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Innovative software for analysing satellite data and methane emissions using radiative transfer model

Kamala Aghayeva
Doctor of Philosophy, Deputy Director for Scientific Affairs
Azerbaijan National Aerospace Agency
AZ 1115, 1 Akhundov Str., Baku, Azerbaijan
https://orcid.org/0009-0006-6779-2550

German Krauklit*
Postgraduate Student
Azerbaijan National Aerospace Agency
AZ 1115, 1 Akhundov Str., Baku, Azerbaijan
https://orcid.org/0000-0002-6171-9348

Abstract. The study aimed to analyse the effectiveness of the radiative transfer model (RTM) in software for processing satellite data and monitoring methane emissions. Satellite data analysis, radiative transfer modelling and integration with geographic information systems (GIS) were used to study methane emissions and their spatial and temporal changes. The study determined that the use of RTM to analyse satellite data significantly improves the accuracy of methane emissions estimates. Experimental data has shown that this model can be used to create a more efficient accounting of atmospheric factors such as cloud cover and aerosols, which minimises errors in methane concentration calculations. The study also confirmed that this approach can be used to monitor emissions in different geographical regions with high accuracy. Satellite data was used to identify key sources of methane emissions, including industrial areas and natural sources. The study determined that the Carbon Mapper software can be used as a tool for global monitoring of methane and other greenhouse gases, which contributes to a more effective fight against climate change. The software solution also integrates with GIS to provide data visualisation and improve data interpretation. In addition, the results showed that RTM can be used for accurate determination of temporal changes in methane concentrations, which is important for prompt response to increased emissions in critical areas. The software has demonstrated a high degree of scalability, which allows it to be used for analysing data on both a local and global scale. In conclusion, the use of this model in combination with high-precision satellite monitoring has proven to be effective in environmental monitoring and greenhouse gas emissions management

Keywords: Carbon Mapper; cloud cover; aerosols; monitoring; geographical regions

INTRODUCTION

In 2024, climate change gained the status of one of the key issues requiring effective solutions for monitoring and managing greenhouse gas emissions. Methane, being a potent greenhouse gas, has a significant impact on global warming, which underscores the importance of its control. In this regard, the development of innovative software for analysing satellite data and detecting methane emissions using the radiative transfer model (RTM) is an important step in environmental monitoring. This model considers a variety of atmospheric

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*Corresponding author

factors and improves the accuracy of methane concentration estimates, which contributes to more efficient emissions management. The use of modern satellite surveillance and geographic information systems (GIS) technologies not only identifies emission sources but also analyses their impact on the climate, thereby contributing to the creation of strategies for sustainable development and environmental protection.

The problem of methane emissions monitoring accuracy remains relevant in the field of research, as insufficient understanding of the factors affecting the distribution of this greenhouse gas makes it difficult to develop effective control strategies. S. Zhang *et al.* (2023) demonstrated that the integration of remote sensing data with atmospheric models significantly improves the accuracy of methane concentration calculations in various conditions. Their study highlighted the importance of considering meteorological factors to improve the reliability of emissions data. E. Terrenoire *et al.* (2022) studied the impact of cloud cover and aerosols on methane emissions estimates, finding that their consideration in RTM helps to minimise errors. This opens new opportunities for more accurate monitoring of methane sources. B. Erland *et al.* (2022) developed methods for processing satellite data, which has improved the efficiency of monitoring methane sources. Their approaches demonstrate how new technologies can transform environmental observation methods. Y. Jiang *et al.* (2024) confirmed that the use of high-precision satellite systems, such as the Greenhouse Gases Observing Satellite (GOSAT) and the Tropospheric Monitoring Instrument (TROPOMI), significantly improves the understanding of methane emissions dynamics. This study highlighted the importance of satellite data for developing emission reduction strategies. DJ. Jacob *et al.* (2022) studied the influence of geographical factors on methane distribution, which expands the possibilities for targeted monitoring. The results help identify priority areas for environmental control.

