A fast and efficient method for calculation of background methane concentrations using Sentinel-5P satellite data

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ABSTRACT

Increased emissions and thus higher concentrations of greenhouse gases in the atmosphere as a result of human activities are one of the main reasons for the observed rise in temperatures in recent years. Methane is the second most abundant greenhouse gas and plays a significant role in global warming. With the oil and gas industry and coal mining accounting for the majority of anthropogenic emissions, atmospheric methane concentrations are increasing at an accelerating rate. In this paper, using satellite data from the Sentinel-5P for the period of May 2018 to December 2022, we present an efficient and fast method to calculate background atmospheric CH_4 concentrations. The emission source in the study area is homogeneous, allowing the proposed method to be used as a benchmark for building models to estimate and track emissions in heterogeneous regions. The knowledge of background concentrations allows the tracking of seasonal and annual variations and trends, as well as the rapid detection of regular or accidental emissions from unregulated sources.

Keywords: Remote Sensing, Background concentration, CH_4, TROPOMI

1. INTRODUCTION

Methane (CH_4) is the second most abundant greenhouse gas after carbon dioxide (CO_2). Its concentration in the atmosphere has increased at an accelerating rate in recent years and is one of main reasons for the observed faster climate warming. To slow down climate change in the short term, it is vital that emissions of this greenhouse gas be reduced rapidly in the current decade[1]. The atmosphere's methane budget is the sum of all the individual sources and sinks that determine the amount of methane in the atmosphere on a particular day. However, accurate quantification of this budget is a major challenge[2].

Technologies and scientific methods for tracking and accurately determining atmospheric methane levels, taking into account all sources at local and global scales, need to be developed and applied. An essential part of the process of quantifying the global methane budget is to investigate the dynamics of changes in methane concentrations and fluxes from a given emission source, as well as the mechanisms of uptake and transport. An important step is the development of detailed inventories of anthropogenic sources of methane and other important air pollutants such as carbon monoxide (CO) and nitrogen dioxide (NO_2), their nature and location[3]. The quality of emission monitoring and reporting systems needs to be greatly improved. Methane emissions vary widely between sectors and countries. There are several options for tracking emissions with varying degrees of accuracy[4]. It is important that monitoring and reporting programs take into account the spatial and temporal variability of emission fluxes. The choice of monitoring sites and the frequency of measurements are critical to the reliability of the results obtained[5].

By their very nature, low and medium resolution satellites are not designed to identify and quantify point source emissions, but rather to study methane emissions from facilities and sites, locate large areas, and track and analyze medium and long range transport[6]. Generally speaking, it is a detection technology as this kind of satellites measures the concentration per pixel, but in certain circumstances, e.g. very high emissions, they can be used for quantification.

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Ninth International Conf. on Remote Sensing and Geoinformation of the Environment (RSCy2023), edited by K. Themistocleous, et al., Proc. of SPIE Vol. 12786, 1278624 · · doi: 10.1117/12.2681793

2. MATERIALS AND METHODS

2.1. Study areas

This manuscript tracks methane emissions in two study areas - Turkmenistan (Figure 1) and Bulgaria (Figure 2). Turkmenistan has had some of the highest methane emissions in the world in recent years, mostly from the oil and gas sector. The study also found that despite the huge methane emissions, little or no nitrogen oxide and carbon monoxide emissions are recorded over this area at scales detectable by medium-resolution satellite imagery[7].

Due to the climatic and geographical characteristics of Turkmenistan, the satellite data used in this study have a high density (high percentage of available pixels in the satellite images). Therefore, selecting this area as a test zone for applying the methodology presented here to determine background levels is reliable. According Köppen climate classification Turkmenistan has an arid, cold desert (Bwk) and steppe (Bsk) climate that is severely continental[8], with low rainfall and relatively little cloud cover year-round. This determines the high percentage of available satellite data throughout the year.

