate and air quality challenges.
Keywords: Gaussian plume model; TROPOMI satellite data; Methane emissions; EDGAR

1 INTRODUCTION

As an important short-lived greenhouse gas, methane (CH_4) has a global warming potential about 28 times that of carbon dioxide (CO_2) on a 100 year scale, and its contribution to global warming can not be underestimated, second only to carbon dioxide[1]. In the atmosphere, methane not only affects the greenhouse effect through a series of complex photochemical reactions, but also participates in the formation of secondary pollutants such as tropospheric ozone, which has a negative impact on air quality. As an important heavy industry base in China, Liaoning Province has rich coal resources, and coal mining, steel production, chemical industry and other industries are booming. In terms of steel production, the crude steel output of Liaoning Province reached 70.682 million tons in 2024, accounting for 7.03% of the national crude steel output, ranking fourth in the country. As a large iron and steel enterprise in Liaoning Province, Angang Group's annual crude steel production capacity will reach 70million tons in 2024, accounting for 67% of the crude steel production in Liaoning Province and 51% of the crude steel production in Northeast China. In addition, the steel output of Liaoning Province in 2024 was 78.6768 million tons [2].While these industrial activities promote economic growth, they are also accompanied by a large number of methane emissions. In the process of coal mining, the methane in the coal seam will be released into the atmosphere with the coal mining; Steel production and chemical processes involve a variety of chemical reactions, which are also important sources of methane emissions [3]. These methane emissions have a significant impact on air quality and global climate change in Liaoning Province and even surrounding areas. Traditional bottom-up emission inventory preparation methods, such as Edgar (emissions database for Global Atmospheric Research), mainly rely on statistical data and emission factors [4]. This method has some limitations in practical application, it is difficult to accurately capture the dynamic characteristics of emission sources, and it is easy to omit some "super emission sources". Although the number of "super emission sources" is relatively small, the emission intensity is great, which has a significant impact on the total amount of methane emissions in the region and even the world. Therefore, it is of great practical significance to develop a more accurate and comprehensive methane emission monitoring and quantification method.

Based on TROPOMI satellite data and Gaussian plume model, a top-down quantitative method of methane emission is proposed in this study. This method aims to accurately identify the hot spots of methane emissions in Liaoning Province, quantify the emission rates of major industrial sources, clarify the contribution of different industrial activities to methane emissions, assess the consistency between the satellite retrieval results and the existing inventory, identify possible differences and analyze the reasons.

2 METHODOLOGICAL FRAMEWORK AND DATA ACQUISITION

2.1 Data Source and Pretreatment

TROPOMI data: This study obtained the XCH_4 data observed by TROPOMI satellite for some days from 2019 to 2021, with a spatial resolution of 49 km^2. To ensure the data quality, the observation data with quality mark (QA>0.8) and cloud fraction<0.2 were selected. The quality mark QA is used to measure the reliability of data. The higher the value of QA, the higher the reliability of data; Cloud cover will interfere with satellite observations, and low cloud cover data can more accurately reflect the methane column concentration on the ground. Through such screening, noise data and data affected by clouds can be effectively removed, and the accuracy of subsequent analysis can be improved [5]. The following Figure 1 shows the spatial distribution of methane column average dry air mixing ratio in North China in a certain year using TROPOMI satellite data. It can be seen from the figure that the methane mixing ratio shows obvious spatial differences. The color bar displays data ranging from 1700 to 2100 (in 1E-9). The more red the color, the higher the methane mixing ratio, and the more blue the color, the lower the methane mixing ratio.