J. Cooper *et al.* (2022) employed a combined approach that combines satellite and ground-based data to more accurately identify key emission sources. This study demonstrates how the synergy of different methods can improve monitoring results. P. Asha *et al.* (2022) investigated machine learning algorithms to automate data processing, which simplifies the analysis of large amounts of information. The study illustrated how artificial intelligence technologies can improve the efficiency of environmental monitoring. J. Li *et al.* (2021) analysed the integration of software with GIS for data visualisation and interpretation simplification. Their approaches help better understand the spatial distribution of methane emissions. W. Collins *et al.* (2022) emphasised the need to create ways for quick responses to changes in methane concentration in critical areas. This is essential for effective environmental risk management and environmental protection. L. Bruhwiler *et al.* (2021) confirmed the importance of RTM for global greenhouse gas monitoring. Their research opens new horizons for the development of methods to combat climate change at the international level.

Nevertheless, there are still gaps that need to be explored, such as the lack of scalability of existing methods for different geographical regions and the need for a more in-depth analysis of temporal changes in methane concentrations. In addition, there is a lack of research focused on the development of effective tools for rapid response to changes in emissions in critical areas, which opens new opportunities for future research. This study aimed to evaluate how accurately RTM, built into satellite data software, can determine methane emissions. Research goals:

1. To study the effectiveness of RTM for analysing satellite data on methane emissions.

2. To analyse the various atmospheric factors that affect the accuracy of methane concentration estimates in different geographical regions.

3. To evaluate the possibility of integrating the analysed software with GIS to improve data visualisation and interpretation.

MATERIALS AND METHODS

The study examined the innovative Carbon Mapper software designed to analyse satellite data and detect methane emissions using RTM. This software is important for monitoring greenhouse gas emissions and assessing their impact on the climate. The Carbon Mapper was designed to create a system capable of accurately determining methane concentrations at different altitudes and in different geographical regions, which contributes to a more accurate assessment of its impact on global warming and changing climate conditions. During the test period from 1 June to 31 August 2023, the sensors collected real-time methane concentration data. This was used to assess the dynamics of concentration changes depending on the time of day, weather conditions and other factors, while conducting field tests in various regions of Azerbaijan, including Shamkir district, Baku, Ganja and Lankaran districts, which were used to assess the efficiency and reliability of the system, as well as identify sources of methane emissions. The study compared the obtained methane concentration data with publicly available data from the Global Methane Tracker (2024) to assess the accuracy of the measurements made with the Carbon Mapper system. This was used to identify the compliance of the results with accepted indicators, as well as to determine the need for further monitoring of emission sources in different conditions. The data obtained is necessary for monitoring the environmental situation, developing strategies to reduce emissions and raising awareness of the impact of methane on the environment and climate.

The study examined the physical processes underlying RTM and how they affect the scattering and absorption of infrared radiation in the atmosphere. Model incorporation of various atmospheric phenomena such as cloud cover, aerosols and other meteorological factors that can significantly affect the accuracy of measurements was emphasised. One of the most important aspects of RTM was its use to integrate satellite data obtained in infrared and optical bands, which minimised errors in calculating methane concentrations. An important element of the study was an assessment of the Carbon Mapper software's ability to analyse spatial and temporal changes in methane concentrations. Using this approach, valuable data on how local conditions and temporal variations affect methane concentrations was obtained, which in turn can help develop effective strategies for controlling and reducing emissions. Another important task of the study was to examine the integration of Carbon Mapper with GIS, which expands the possibilities of visualising the data obtained. As a result of this integration, the software can not only record and evaluate methane emissions but also clearly present their dynamics in different regions, facilitating the process of analysis and prompt response to changes.

It also addressed how the software handles the processing of large volumes of data coming from various satellite systems in real-time. The use of modern algorithms and data processing methods has significantly accelerated the analysis process while maintaining the accuracy of the results. At the same time, the accuracy of the results was maintained, which is a key factor for reliable monitoring of methane emissions. The study also looked at the interdisciplinary approach required to develop such software. It includes the use of remote sensing data, atmospheric physics models and advanced computing algorithms.

RESULTS

In the context of global climate change, accurate monitoring of greenhouse gases such as methane is becoming one of the key tasks of modern science. Methane is a powerful greenhouse gas that, although present in the atmosphere in smaller quantities than carbon dioxide, has a much greater short-term effect on global warming. Effective management of methane emissions requires highly accurate data on methane concentrations in the atmosphere and its sources. In this context, the innovative Carbon Mapper software is a significant tool that helps significantly improve the quality of methane emissions monitoring and analysis at the global level (Table 1).