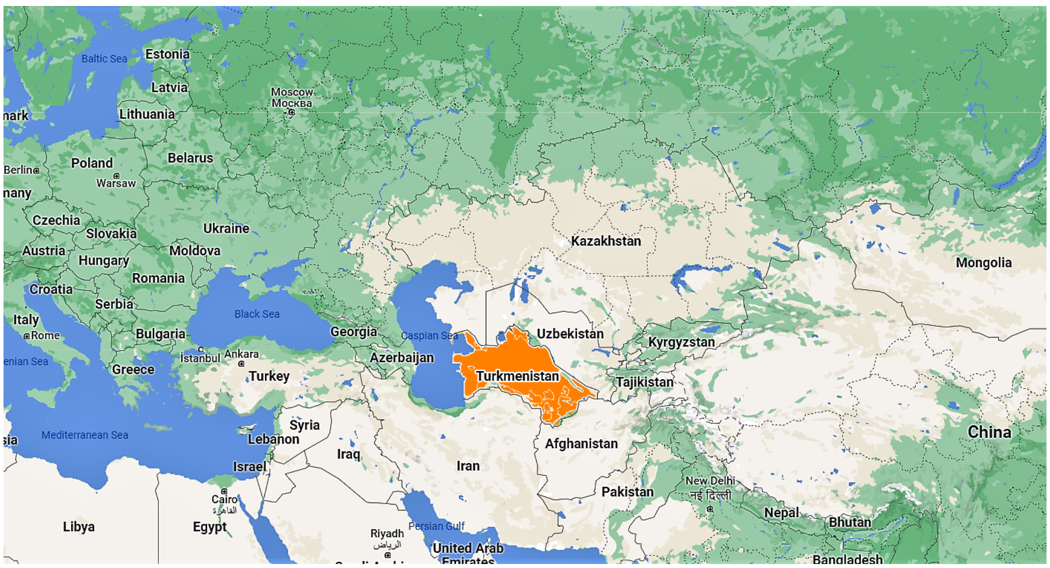

Figure 1. The study area of Turkmenistan. Map provided by Google Map

The percentage of missing pixels from satellite images taken by the TROPOMI sensor on the board of the European Sentinel-5P satellite is significantly higher for the second study area (Bulgaria). This is determined by the character of atmospheric circulation and climatic conditions in the country. The climate in Bulgaria is more diverse than in Turkmenistan. In Bulgaria are presented seven Köppen climate types including tundra climate (ET) in the highest mountainous territories, subarctic (Dfc), warm-summer humid continental (Dfb), humid temperate climate (Cfb), humid subtropical (Cfa), warm-summer Mediterranean (Csb), and hot-summer Mediterranean (Csa)[9,10].

However, this paper demonstrates the feasibility of determining background methane concentrations using the method presented here. Two major methane sources in Bulgaria are energy-related facilities (Figure 2, red and blue squares). The first is the largest coal mining area in Bulgaria, the Maritsa East Mines, which is located in the south-central part of Bulgaria (Figure 2, red rectangle). The second one is the oil refinery northwest of the city of Burgas (Figure 2, blue rectangle).

The lack of a certain percentage of pixels in the imaged area is a major difficulty when using medium-resolution satellite imagery to monitor methane emissions. This percentage depends on various factors such as cloud cover over the study area, low albedo, high atmospheric aerosol content, etc.

Figure 2. The study area of Bulgaria. Map provided by globalenergymonitor.org

2.2. Data and data processing

Daily satellite data from the Sentinel 5P - TROPOMI instrument were used to determine background methane concentrations for the period between May 2018 and December 2022 over Turkmenistan and Bulgaria. From mid-2018, the TROPOMI instrument on board the Sentinel-5P satellite provides open source data on key air pollutants such as CH_4, NO_2, CO. Sentinel-5P is a product of the European Space Agency and is in a sun-synchronous orbit. Its data are open access and available 2 to 4 days after the acquisition, which is daily, with a bandwidth of 2600 km, local flyby time of about 13 h. The spatial resolution for each pollutant is between 3.5 and 7 km[11,12]. The TROPOMI data has irregular geometry and precise georeferencing is required. This data enables more detailed spatial and temporal monitoring compared to previously used satellite information.

2.3. Methodology

Background levels are one of the most important indicators to monitor when studying GHGs such as methane. The knowledge of background concentrations for the study area makes it possible to explore seasonal and annual trends in their variation, to quickly detect periodic or occasional average and relatively small volume emissions from unregulated sources, as well as track transport from other areas, etc.

Both study areas here are subjected to an integrated analysis on a weekly basis in order to determine the background methane level using the equation:

$$XCH4_{fn} = k * \mu - (k - 1) * \bar{x}, \quad (1)$$

where $XCH4_{fn}$ is the background methane value, μ is the median, $\bar{x}$ is the mean of the dataset. The factor **k** in equation (1) is predetermined. For the purpose of our work we use k = 3 as a more precise value after a preliminary analysis to estimate the error. This is a very popular technique for automatic image analysis in background determination and astronomical object retrieval[6,13]. This approach is iterative (it consists of one or more iterations), since the sigma-cropping is carried out in one or more steps. The first step is to compute the standard deviation σ (Equation 2).

