Temporospatial Analysis of methane trend in China over the last decade --- Estimation of Anthropogenic Methane Emission and Contributions from Different Anthropogenic Sources

Zhi-yuan Chen¹,*

¹Nanjing University of Information Science and Technology, Nanjing, Jiangsu 211800, China.
*chenzhiyuan2000@icloud.com

Abstract. China’s atmospheric methane burden has been on the rise in the past decades. However, the relationship between trends and major anthropogenic sources of methane emissions in China has not been well understood. The temporal and spatial distribution of methane concentration in China is investigated using ten years of methane column data (2010-2019) from the Greenhouse Gases Observing Satellite (GOSAT). High-value regions of methane enhancement are found in the northern provinces of China (northeast Xinjiang, northwest Gansu, inner Mongolia, and the border region of Heilongjiang and Jilin). Based on 2010-2018 China Official Statistical Yearbook data and the latest research about methane emission factors, the major anthropogenic methane emissions in China through 2010-2017 are estimated. With Principal Component Analysis (PCA) method on data of estimated anthropogenic emissions and deseasonalized year-averaged methane concentrations in China, it is found that the top three anthropogenic sources with the greatest impact on methane emissions are coal mining, sanitary landfill, and domestic animal rumination. They could have a potential connection with methane enhancement trend high value regions.

1. Introduction

As the second most important anthropogenic greenhouse gas (GHG), methane has the fastest growing speed from 1750 to 2011 among the three largest anthropogenic GHGs (CO2, CH4, NO2), rising by 150% in its concentration, as compared to 40% for CO2 and 20% for NO2 [1]. Methane could significantly affect the global temperature due to the high radiative forcing produced by it from preindustrial time to 2011, which is around 0.48W/m², contributing to 17% of the increase in radiative forcing GHGs [2]. Although methane has a short life period (9.1 years) compared to CO2, the Global Warming Potential (GWP) could be 84 and 28 times as many as CO2 in a 20-year-period and 100-year-period, respectively. Therefore, getting a thorough understanding of the influences on methane emission provided by man-made sources is raring for people to better control the greenhouse effect in the globe.

There have been many speculations about the major anthropogenic sources of methane in different areas in order to explain the rising trend of the methane burden. Researchers mainly use the “top-down” method to observe how different attributes of gases change in time and space based on data provided by atmospheric observing instruments or satellites. “Bottom-up” methods are usually used to estimate the emission of gases based on emission factors and overland data collected by institutions. The estimated result could be used to verify the accuracy of results provided by the “top-down” method or probe into the relationship between emissions and factors that might affect emissions. Based on Greenhouse Gases Observing Satellite (GOSAT) data (top-down) and inverse method (bottom-up), Turner et al. inferred
that U.S. methane emissions had been rising by over 30% in the time period of 2002-2014, which caused
30%–60% of global atmospheric methane growth [3]. Similar work by Sheng et al. used GOSAT data
as top-down method to show a 2.5±1.2%/a trend in North America’s methane concentration from 2010
to 2016. Data of U.S. oil-gas production and cattle population in mid-west America and Mexico were
used as bottom-up method to investigate the relationship between methane emission and anthropogenic
sources [4]. According to past researches by Yue et al., Huang et al., the major known sources of
anthropogenic methane emissions in China could be summarized as coal mining, waste disposal,
biomass burning, paddy fields, domestic animal rumination, and manure management systems [5, 6].
However, most of the researches on methane in China only focus on simulating methane emission with
bottom-up methods or how the trend developed in past decades. The relationship between the simulated
results and the actual situation was not taken seriously enough, which should be paid more attention to.

In this paper, spatial and temporal analysis of the methane changes and its enhancement trend in
China and surrounding areas is conducted by using GOSAT data in the past decade (2010-2019) to find
out how the trend was going and where are the worst-affected areas. Based on the latest China Official
Statistical Yearbook data, the up-to-date methane emission factors provided by IPCC 2014 and the latest
research results to quantification the methane emission in China (Except Hong Kong, Macao, and
Taiwan) are used, which include major anthropogenic emission sources like coal mining, paddy fields,
straw burning (biomass burning), domestic animal rumination, manure management, waste incineration,
sanitary landfill, industrial effluents, and sanitary sewage (waste disposal). Furthermore, principal
component analysis (PCA) on methane emission produced by different sources and satellite observed
methane column average dry mole fractions in China are used to find out the predominant sources that
affect China’s methane trend, which also shows the potential correlation between them and methane
enhancement trend high-value areas.