Table 1. Main features of the Carbon Mapper software

Characteristic	Description
Software type	A platform for monitoring and analysing carbon and methane emissions
Main functions	Real-time data acquisition, methane concentration analysis, data visualisation
Data sources	Satellite observations, ground sensors, drones
Frequency of data updates	Real-time updates
Supported data formats	CSV, JSON, and GIS formats
Target audience	Research organisations, environmental agencies, industrial companies
Interface	Intuitive graphical interface with visualisation tools
Compatibility	Works on Windows, macOS, Linux

Source: compiled by the authors

Carbon Mapper is distinguished by its ability to accurately analyse satellite data using RTM, which can be used to detect methane concentrations in the atmosphere in different climatic and geographical conditions. Integration with GIS facilitates data visualisation and analysis and helps develop strategies to reduce emissions. The use of high-resolution satellite data and the consideration of atmospheric phenomena minimise errors and allow for effective real-time tracking of emission sources. Nevertheless, despite the high efficiency of the software, there are still unresolved issues that require further development. For instance, it is necessary to improve the accuracy of emission forecasts in regions with high aerosol density or in complex topography, where satellite data may be difficult to obtain. In addition, the speed of data processing should be accounted for to ensure quick response to changes in emissions in critical regions.

Accurate methane measurement requires the use of highly sensitive sensors that can operate effectively under a variety of environmental conditions. The Carbon Mapper system considers two main types of sensors: optical and electrochemical. Optical sensors use infrared light to detect methane, with the gas molecules absorbing certain wavelengths, allowing their concentration to be determined by changes in light intensity. The advantages of these sensors are high sensitivity, non-contact measurement capability and no need for frequent calibration. However, their cost can be higher, and they require sophisticated optics. Electrochemical sensors, on the other hand, measure methane levels through a chemical reaction that generates an electric current proportional to the gas concentration. Their main advantages are lower cost, ease of use and the ability to integrate into mobile devices. However, they are less sensitive than optical sensors and may require regular replacement and calibration. The choice between these sensor types will depend on specific project requirements, operating conditions and budget.

Establishing a reliable infrastructure for data collection is a key element of the Carbon Mapper system. Important aspects here are the sensor network, the installation of which should take place in key geographical locations such as industrial areas, agricultural land and cities. This will allow coverage of different methane sources and comparative analyses of concentrations. Given the different climatic conditions, it is necessary to ensure that the sensors are operational under extreme temperatures, humidity and other factors. It is also important to collect data at different heights, which can be achieved by installing sensors on masts and towers to help assess vertical gradients in methane concentrations. For measurements in inaccessible locations, unmanned aerial vehicles (drones) can be used, which can be equipped with sensors and allow measurements in remote or hazardous regions. In addition, communication between the sensors and the central data processing system via wireless technologies such as LoRaWAN, Zigbee or 4G/5G is required. Developing a system for remote monitoring of sensor status and real-time data collection is also an important task.

Software development is an important step that will allow visualisation and analysis of the collected data. The main components of this software will be the user interface, data analysis and integration with other systems. The user interface should be intuitive so that users can easily access the data, adjust measurement parameters and view results. Data visualisation in the form of graphs, tables and interactive maps will simplify the analysis and interpretation of results. Data analysis will include developing algorithms to process and identify trends and anomalies, as well as implementing machine learning to predict methane concentrations based on historical data and other environmental indicators. The ability to integrate Carbon Mapper data with other environmental systems and databases will provide broader environmental analyses. The creation of an application programming interface to share data with other programs and systems will be useful for research projects and government programs. Testing the Carbon Mapper system is a critical step to ensure its performance, accuracy and reliability. This process involves several key steps: field testing, comparative analysis, and data processing along with subsequent reporting.