The standard deviation is determined using the equation:

$$\sigma_x = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n-1}}, \tag{2}$$

where $\bar{\boldsymbol{x}}$ is the mean of the dataset, x_i - the ith element of the dataset, n – the size of the dataset.

The next step is to remove all pixels that do not fall within the interval of ±3σ around the median value μ. For a result of more than 95% of the pixels in this interval, the equation (1) is applied, which gives the background value of methane for study areas. Any pixels that do not meet this condition are eliminated from further inspection.

The advantage of this approach is the relatively fast processing time performed in the R statistical and mathematical data processing environment. This is especially true when extracting information from large datasets, such as the image files acquired daily by the TROPOMI sensor.

3. RESULTS

3.1. Data availability

Summary statistics of data availability about the study areas for the research period from May 2018 to December 2022 are shown in Figure 3 (Turkmenistan) and Figure 4 (Bulgaria). The percentage of available TROPOMI satellite data for the column dry molecular fraction xCH4 over Turkmenistan ranges between 52% and 96%, with a few exceptions for the months February - April. Moreover, almost each of the images has a higher pixel density (compared to Bulgaria), and the reasons for the observed pattern has been explained above in detail. The Turkmenistan data is an excellent benchmark for tracking atmospheric methane concentrations, including determining background levels - as we have a significantly higher density of information and hence different approaches can be modelled and evaluated; estimating residence time, dissipation and methane cleanup in this area when detecting large volume emission events, etc.

Two conclusions can be drawn for the second study area (Bulgaria). First, there is no clear-cut specific period of the year with very high or very low percentages of available data. This is due to the faster dynamics of atmospheric processes and also other factors, explained above. Most satellite images here have significantly lower pixel densities compared to the first study area. This complicates the determination of atmospheric methane concentrations over Bulgaria, especially to record and quantify significant emissions with a sufficient degree of consistency, detail and unambiguity. Combining the available information with drone imagery, ground-based measurements and data derived from high spatial resolution (30-50 m), temporally and spatially consistent satellite measurements is the most effective solution.

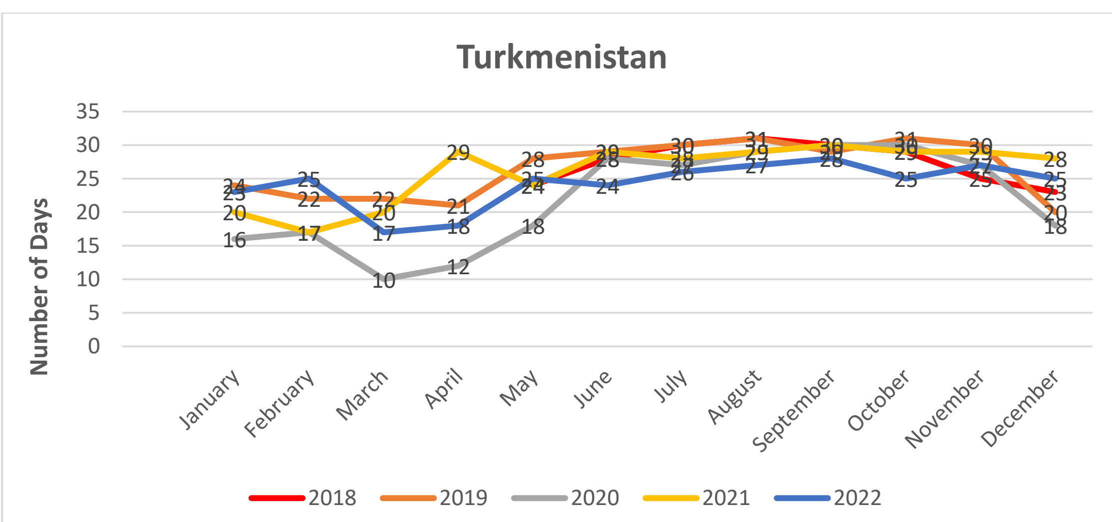

Figure 3. Number of days with methane data available from the Sentinel-5p satellite, Turkmenistan