Figure 1. The 2010-2019 methane enhancement trend in China and its linearization based on data from
GOSAT with error standard deviation. The methane enhancement is defined as the difference between
column average dry mole fractions values, and the background is defined by the averaged value of
random sampling result of the 10th-25th percentiles of the values.
2. Data and Methods

2.1 Data sources
GOSAT satellite was launched in a Sun-synchronous low Earth orbit in January 2009, which retrieves the atmospheric methane column values in sampling locations settled every 90–280 km along the orbit tracks by observing infrared light. The satellite provides dense temporal data by returning to the same point every three days, which is suitable for analysis along a specific period. The observation instrument carried on is a Thermal and Near-infrared Sensor for carbon Observation (TANSO), which is consisted of a Fourier Transform Spectrometer (FTS) and a Cloud and Aerosol Imager (CAI). It is of necessity to mention that water could absorb sunlight that may affect the precision of FTS observing results. However, a large water surface that reflects sunlight specularly in certain directions could be detected accurately.

For top-down methods, GOSAT Proxy XCH4 v9.0 retrievals provided by University of Leicester is used [7], which is an updated dataset of the European Space Agency Climate Change Initiative (CCI) CH4_GOS_OCPR V7.0., and the Copernicus Climate Change Service (C3S) CH_4 v7.2. Based on different underlying L1B radiance data with additional changes, data are processed using methods like recommended radiometric calibration and degradation corrections, which improved the variability in methane significantly [8, 9]. The accuracy of processed data has been validated to be of high quality comparing to the ground-based Total Carbon Column Observing Network data, which has a 0.7% single-scene precision (random error method) and a 4–6 ppb systematic error [10-12].

Most of the data used in bottom-up methods are collected from China Official Statistical Yearbook data from 2010 to 2018 [13], including data on activity levels, such as the number of ruminants in each province, the production of rice, exploitation quantities of coal, oil and natural gas, and municipal solid waste disposal and Chemical Oxygen Demand (COD) in wastewater treatment. Due to the lack of necessary data and decrease in the reliability of GOSAT data, we neither use the bottom-up method to calculate anthropogenic methane emissions in 2018 and 2019, nor do further analysis on these two years’ data.

2.2 Data Preprocessing Methods
Methane concentration could fluctuate intensely in summer and winter due to its large seasonal variability [14]. In order to eliminate seasonal effects on methane concentrations, the seasonal-trend-loess (STL) decomposition method is used on all GOSAT data [15]. To observe the change of methane concentration more specifically, we point out the methane enhancement, which is defined as the difference between the actual value of the deseasonalized column average dry mole fractions and the corresponding local background values. Here, the local background values are selected by averaging the values of a random sampling of 10%-25% of all corresponding yearly-averaged-data for 1000 times (Monte Carlo method), which has been validated by Sheng et al. [4]. Figure 1 shows the methane enhancement changes from 2010 to 2019, from which a fluctuated rising trend of 0.3 ppb/year and decreasing data credibility (from lengths of error bars) can be seen. To observe the spatial distribution of methane trends, the methane enhancements in 0.5° × 0.5° grids are aggregated, and the trend of each grid’s data is calculated, separately. For each grid, 8 available data for each year are required to increase the accuracy of the annual mean value and percentiles.

2.3 Estimating methods
To estimate anthropogenic methane emission with a bottom-up method, the latest emission factor and equations are used respectively to do calculations in 9 different parts. They are coal mining, paddy fields, straw burning, waste incineration, domestic animal rumination, manure management, industrial effluents, sanitary landfill and sanitary sewages.

2.3.1 Ruminants
Domestic animal rumination and manure management could be summarized as ruminants’ emissions.
Based on researches by Zhou et al. and Huang et al., the ruminants’ emission in China is calculated by the following equation:

\[ \sum_i \mathcal{P}_L \times (E \mathcal{F}_i \times E \mathcal{M}_i) \quad (1) \]

where \( \mathcal{E}_{L_{CH4}} \) represents the methane emissions from ruminant intestinal fermentation and manure management (\( kg \cdot a^{-1} \)); \( \mathcal{P}_L \) is the number of ruminants; \( \mathcal{E} \mathcal{F}_i \) is the intestinal fermentation emission factors of different types of livestock; \( \mathcal{E} \mathcal{M}_i \) represents the manure management emission factors for different types of livestock. The two emission factors were derived from Zhang et al. [16].