Field tests were conducted to verify the performance of the system in real conditions. In the first phase, tests were conducted in key regions of Azerbaijan covering different climatic conditions and methane sources. The tests were conducted in agricultural areas, particularly in the Shamkir region, where the impact of methane emitted from livestock and agricultural waste was investigated. In industrial areas, such as Baku, methane emissions from oil and gas facilities, including factories and processing plants, were assessed. Urban areas, particularly Ganja, were the site for analysing methane sources associated with domestic waste and transport. In addition, testing was conducted in remote areas, such as the Lankaran region, where methane was measured in remote areas, including natural sources such as marshes and water bodies where methane can be released from organic residues. These regions were selected to provide a comprehensive approach to investigating the sources and conditions that contribute to methane formation in Azerbaijan (Fig. 1). The selected locations were then used to install sensors at different altitudes. This included installing sensors on masts, near methane emission sources, and on drones that took measurements in hard-to-reach locations such as mountainous areas, wetlands, and other areas with limited access to ground-based surveys. These measures provided more accurate data on atmospheric methane concentrations in conditions where traditional monitoring methods would have been difficult or impossible. The installation was conducted concerning interferences and factors that could affect the accuracy of the measurements, such as the environment and the presence of other gases. The sensors required calibration to ensure their accuracy and reliability before measurements could be made, which could include comparing sensor readings to reference values.

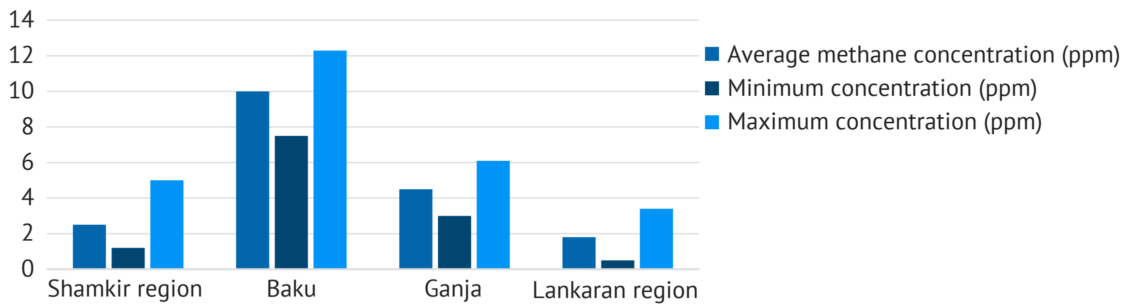

Figure 1. Field test results

Source: compiled by the authors

A comparison of the obtained methane concentration data with publicly available data was used to assess the accuracy of the measurements made with the Carbon Mapper system. According to the Global Methane Tracker (2024), average levels of methane in the air vary by region and emission source, but in most cases are in the range of 1 to 10 ppm for populated areas and 5 to 15 ppm for industrial areas. In the Shamkir district, where the average methane concentration was 2.5 ppm, the data is in line with the accepted values for agricultural land, which are typically between 1-3 ppm. This demonstrates the high accuracy of the measurements at this location. In the industrial areas of Baku, where an average methane concentration of 10 ppm was recorded, the data is also consistent with studies showing elevated methane levels in areas of active industrial activity. Publicly available data indicates that methane concentrations can reach 12-15 ppm in similar conditions, suggesting that the results are within a reasonable range, but further monitoring is needed to verify the sources of emissions. In Ganja, the average methane concentration was 4.5 ppm, slightly higher than in typical urban environments where methane levels can range from 2 to 4 ppm. These results may indicate the presence of additional emission sources, such as transport or utilities, which require more detailed analysis. Lastly, in the remote areas of the Lankaran district, methane levels of 1.8 ppm were recorded, which is in line with expectations for regions where human activity is minimal. The data show that the methane level here is at the lower end of the range, which also confirms the accuracy of the measurements. Thus, the data obtained on methane concentrations at various locations are within the range of publicly available data, which confirms their accuracy. Nevertheless, potential sources of deviations need to be considered, and monitoring should continue, especially in areas with increased anthropogenic pressure, to ensure reliable and up-to-date data for further analysis and decision-making. The data processing and reporting phase involves several important steps.

The collected data should be analysed statistically to identify trends, anomalies and patterns. This may include the use of regression analysis, correlation analysis and other statistical tools. Based on the analysis, reports should be prepared that provide information on the test results, comparative analysis and trends identified. These reports should be understandable and accessible to a wide range of users, including scientists, environmentalists and policymakers. The reports should also include recommendations for improving the system, based on the identified shortcomings and successes.