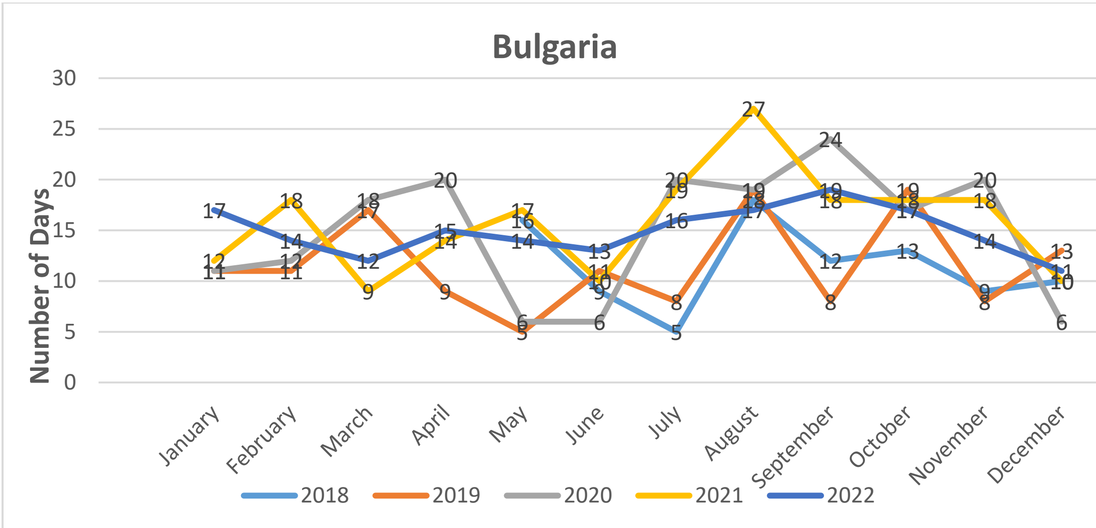

Figure 4. Number of days with methane data available from the Sentinel-5p satellite, Bulgaria

3.2. Background concentrations

The filtering procedure were applied to the data quality for the period May 2018 - December 2022 to eliminate files with low or no percentage of pixels present in the imagery, and the weekly background methane concentrations for methane were obtained as shown in Figure 5 (Turkmenistan) and Figure 6 (Bulgaria).

There is a steady increasing trend in background levels of methane in the atmosphere over the two study areas on an annual basis. Background concentrations of methane in the atmosphere over Turkmenistan (Figure 5) are higher compared to those for Bulgaria (Figure 6). Moreover, the amplitudes in monthly variations in Turkmenistan are higher compared to those in Bulgaria. This is due to the presence of several super-emitters on the territory of Turkmenistan, which periodically release huge amounts of methane into the atmosphere and thus sharply and permanently increase its concentrations. Hundreds of emission events from these sources have been recorded by Trenchev P. (2022)[7] for the study period.