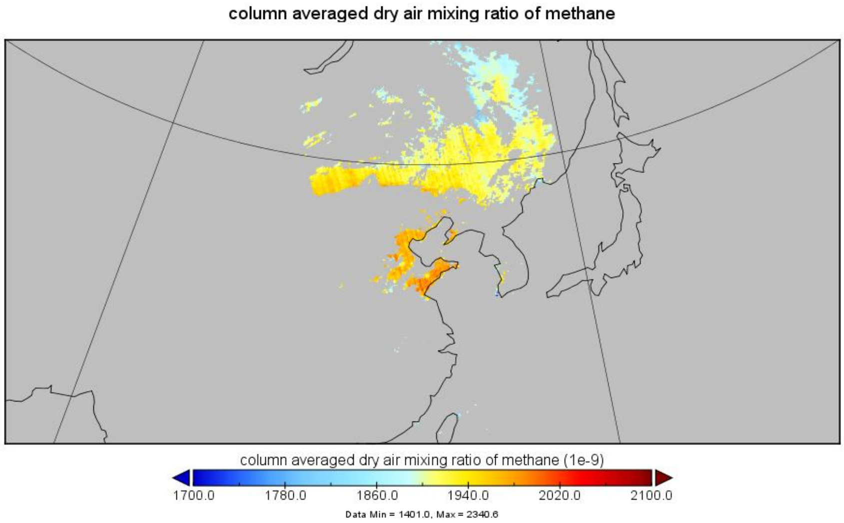

Figure 1 Data Visualization Display

Meteorological data: ERA5 reanalysis data is provided by the European Center for medium range weather forecasting (ECMWF), with high spatial-temporal resolution and extensive coverage of meteorological parameters. In this study, 10 m wind speed (U,V), boundary layer height and atmospheric stability classification are used. The wind speed and direction determine the transmission direction and diffusion speed of methane in the atmosphere; The height of the boundary layer affects the diffusion range of methane in the vertical direction; The classification of atmospheric stability is closely related to the diffusion degree of methane. Under different stability conditions, the diffusion parameters of methane are different. These meteorological data are very important for accurately simulating the diffusion process of methane.

Location of emission sources: in order to determine the key research areas, Fushun and Fuxin coal mine groups and other typical areas were selected in combination with the global energy Observatory (GEO) and the coal mine distribution map of Liaoning Province. The global energy Observatory provides basic information about energy related facilities around the world, while the coal mine distribution map of Liaoning Province shows the distribution of coal mines in the province in detail. Through the combination of the two, the geographical location of coal mines can be accurately determined, which provides the basis for the subsequent research on methane emission in these key areas.

2.2 Gaussian Plume Model Construction

Assuming that the diffusion of methane obeys the Gaussian distribution under steady-state conditions, its concentration enhancement C (x, y) can be expressed as:

$$\mathrm{C}(x, y) = \frac{Q}{2\pi\ \sigma_y \sigma_z \mu} \exp\left(-\frac{y^2}{2\sigma_y^{\ 2}} - \frac{(\mathrm{z}-H)^2}{2\sigma_z^{\ 2}}\right) \quad (1)$$

Where, Q is the emission rate ($\mathrm{kg \cdot h^{-1}}$), which is the key parameter to be retrieved in the model and reflects the mass of methane emitted by the emission source per unit time; σ_y and σ_z are horizontal and vertical diffusion parameters respectively, and their values are determined by Pasquill - Gifford stability classification [6]. The values of these two parameters are also different with different atmospheric stability, which determines the diffusion degree of methane in the horizontal and vertical directions; U is the wind speed ($\mathrm{m \cdot s^{-1}}$). The greater the wind speed is, the farther the transmission distance of methane is and the faster the diffusion speed is; H is the effective height of emission source, which can be assumed to be 50m for coal mine ventilation shaft. This height is determined by comprehensively considering the general building height of coal mine ventilation shaft and the actual position of methane emission outlet and other factors. Through this formula, the concentration distribution of methane in space can be described under given meteorological conditions.

