Estimation of atmospheric methane levels over the Republic of Tatarstan (Russia) territory in 2019–2023 using satellite remote sensing data: effects of anthropogenic and climate drivers

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Abstract. Methane (CH$_4$) is the second most prevalent greenhouse gas after carbon dioxide. Its concentration in the atmosphere has been increasing at an accelerated rate in recent years, primarily attributed to anthropogenic activities. The article provides an assessment of methane concentrations over the Republic of Tatarstan (Russia) territory for a five-year period (2019–2023) using TROPOMI/Sentinel-5P data. Access to the data and key operations were conducted through the Google Earth Engine cloud platform. On average, the methane concentration was 1835±9 parts per billion (ppb) in 2019, 1854±12 ppb in 2020, 1863±9 ppb in 2021, 1868±10 ppb in 2022, and 1877±8 ppb in 2023, respectively. The average CH$_4$ concentration for the study period (2019–2023) was 1865±7 ppb. There is a steady trend of increasing annual background methane levels.

1 Introduction

Methane (CH$_4$) significantly exacerbates climate change and exerts a series of indirect impacts on human health, agricultural crop yields, and ecosystem health. As one of the most potent greenhouse gases, its direct radiative forcing renders it the second-largest anthropogenic climate influencer over the historical period. Methane accounts for approximately 30% of the global temperature increase since the Industrial Revolution. While carbon dioxide (CO$_2$) has a more prolonged impact, methane sets the pace for near-term warming, contributing to at least 25% of current anthropogenic global warming. It is crucial to highlight that over the past two centuries, the concentration of methane in the atmosphere has more than doubled, largely attributable to human activities. This rise underscores the significant impact of anthropogenic contributions to the methane budget, emphasizing the need for targeted mitigation strategies across various sectors to address this concerning trend [1-3].

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Among the primary sources of atmospheric methane, both natural and anthropogenic emissions play significant roles. Natural sources encompass freshwater ecosystems, especially wetlands, methane clathrates, geologic seepage, melting permafrost, wild animals, termites, vegetation, wildfires, and others [2].

Human activities contribute to methane emissions primarily through agriculture, energy production, and waste management. According to the Global Methane Budget [3], agriculture stands as the largest anthropogenic source, accounting for approximately one-quarter of total emissions, with significant contributions from livestock farming, rice cultivation, and animal waste. The energy sector, encompassing emissions from coal, oil, natural gas, and biofuels, represents another substantial anthropogenic source of methane emissions. Waste management practices, including landfilling and wastewater treatment, also make a significant contribution to anthropogenic methane emissions [4]. Other minor sources of anthropogenic methane emissions include gas release during the extraction and production of fossil fuels, as well as emissions from natural gas and petroleum systems, and certain industrial processes. In 2019, approximately 60% (360 million tons) of the globally emitted methane resulted from human activities, whereas natural sources accounted for about 40% (230 million tons). Consequently, anthropogenic emissions constitute a significant majority of the world’s methane emissions, with human activities contributing a substantially higher proportion compared to natural sources [1-2].

Various scientific approaches are used to assess the methane content and emissions in the atmosphere. These approaches include field measurements, atmospheric monitoring, and the development of process-based emission models. Field measurements from diverse industrial sources contribute to a better understanding of methane emission sources, facilitating the development of emission models at regional and urban scales [5]. Various field methods have been employed in research projects to measure methane emissions, considering the temporal and spatial variability of emissions from specific sources [4]. Additionally, atmospheric monitoring of methane concentrations is essential for detecting regional and global emission trends [6].

The assessment of atmospheric methane levels using satellite remote sensing data involves the observation and monitoring of methane emissions into the atmosphere. This method complements other leak detection techniques such as optical gas visualization and thermal infrared spectrometry, expanding the capabilities of contemporary emission monitoring through remote measurement of the dynamic nature of methane releases. Satellite observations of atmospheric methane are of particular interest due to their high observational density and coverage. These observations can be utilized for a quantitative assessment of methane emissions on a global scale, extending to point sources [6-8].

The scope of this study is to assess methane concentrations in the atmosphere over the Republic of Tatarstan territory during a five-year period (2019–2023) based on remote sensing data. This evaluation is conducted in the context of ongoing climate change and significant anthropogenic impact.

2 Materials and methods

2.1 Study area

Tatarstan is situated in the centre of the European part of Russia on the East European Plain, at the confluence of two major rivers – the Volga and the Kama. The total area of the republic is 67.8 thousand square kilometres, with a population of 4 million people. The capital of the Republic of Tatarstan, Kazan, is located 800 kilometres east of Moscow [9].
The territory comprises a plain in the forest and forest-steppe zones with minor elevations on the right bank of the Volga and in the southeast of the republic. Ninety percent of the territory lies at an elevation not exceeding 200 meters above sea level. Approximately 18% of the republic’s territory is covered by forests, consisting of deciduous and coniferous tree species. Tatarstan is rich in water resources, featuring four major reservoirs, 500 small rivers, and over 8000 lakes and ponds.

The climate is moderately humid continental with warm summers (classified as Dfb according to Köppen), characterized by warm summers and moderately cold winters. The warmest month is July, and the coldest is January. Recently, there has been a noted shift in climate towards warming and increased humidity.