To calculate \( \mathcal{P}_L \), former studies use this equation:

\[ \mathcal{A} \mathcal{P} \mathcal{P} = \text{Days}_\text{alive} \times \left( \frac{\mathcal{N} \mathcal{A} \mathcal{P} \mathcal{A}}{365} \right) \quad (2) \]

where \( \mathcal{A} \mathcal{P} \mathcal{P} \) is an average number of animals raised per year; \( \text{Days}_\text{alive} \) is raising periods of different livestock; \( \mathcal{N} \mathcal{A} \mathcal{P} \mathcal{A} \) is the number of livestock produced per year [17]. Considering the influence produced by the stock of livestock leftover from the previous year, a new equation is defined based on Equation (2) to calculate \( \mathcal{A} \mathcal{P} \mathcal{P} \):

\[ \mathcal{A} \mathcal{P} \mathcal{P}_i = \mathcal{O} \mathcal{U} \mathcal{T}_i + \frac{\mathcal{S} \mathcal{T} \mathcal{O} \mathcal{K}_i - \mathcal{S} \mathcal{T} \mathcal{O} \mathcal{K}_{i-1}}{2} \quad (3) \]

where \( \mathcal{A} \mathcal{P} \mathcal{P}_i \) is the number of animals raised in the \( i \)th year; \( \mathcal{O} \mathcal{U} \mathcal{T}_i \) is the livestock output in the \( i \)th year; \( \mathcal{S} \mathcal{T} \mathcal{O} \mathcal{K}_i \) is the stock of livestock in the \( i \)th year.

### 2.3.2 Coal Mining

China, the largest producer of coal in the globe, has a raw coal production of 3.85 billion tons in 2019, which accounts for 47.4 percent of the world’s total coal production. The formula for calculating total methane emission from coal mining [7]:

\[ \mathcal{E}_{C_{CH4}} = \rho \times (Q_h \times \mathcal{E} \mathcal{F}_h + Q_1 \times \mathcal{E} \mathcal{F}_1 + Q_s \times \mathcal{E} \mathcal{F}_s) \quad (4) \]

where \( \mathcal{E}_{C_{CH4}} \) is the escaped emission of methane (\( kg \)) during coal mining; \( Q_h \) represents the yield of high-gas mines; \( Q_1 \) is the yield of low-gas mines; \( Q_s \) is the yield of open-pit mining; \( \mathcal{E} \mathcal{F} \) represents the respective emission factor (\( m^3 \cdot t^{-1} \)); \( \rho \) is the density of methane under standard state (0.717 \( kg \cdot m^{-3} \)). What’s more, methane emissions are also produced in the after-mining activity, with a weighted average emission coefficient of 1.3 \( m^3 \cdot t^{-1} \) [18]. Factors of different types of coal mine methane emissions are derived from [19], followed IPCC 2006 guidelines [20].

### 2.3.3 Paddy fields

Paddy field is one of the most important anthropogenic sources of atmospheric methane emissions. Meanwhile, China is the largest rice producer in the world nowadays. In recent studies, lots of researchers have done field observations and studies on China’s paddy fields methane emission, using estimating means, like extrapolation [21], and modeling methods [17]. Considering the domestic situation, the estimation formula provided by Jiangxi Provincial Administration of Market Supervision is selected:

\[ \mathcal{E}_{C_{CH4}} = \sum_i (\mathcal{E} \mathcal{F}_i \times AD_i \times 10^{-3}) \quad (5) \]

where \( \mathcal{E}_{C_{CH4}} \) is the total methane emission provided by paddy fields; \( \mathcal{E} \mathcal{F}_i \) is the emission factors of different types of paddy fields (\( kg \cdot ha^{-1} \); \( AD_i \) is the area of different types of paddy fields (ha). Methane emission factors of different types of paddy fields are derived from Criterion for agricultural greenhouse gas inventory [22].
2.3.4 Waste Disposal
Waste incineration, sanitary landfill, industrial effluents, and sanitary sewage are the four major ways of waste disposal [18,23]. According to the existing researches, most of the estimations are based on IPCC list guidelines.