2.3 Emission Rate Inversion

Deduction of background concentration: in order to accurately obtain the change of methane concentration caused by emission sources, the background concentration needs to be deducted. In this study, the wind direction in the Yellow

Sea (38°N-40°N, 120°E-122°E) to calculate the background XCH_4 concentration. The region is far away from the main methane emission source in Liaoning Province, and its methane concentration can represent the natural background level in the atmosphere. By subtracting the background concentration from the observed data, a more accurate enhancement of methane concentration caused by local emission sources can be obtained.
Plume identification: extract the methane enhancement along the wind direction section, and carefully eliminate the interference from other sources. During the growth of rice fields, methane emissions will occur, and the decomposition of organic matter in landfills will also release methane. These non target emission sources will interfere with the analysis of methane emissions from industrial sources. Through the identification and elimination of emission source types, combined with geographic information and related field knowledge, these interference factors are removed, so as to extract the methane plume emitted by industrial sources more accurately.
Least squares optimization: the least squares optimization method is used to minimize the mean square error between the predicted value of the model and the observed value through iterative solution, so as to obtain the best Q value. In the iteration process, the value of emission rate Q is continuously adjusted to calculate the mean square error between the methane concentration predicted by the model and the actual observed concentration. When the mean square error reaches the minimum, the corresponding Q value is the emission rate retrieved [7]. This method can make full use of the observation data and improve the accuracy of emission rate inversion.

2.4 Uncertainty Analysis

Sensitivity of meteorological parameters: the uncertainty of meteorological parameters will affect the emission rate inversion results. This study can test the influence of wind speed error (± 20%) and stability classification deviation on Q value. The change of wind speed will directly affect the diffusion speed and transmission distance of methane. When there is error in wind speed, the diffusion range and concentration distribution of methane in the model will change, which will affect the inversion results of emission rate. The deviation of stability classification will also affect the values of diffusion parameters σ_y and σ_z, leading to the deviation of the model in the simulation of methane diffusion, and ultimately affecting the accuracy of Q value.
Selection of background area: the selection of background area also has a certain impact on the calculation results of emission rate. The research process can compare the emission differences caused by different background ranges. Here, Taking Bohai Bay and Inner Mongolia grassland as examples, their relative positions are different from those of Liaoning Province, and their atmospheric background methane concentrations are also different. Selecting different background areas to calculate the background concentration, the enhancement of methane concentration after deducting the background will be different, resulting in differences in the calculated emissions. By comparing the results of different background regions, we can evaluate the Uncertainty Impact of background region selection on the research results.

3 EMISSION QUANTIFICATION AND COMPARATIVE ANALYSIS

3.1 Emission Hot Spot Identification

Through the analysis of the data, it can be found that the high value area of methane enhancement is mainly concentrated in Fushun (123.8°E, 41.8°N), Fuxin (121.6°E, 42.0°N) coal mine cluster and Anshan Iron and steel industrial zone. Fushun and Fuxin coal mine groups are important coal producing areas in Liaoning Province. Coal mining activities are frequent, and a large amount of methane is released from the coal mining process. Anshan Iron and steel industrial zone has become an important area for methane emission due to chemical reactions in the process of steel production.
The study also found that the methane emission in Liaoning Province showed obvious seasonal characteristics of high in winter and low in summer. This is closely related to the enhancement of coal-burning activities in the heating season. In winter, in order to meet the heating demand, the amount of coal combustion increases significantly, which not only increases the methane emission in the process of coal mining, but also produces a certain amount of methane emission in the process of coal-fired heating. In summer, the demand for heating is reduced, the use of coal is reduced, and methane emissions are also reduced.

3.2 Quantification of Emission Rate

Fushun mining area, as the main coal producing area in Liaoning Province, plays an important role in the emission of methane in Liaoning Province. The ventilation system in the process of coal mining will discharge the methane in the coal seam. At the same time, if there is leakage in the process of gas drainage, it will also cause a large amount of methane to be discharged into the atmosphere. Accurate quantification of methane emissions from Fushun mining area plays a key role in evaluating the contribution of coal mining industry to methane emissions in the province.
Comparing the satellite retrieval results with the EDGARv6.0 list, it can be found that the satellite retrieval results will be overestimated by about 35% compared with the EDGARv6.0 list,corresponding to an EDGARv6.0 baseline estimate