2.2 Satellite data processing

The study relies on methane measurements in the atmosphere using the TROPOMI data (ESA Copernicus Sentinel-5P mission). The TROPOMI is a nadir-viewing imaging spectrometer, covering wavelength ranges from ultraviolet to shortwave infrared. The instrument operates in a push-broom configuration (non-scanning), with a swath width of ~2600 km on the Earth’s surface. The typical pixel size (near nadir) will be 7x3.5 km² for all spectral bands, with the exception of the UV1 band (7x28 km²) and SWIR bands (7x7 km²) [10]. Access to satellite data and primary operations were conducted using the Google Earth Engine (GEE) cloud platform [11].

2.3 Climate characteristics

To determine climatic conditions and specific meteorological characteristics, such as the amount of shortwave solar radiation reaching the study area, cloud cover, near-surface atmospheric temperature, precipitation, wind speed and direction), the ERA5 climate reanalysis was employed (generated using Copernicus Climate Change Service Information).

2.4 Data handling and analysis

For cartographic visualization of the data, QGIS 3.28 software was used. Geodetic coordinates were projected into planar rectangular coordinates in the Universal Transverse Mercator projection on the WGS-84 ellipsoid (Universal Transverse Mercator, zone 39N, EPSG:32639). Map coordinates are represented as geodetic coordinates (WGS-84, degrees and minutes north latitude and east longitude).

To visualize thematic objects (administrative boundaries, forests, agricultural lands, and water bodies etc.), a set of vector data layers, NextGIS (Russia), was purchased from OpenStreetMap and contributors, 2023 (https://data.nextgis.com). Data license: ODbL. Administrative divisions shapefiles were accessed through the open license resource geoBoundaries Global Administrative Database [12].

Statistical processing of the obtained data was carried out using Statistica 10.0 software.

3 Results and discussion

The temporal variation of near-surface air temperature in the territory of the Republic of Tatarstan from 1951 to 2023 is presented in Figure 1. The linear trend, representing the average rate of change in near-surface air temperature, indicates a warming trend over the observed period at an average rate of 0.31°C/10 years. However, from the mid-1970s
onwards, the average annual air temperature has been increasing more rapidly, with a rate of 0.52°C/10 years.

The obtained map depicting the five-year average concentration of methane in the atmosphere over the territory of the Republic of Tatarstan, based on satellite monitoring data, is presented in Figure 2.

![Fig. 1. Average annual temperature of the surface layer atmosphere (°C) on the Republic of Tatarstan territory in 1951–2023 according to the ERA5 climate reanalysis.](image1)

![Fig. 2. Average concentration of methane (ppb) in the atmosphere over the Republic of Tatarstan territory in 2019–2023 according to the TROPOMI data.](image2)
On average, the methane concentration was 1835±9 parts per billion (ppb) in 2019, 1854±12 ppb in 2020, 1863±9 ppb in 2021, 1868±10 ppb in 2022, and 1877±8 ppb in 2023, respectively. The mean CH₄ concentration over the studied period (2019–2023) was 1865±7 ppb. A stable trend of increasing annual methane background levels is observed (Figure 3). In comparison to 2019, the concentration in 2023 increased by 2.3% over the territory of the republic. Additionally, significant amplitudes of monthly variations in methane background concentrations are noticeable, with the highest values occurring in the fall and the lowest in the spring season.

**Fig. 3.** Average monthly concentration of methane in the atmosphere over the Republic of Tatarstan territory in 2019–2023 according to the TROPOMI data.

The consistently highest concentrations are observed in the vicinity of major industrial enterprises and thermal power facilities, while minimal concentrations are associated with extensive forested areas and the waters of the Kuibyshev Reservoir. Elevated methane concentrations are also characteristic of populated areas (Figure 4), encompassing both large urban centres and small rural settlements. Seasonal fluctuations in methane concentration are evident above agricultural landscapes.

In some cases, elevated concentrations in specific months exhibit a local character and are likely associated with anthropogenic activities. Nevertheless, they significantly contribute to the regional average concentration assessment. Local maxima are typically associated with the same locations, underscoring the need for attention from state environmental authorities.

It is noteworthy that information about average and maximum methane concentrations for individual months enables the identification of methane anomaly areas within the region. Considering the local nature and short duration of these anomalies, they are associated with anthropogenic activities. This allows for the detection of areas exhibiting increased concentrations indicative of critical situations, as exemplified by an accident on June 4, 2021. During an emergency repair on the Urengoy–Center 1 pipeline (Figure 5), about 2.7 million cubic meters (1,830 metric tons) of methane were released [6].

Reviewing annual and multi-year maps helps discern long-term trends in methane pollution levels in specific areas.
4 Conclusion

Thus, during the study, the methane levels in the atmosphere over the territory of the Republic of Tatarstan and the trends toward its increase were determined. Tendency in the growth of climatic characteristics were identified in the context of the changing global climate. The analysis of the obtained data suggests that the anthropogenic factor is the leading driver of the increase in methane concentration under current conditions for the studied region.

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References