The estimation formula for waste incineration [7]:

$$ EB_{CH4} = \sum (IW_i \times EF_i) \times 10^{-6} \tag{6} $$

where $EB_{CH4}$ is the methane emissions provided by waste incineration ($Gg \cdot a^{-1}$); $IW_i$ is the total amount of waste incineration processing ($t \cdot a^{-1}$); $EF_i$ is the emission factor of different processing method (6.5 kg · t⁻¹ MSW); $i$ represents different processing technologies.

The estimation formula for sanitary landfill is shown as:

$$ ELF_{CH4} = \left[ \left( T_{MSW} \times F_{MSW} \times MCF_1 \times DOC \times F_{DOC} \times \frac{16}{12} \right) - R \right] \times (1 - OX) \tag{7} $$

where $ELF_{CH4}$ is the methane emissions provided in the process of sanitary waste landfill ($Gg \cdot a^{-1}$); $T_{MSW}$ is the total amount of sanitary landfill processing ($Gg \cdot a^{-1}$); $F_{MSW}$ is the proportion of processing (95%); $MCF_1$ is the methane correction factor for sanitary landfill processing; $DOC$ represents biodegradable organic carbon content (0.151); $F_{DOC}$ represents the proportion of dissimilated biodegradable organic carbon (0.5); $R$ represents methane recycling amount (0), and $OX$ represents the proportion of oxidation factor (0.1).

Wastewater could be mainly divided into industrial effluents and sanitary effluents, which would produce methane by biodegradable organic ingredients therein as IPCC manifested. The estimation formula for industrial effluents could be described as [7]:

$$ EI_{CH4} = [COD] \times EF_{COD} \times MCF_i \tag{8} $$

where $EI_{CH4}$ is the methane emissions produced by processing industrial effluents; Chemical Oxygen Demand ($COD$) is an important attribute to evaluate the organic content in industrial wastewater; $EF_{COD}$ is the methane emission factor of $COD$ (0.25 $g \cdot g^{-1}$); $MCF_i$ is the correction factor of industrial wastewater treatment process (0.458) [24].

Similarly, the formula to estimate methane emissions from sanitary sewage is shown as [7]:

$$ ES_{CH4} = [BOD_5] \times EF_{BOD} \times MCF_S \tag{9} $$

where $ES_{CH4}$ is the methane emissions produced by processing sanitary effluents; Biochemical Oxygen Demand ($BOD$) is the attribute to measure the organic content in sanitary sewage; $EF_{BOD}$ is the methane emission factor of $BOD_5$ (0.6g · g⁻¹); $MCF_S$, which is the correction factor of the sanitary sewage treatment process, has a value of 0.165. Due to the lack of domestic BOD data, the same estimation method is used as Huang et al., deriving the $BOD_5$ value by using the ratio method ($BOD_5/COD$) [25].

2.3.5 Biomass Burning
Biomass burning could be mainly divided into a straw open burning part and domestic fuel burning part. The first part is predominant in the whole section, as a result of a large number of straws left by agricultural activities in China every year, which could be calculated with the following formula [26]:

$$ ES_{CH4} = \sum PS_i \times CS_i \times RS_i \times FS_i \times EF_{SI} \tag{10} $$

where $ES_{CH4}$ in the formula means the total emission from straw burning (g); $PS_i$ is the production of various types of grain (kg); $CS_i$ represents the straw/crop ratio of different types of grain; $RS_i$ is the percentage of crops that are burned in the open; $FS_i$ is the burning efficiency; $EF_{SI}$ is the emission factors of different kinds of crops (g · kg⁻¹).
As for the domestic fuel burning part, which consists of fuel burning in urban areas and straw-firewood burning in rural areas, necessary data are inadequate for calculation. Therefore, it is not included in this article.

2.4 Analysis Method
To better understand the relationship between the change of methane concentration and the major anthropogenic sources in China, multifactor analysis is required. Principal component analysis is suitable for data correlated to multiple variables, which are likely to be independent [27]. It is a good way to eliminate the correlation between evaluation indicators and describe the particular status of samples more objectively. Based on the situation that different anthropogenic emission sources are poorly related, the PCA method on deseasonalized column average dry mole fractions is adopted and different estimated anthropogenic methane emission values are used. In order to specifically explore the relationship between anthropogenic emission change and total methane change, the annual variation is derived by doing subtraction between each group of variables from year to year. Then PCA method on the annual variation of methane concentration values is used and anthropogenic emission values are estimated.