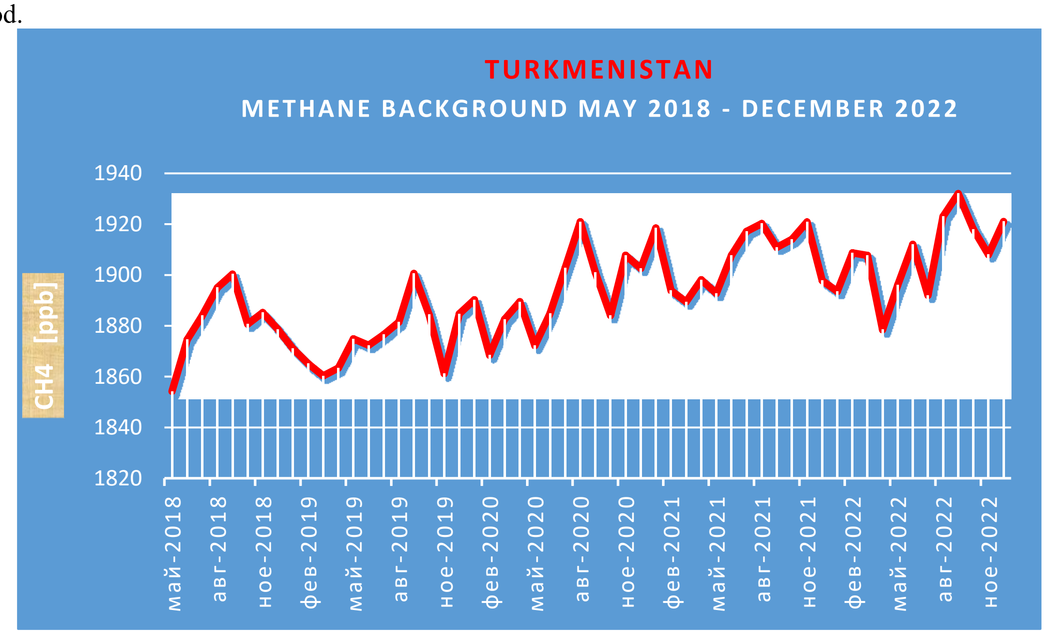

Figure 5. Background methane concentrations in the atmosphere over Turkmenistan for the period May 2018 - December 2022. Data used - Sentinel-5P.

Figure 6 illustrates the lack of clear seasonal trends in atmospheric methane concentrations over Bulgaria during the study period. Transboundary transport and, to a lesser extent, emissions from local sources are mainly responsible for the trend towards increase in background methane concentrations in the atmosphere over Bulgaria.

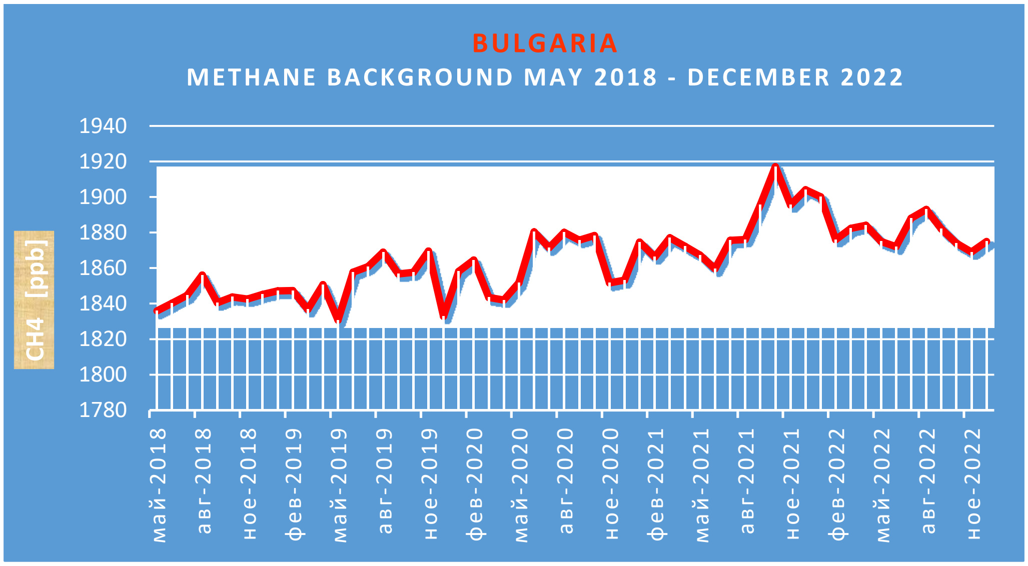

Figure 6. Background methane concentrations in the atmosphere over Bulgaria for the period May 2018 - December 2022. Data used - Sentinel-5P.

4. CONCLUSION

A method for determining atmospheric background methane concentrations is presented in this article. Knowing this key indicator allows monitoring of seasonal and annual trends, rapid identification of periodic or unintentional emissions from unregulated sources, and more. One of the advantages of the presented method is the relatively fast computational procedures in processing data from daily observations of Sentinel-5P. Our study showed that it is possible to track annual trends in methane concentrations despite the relatively low percentage of available data. The results obtained here regarding the density of available data provided by TROPOMI can be used as a basis for further studies and more accurate quantitative assessments of emissions using satellite data with high spatial resolution.

The data and results of this research will be able to serve Destination Earth (DestinE), which is an ambitious initiative of the European Union to create a digital model of the Earth that will be used for monitoring the effects of natural and human activities on our planet, prediction of extreme events and adapting policies to the climate challenges[14]. The data and models will serve the Bulgarian initiative for the construction of the Digital Twins, which is being pilot developed in the department of Aerospace Information, Space Research and Technology Institute – Bulgarian Academy of Sciences. Open Data were used in this study, with the aim of promoting the Open science policy and FAIR principles as much as possible.

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