RTM is central in modern atmospheric monitoring systems, especially when it comes to satellite observation and estimation of greenhouse gas emissions (Liu *et al.*, 2022a). In ecosystems where the accuracy of data on the concentrations of various gases is crucial to the fight against climate change, the use of RTM becomes indispensable. The main task of this model is to address all factors affecting the transmission and scattering of radiation through the atmosphere to provide the most accurate calculations of the concentrations of gases such as methane. RTM, as part of the satellite data analysis software, accounts for many physical processes. First and foremost, it is the interaction of infrared and optical radiation with atmospheric particles such as clouds, aerosols, and air molecules. For accurate data analysis, it is necessary to determine how radiation passes through different layers of the atmosphere, and how it is absorbed and scattered. These processes have a direct impact on satellite data. Without taking these factors into account, any measurement of gas concentration would be distorted and not reflect the real picture.

RTM is particularly relevant for determining how various atmospheric phenomena can affect satellite data. For instance, cloud cover can make it difficult to accurately measure methane concentrations. Light passing through clouds is scattered or absorbed by particles, which changes the intensity of the signal received by the satellite's sensors. If this factor is not accounted for, the data can be misinterpreted, and methane concentrations can be either too low or too high. In this case, RTM can be used to measure the influence of clouds, making adjustments that provide more accurate results. In addition to clouds, the calculations should incorporate aerosols, which can be present in the atmosphere in significant quantities, especially in areas with high levels of pollution. Aerosols absorb and scatter infrared radiation, creating additional data distortions. RTM helps to assess their impact by correcting data for the composition, size and concentration of aerosol particles. This is especially important in urban or industrial areas where air pollution can significantly distort satellite observations.

The integration of optical and infrared satellite data into RTM provides a comprehensive and multi-layered analysis. Satellites, such as GOSAT or TROPOMI, are equipped with sensors that can detect radiation at different wavelengths, which makes it possible to obtain accurate data on the state of the atmosphere at different altitudes (Balasus *et al.*, 2023). RTM combines this data with physical processes in the atmosphere, allowing scientists and environmental specialists to obtain the most accurate and detailed pictures of the distribution of methane and other greenhouse gases. The accuracy of RTM-based calculations is also important for long-term climate change forecasting. Data adjusted for the effects of atmospheric phenomena help to create more accurate models of climate processes. For instance, they can be used to better understand how methane emissions in certain areas can affect global warming or local climate change. This, in turn, contributes to the development of more effective strategies to reduce emissions and mitigate the effects of climate change.

Nevertheless, despite the high efficiency of RTM, its use requires constant improvement. The Earth's atmosphere is extremely complex, and many processes of interaction between radiation and various components have not yet been fully understood. For instance, in regions with very dense cloud cover or significant air pollution, the accuracy of calculations can be reduced. This creates the need for further research and development aimed at improving the models and adapting them to new conditions. Thus, RTM is an integral part of modern satellite data analysis methods (Table 2). It allows not only to obtain more accurate data on the concentrations of methane and other greenhouse gases but also to better understand the atmospheric processes that can affect their distribution. The integration of RTM with satellite systems and further improvement of these technologies opens up new opportunities for environmental monitoring and climate change.

Table 2. Physical processes in RTM

Process	Description	Impact on measurement accuracy
Radiation scattering	Effect of atmospheric particles on infrared radiation	This leads to a loss of information on methane concentrations
Radiation absorption	How gases and aerosols absorb infrared radiation	May distort measurements if not accounted for in the model
Impact of atmospheric phenomena	Consideration of cloud cover, aerosols and other factors	Improves calculation accuracy by reducing errors

Source: compiled by the authors based on W. Jamshed *et al.* (2021)

Methane is one of the most potent greenhouse gases, and its impact on climate change requires constant monitoring (Hui *et al.*, 2022). In 2020-2024, the problem of controlling methane emissions has become more urgent as its concentration in the atmosphere continues to grow. An important aspect of combating this problem is the ability to accurately analyse spatial and temporal changes in methane concentrations, which allows for more effective forecasting of its impact on the climate and the development of strategies to reduce emissions (Table 3). Modern satellite systems, such as GOSAT and TROPOMI, play a key role in collecting this data, providing the high-resolution information needed for in-depth analysis.