The method could be mainly separated into four steps: (1) Arrange data into a matrix by columns and standardize the matrix; (2) Find the corresponding covariance matrix; (3) Find the eigenvalues and eigenvectors of the covariance matrix, and then arrange the eigenvectors in descending order according to the magnitude of corresponding eigenvalues; (4) Choose the first few corresponding eigenvalues (accumulative contribution >85%) as principal components and do the further explanation.

3. Results

3.1 Trends based on GOSAT
From 2010 January to 2019 December, as figure 2 shows, the methane concentration over China has increased by over 70 ppb with an averaged trend of +8.36 ppb per year. According to Figure 2, there is a good linear relationship between methane concentration and time, and therefore, China is experiencing a relatively stable methane increasing period. However, Figure 2 doesn’t show any obvious changes in the rising trend. There is still a +0.3 ppb trend of methane enhancement in China from 2010 to 2019 (as shown in Figure 1). Considering the accuracy of GOSAT data and the time constraints of the estimated emissions data to be analyzed later, we look into the 2010 to 2017 methane enhancement over China detailly from temporospatial perspective.

![Figure 2](image.png)

Figure 2. The 2010-2019 deseasonalized methane column average dry mole fractions XCH4 changes and linearization in China and surrounding regions (70°E-140°E, 15°N-60°N), measuring by GOSAT.
China’s methane enhancement shows a +0.31 ppb/year trend over the 2010-2017 period as shown in Figure 3 (a), which is slightly higher than the trend along the 2010-2019 period (see Figure 1.), but not significantly. Figure 3 (b) shows the spatial distribution of methane enhancement trend over 8-year-period in China, indicating no significant trends in the middle and south part of China but obvious complex trends in the north part of China. High-value areas respectively aggregate in northeast Xinjiang, northwest Gansu, inner Mongolia, the border region of Heilongjiang and Jilin. Low-value areas are relatively sparse in space, mainly aggregate in southwest Xinjiang, north part of Qinghai, and middle Gansu.

Figure 3. The 2010-2017 methane enhancement trend in China. (a) Methane enhancement and its linearization based on data from GOSAT with error standard deviation, using the background defined by averaging values of random sampling result of the 10th-25th percentiles of enhancement values. (b) Simulated relative local trends in average column methane for 0.5° × 0.5° grid cells using background correlated to a local low-percentile background as described in the text.
3.2 Estimated methane emission from major anthropogenic sources
Table 1 shows the 2010-2017 methane emissions from different major anthropogenic sources in China [5,6,7]. From the table, paddy field can be seen, and straw burning has a similar slight rising trend of methane emission by comparing with each other, methane emissions produced by solid waste treatment (waste incineration and sanitary landfill). Wastewater treatment (industrial effluents and sanitary sewages) generally showed opposite trends by regular rise and drop, respectively. Emissions from domestic animal rumination, manure management, and coal mining do not show significant trends.

Most of the estimation methods used in this article are consistent with Huang et al. except for paddy fields and the way to estimate the number of ruminants. Therefore, the result of estimation is highly consistent with Huang et al. and highly similar to Yue et al. and Zhang et al.

Table 1. estimated methane emissions from major anthropogenic sources in Chinese mainland

| Time (year) | Anthropogenic Sources emission (Gg) | 2005 [Yue et al., 2012] | 2007 [Zhang et al., 2014] | 2015 [Huang et al., 2019] | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|-------------|------------------------------------|-------------------------|--------------------------|--------------------------|------|------|------|------|------|------|------|------|
| domestic animal rumination | 11581 | 8245 | 8920 | 8639 | 8454 | 8450 | 8489 | 8674 | 8790 | 8573 | 7590 |
| manure management | 812 | 1674 | 1290 | 1524 | 1530 | 1609 | 1621 | 1651 | 1619 | 1576 | 1555 |
| coal mining | 13267 | 14785 | 19917 | 18444 | 20502 | 20700 | 20912 | 20566 | 20132 | 18612 | 19206 |
| paddy fields | 6992 | 5538 | 9774 | 7352 | 7411 | 7445 | 7502 | 7515 | 7520 | 7511 | 7511 |
| waste incineration | 401 | 151 | 169 | 233 | 301 | 346 | 401 | 480 | 550 |
| sanitary landfill | 2576 | 3175 | 4662 | 2787 | 3155 | 3539 | 3775 | 4114 | 4662 | 5092 | 5444 |
| industrial effluents | 2293 | 1577 | 2558 | 1418 | 2862 | 2775 | 2694 | 2627 | 2546 | 1198 | 1170 |
| sanitary sewages | 1242 | 564 | 1014 | 565 | 1140 | 1105 | 1073 | 1046 | 1014 | 477 | 466 |
| straw burning | 335 | 434 | 414 | 442 | 462 | 477 | 484 | 500 | 496 | 497 |

Note: Provinces except Hong Kong, Macao and Taiwan.