of approximately 530 Gg yr^{-1} for total provincial methane emissions. It can be inferred that the specific reason is mainly due to the mine ventilation and gas drainage leakage not reported in the existing list. In the traditional emission inventory preparation process, due to the limitations of data acquisition and insufficient understanding of some emission processes, some emission sources may be omitted or the emission intensity may be underestimated. The results of this study reveal the potential problems of the existing inventory in the quantification of industrial sources, and provide a reference for the subsequent improvement of the emission inventory compilation method. At the same time, relevant studies have pointed out that there is a deviation between the satellite retrieval results and the emission inventory, in which the satellite retrieval results are higher than the inventory emission intensity as a whole, the straight-line slope across the origin is 1.08, and the Pearson correlation coefficient is 0.7 [8].

3.3 Sources of Uncertainty

In the process of simulating methane diffusion, the Gaussian plume model ignores the influence of terrain disturbance and unsteady meteorological conditions, while the Gaussian plume model assumes flat terrain and steady meteorological conditions, which makes the simulated methane diffusion in these areas deviate from the actual situation and may lead to underestimation of emissions. In addition, the meteorological conditions in the actual atmosphere are constantly changing, and the diffusion law of methane under unsteady meteorological conditions is more complex. Gaussian plume model is difficult to accurately describe, which will also affect the accuracy of emission rate inversion. These are the main causes of uncertainty.

Of course, the quality of the data will also slightly affect the uncertainty of the results. The pixel resolution of TROPOMI satellite data is 49 km^2, which means that one pixel may cover multiple emission sources. In this case, the contributions of different emission sources will mix with each other, leading to the fuzziness of point source contributions. For some small-scale point sources with high emission intensity, their emissions may not be accurately identified and quantified under the existing resolution, which will affect the accurate assessment of the total amount and distribution of regional methane emissions.

4 CONCLUSIONS

This study confirmed the applicability of TROPOMI satellite and Gaussian plume model in regional methane emission monitoring. Through this method, the hot spots of methane emission in Liaoning Province can be identified, the emission rates of major industrial sources can be quantified, and the existing emission inventories underestimate the contribution of industrial sources. In order to further improve the accuracy and refinement of methane emission monitoring, the following measures need to be taken in the future:

Build a comprehensive observation network by combining satellite observation, ground monitoring stations, UAVs and other observation means, such as the functions of sentinel-5p satellite and ground sensors. Ground monitoring stations can provide high-resolution near ground methane concentration data, while UAVs can flexibly observe in specific areas to obtain more detailed emission source information. Through the fusion of multi platform data, the shortage of single observation method can be made up, and the monitoring accuracy of methane emission can be improved.

Increase the R&D and promotion of methane recovery technology for key industries such as coal mine and steel. For example, in the process of coal mining, more advanced gas extraction and utilization technologies can be adopted to use the extracted methane for power generation, heating, etc., which not only reduces methane emissions, but also realizes the comprehensive utilization of energy. In the process of steel production, the production process should be optimized to reduce the generation and emission of methane. At the same time, the Liaoning provincial government can refer to Shanxi coal mine gas power generation subsidy policy for the formulation and implementation of relevant programs.

Improve the preparation method of emission inventory based on the problems of existing emission inventory found in this study. Strengthen the research on the emission process of industrial sources, improve the determination method of emission factors, and give full consideration to unreported emission sources and leakage. At the same time, technical means such as big data and machine learning are used to improve the accuracy and timeliness of emission inventory preparation.

In view of the limitations of Gaussian model and TROPOMI satellite data resolution, research on high-resolution model is carried out. Combined with more refined terrain data and meteorological data, develop a model that can more accurately describe methane diffusion under complex terrain and unstable meteorological conditions, improve the simulation ability of small-scale emission sources, and provide more powerful technical support for the precise control of regional methane emissions.

Through the implementation of the above measures, it is expected to further improve the understanding and control ability of methane emissions in Liaoning Province, and contribute to coping with climate change and improving regional air quality.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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