3.3 Principal Component Analysis results
By using the PCA method on the annual variation of column average methane values and estimated anthropogenic emissions from different sources (described in 2.4), it can be found that the first 4 components could explain up to 99.5% of the information (as shown in Figure 4), which could be called as principal components.
Figure 4. Descending distribution of different principle components’ contribution of variance. X-axis means different components, y-axis means a contribution rate of variance. The broken yellow line shows the cumulative contribution of variance.

Table 2 shows the values of the four principal components (PC) and corresponding variables. As shown in Table 2, PC1 has a variation contribution of 69.95%, PC2 has a variation contribution of 16.88%; PC3 and PC4 have a relatively small variation contribution of 9.16% and 3.54% separately. As suggested by [28], the principal components outside the first principle component contain not only evaluation information of the dataset but also some of the characteristic information of each unit in the analysis. Only the first PC is used for the comprehension evaluation.

By considering the different coefficients shown in PC1, the weights of sources in descending order are ranked as coal mining, sanitary landfill, domestic animal rumination, manure management, waste incineration, industrial effluents, paddy fields, straw burning, and sanitary sewage. Consequently, coal mining, sanitary landfill, and domestic animal rumination could be considered the three major sources that dominate the methane emission changes in China. The coefficients for the other sources are relatively small, which could show the poor relationship between these anthropogenic methane sources and the methane variation in China. It’s worth noting that sanitary sewage has a large negative index, which could be due to the negative effects on methane emissions produced by it.

| variables         | domestic animal ruminatio n | manure management | coal mining | sanitary landfill | waste incineration | industrial effluents | sanitary sewage | paddy fields | straw burning |
|-------------------|-----------------------------|-------------------|-------------|-------------------|-------------------|---------------------|----------------|--------------|--------------|
| **PC1**           | 0.40                        | 0.07              | 0.71        | 0.47              | 0.05              | 0.05                | -0.33          | 0.03         | 0.01         |
| (69.95%)          |                             |                   |             |                   |                   |                     |                |              |              |
| **PC2**           | 0.11                        | -0.06             | -0.28       | 0.04              | 0.86              | -0.21               | -0.33          | 0.04         | -0.03        |
| (16.88%)          |                             |                   |             |                   |                   |                     |                |              |              |
| **PC3**           | -0.81                       | -0.37             | 0.21        | 0.19              | 0.03              | 0.06                | -0.33          | 0.02         | -0.01        |
| (9.16%)           |                             |                   |             |                   |                   |                     |                |              |              |
| **PC4**           | 0.25                        | -0.48             | 0.24        | -0.73             | -0.07             | 0.06                | -0.33          | -0.01        | -0.07        |
| (3.54%)           |                             |                   |             |                   |                   |                     |                |              |              |
Furthermore, the result also means a potential relationship between the high emission areas and the major anthropogenic emission sources, which is not discussed in this research.

4. Discussion

4.1 Comprehension analysis of methane concentration trend

From a temporal perspective, methane concentration over China steadily rose from 2010 to 2019 with +8.36 ppb rise per year (R-squared=0.995). China’s methane enhancement shows a wavelpike rise of +0.31 ppb per year (R-squared=0.242) in the time period from 2010 to 2017. By and large, methane concentration over China has increased roughly in step with the globe. However, differences between annual methane enhancement varied a lot, which could be largely influenced by different emission sources over China.

Methane emission sources could be mainly divided into natural sources and anthropogenic sources. Wetland emissions are considered as an important natural source indicated by former researches [7], lacking an effective quantification method, which is not included in this research. Emission from major anthropogenic sources, including coal mining, paddy fields, straw burning, waste incineration, domestic animal rumination, manure management, industrial effluents, sanitary landfill, and sanitary sewages, are simulated by using bottom-up methods and analyzed with processed satellite data. Annual variations of anthropogenic methane emissions show a large correlation with annual variations of methane enhancements (R-squared=0.694, p-value=0.02), which indicates that these major anthropogenic sources could influence China’s methane concentration. According to the result of PCA, we could point out more explicitly that the fluctuation of China’s methane enhancement could be largely influenced by coal mining, sanitary landfill, and domestic animal rumination.

Simultaneously, the spatial distribution of methane enhancement over China shows that a large increase over 2010 to 2017 happened in northeast Xinjiang, northwest Gansu, inner Mongolia, and the border region of Heilongjiang and Jilin. From previous inferences, these regions are likely to be influenced by the three important anthropogenic sources, among which we could find that northeast Xinjiang has 2 of the largest coalfields in China, which are east Junggar basin coalfield, the largest integrated coalfield in China, and Turpan-Hami basin coalfield, producing one-third of coals in Xinjiang province. This could be a piece of strong evidence to prove the relationship between coal mining and northeast Xinjiang. Meanwhile, Inner Mongolia, Xinjiang, and Gansu are the first, second, and fifth-largest animal husbandry areas in China. The information could correlate the rise of methane concentration in these areas with the source of domestic animal rumination. It is worth mentioning that the high-value region of methane enhancement had relative low methane emission from sanitary landfill among China in 2007 [29], which might state a large increase has happened in emission from sanitary landfill in these areas.

However, there are still some deficiencies in these analytical methods. First of all, it’s hard to test our simulation of anthropogenic methane emissions due to the lack of data. Secondly, the data collected from China Official Statistical Yearbook also faces the problem that it could not be tested. It is not sure that natural factors or statistical errors cause a sharp decrease in sanitary sewage and industrial effluents. Last but not least, we lack the means to clearly illustrate and quantify the influents produced by anthropogenic methane sources on the high-value methane enhancement areas over China, which could be related to the atmospheric transmission mode of methane.

4.2 Suggestions on controlling methane concentration

Most of the researches on methane sources could over-focus on the largest emission sources in a place, and so does the researches on controlling methane emissions. However, the large increase from small sources like a sanitary landfill in Inner Mongolia could be easily neglected. To better control methane emission, we need to have an overall understanding of the development of the emission source. Sanitary landfills, for example, produce methane by the decomposition of organic matter. Suppose we combine the analysis and prediction of organic matter content in landfills in different areas with the methane
emission produced by it. In that case, the accuracy of the prediction on methane concentration produced by sanitary landfill could be largely increased and better explained. Apart from comprehension analysis, models like ANN are also helpful in predicting changes in methane concentration [30].

5. Conclusion

GOSAT, as the most common and reliable source of atmospheric methane data, supporting to show how column average methane changed from 2010 to 2019 in China. Defining the local background by using this method, we have shown the methane enhancement changes from 2010 to 2019 with a rising trend of +0.3 ppb/year.

Based on 2010-2018 China Official Statistical Yearbook data, we have estimated methane emissions provided by nine different major anthropogenic sources in China by using the estimation methods, following the latest IPCC guidelines. In order to raise the accuracy of estimation, a revised formula (formula (3)) is presented to estimate the number of animals raised in a year when estimated ruminants’ emissions. However, there are still many factors that could interfere with the accuracy of estimation. One of the most important factors is the lack of data. We did not find any data of annual BOD produced in China or paddies’ area data, which could only be obtained by the ratio method now. Therefore, the deficiency of methane emission estimation through a relatively long time-period is also short of comparative samples. It is hoped that the domain could be focused on by more researchers.

After doing PCA on the variation of column atmospheric methane concentrations and estimated anthropogenic sources’ emission from 2010 to 2017, the four PCs are analyzed by ranking the weights of different anthropogenic sources. Five major emission sources have been summarized into coal mining, ruminants, paddy fields, and sanitary landfill, indicating how anthropogenic sources affect the methane trends in China. Results show that there should be a potential correlation between the methane enhancement trend in high-value areas and dominant anthropogenic methane sources, which need more researchers to research and inquire. As a starting idea, a casual analysis could be used in the research of this relationship. Likewise, research on geographical clustering analysis of methane concentration is also in need of development, which could help better understand how methane is affected along with time and space and how to better control the increase of methane concentration.

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