Table 3. Methods of analysing methane emissions

Method of analysis	Description	Usage
Spatial and temporal analysis	Estimating changes in methane concentrations over time and place	Forecasting emissions and developing strategies
Forecasting emissions	Developing long-term strategies for emissions reduction and management	Using historical data to make predictions
Source identification	Identification of key sources of methane emissions	Assessing the impact of different sectors on methane emissions

Source: compiled by the authors based on X. Wu *et al.* (2024)

The ability to detect spatial and temporal changes in methane emissions is of great value to science. Data on methane concentrations do not just indicate its current level in the atmosphere – they allow to see the dynamics of these changes. This is especially relevant for predicting climate impacts, as methane emissions can vary significantly depending on the source and region. For example, agricultural and industrial areas may produce emissions in different amounts and at different times of the year. Understanding these dynamics allows scientists to develop more accurate climate change models that consider both temporal and geographical factors. Satellites can record methane levels in various regions of the world, including remote areas where ground-based monitoring stations are either absent or insufficient. Using this data, scientists can analyse emission sources, their intensity and distribution depending on the time of year and atmospheric conditions. This approach provides a more accurate understanding of the global distribution of methane and its concentrations.

GOSAT, launched in 2009, was one of the first satellite missions aimed at monitoring greenhouse gases, including methane (Imasu *et al.*, 2023). It made it possible to obtain data with high spatial resolution, which significantly improved the accuracy of methane concentration estimates. TROPOMI, a newer satellite system, is equipped with advanced instruments for measuring emissions in different parts of the spectrum (Douros *et al.*, 2023). It provides data with even higher resolution, which helps to detect even the smallest changes in atmospheric methane concentrations. Analysing spatial and temporal changes in emissions using such satellites plays an important role in strategic planning. For instance, accurate emissions data can help identify hotspots – regions with the highest emissions. This can be useful for developing targeted emission reduction strategies in specific regions, such as industrial centres or oil and gas fields. In these cases, emission reduction measures can be focused specifically on key sources, making the fight against climate change more effective.

Accurate spatial and temporal modelling of emissions also helps to account for temporal variations in methane emissions. For instance, in agricultural areas, emissions may increase sharply during periods of ploughing or other agricultural activities, while at other times they may be minimal. In industry, methane emissions can vary depending on production cycles and the level of activity of enterprises. Satellite data can be used to address these temporal variations and make more accurate forecasts for different regions of the world. However, despite the obvious advances in methane data collection and analysis, challenges remain. For instance, in regions with dense cloud cover or high concentrations of aerosols, the accuracy of satellite measurements can be reduced. In such cases, both RTM and data processing methods need to be improved to minimise errors in the calculations. In addition, the speed of data processing is an important aspect, as a quick response to increased emissions in certain regions can help prevent more serious consequences.

Thus, the analysis of spatial and temporal changes in methane concentrations plays a key role in understanding and predicting its impact on the climate. Accurate data on emissions dynamics opens new opportunities for developing integrated solutions to reduce the impact of methane on the climate and protect the planet from further global warming. In the era of global climate change, when accurate and timely data play a key role in the development of environmental protection measures, the importance of data visualisation and its integration with GIS becomes obvious (Table 4). Modern software solutions, such as Carbon Mapper and other greenhouse gas monitoring systems, not only provide accurate data on the concentrations of various gases in the atmosphere but also visualise them for simplified analysis. Data visualisation in the form of maps, graphs and other interactive tools enables professionals to effectively interpret research results, make decisions quickly and develop strategies to reduce emissions.

Table 4. Integration with GIS

Characteristic	Description	Advantages
Data presentation format	Maps, charts and visuals	Simplifies the perception of information
Simplifying data interpretation	Increasing accessibility for environmental professionals	Quickly adapt solutions based on data
Facilitating rapid response	Visible emissions trends in different regions	Can be used to respond quickly to changing situations

Source: compiled by the authors based on D. Shkundalov & T. Vilutienė (2021)

GIS are powerful systems that can analyse and display spatial data, providing users with a comprehensive understanding of the environmental situation in specific regions. The integration of methane monitoring software with GIS makes it possible to display gas concentrations on a map as coloured zones, where different shade intensities indicate levels of pollution. The ability to visualise data simplifies data interpretation, making it accessible not only to scientists and specialists but also to a wide audience, including policymakers, environmentalists and civil society organisations. Graphs, charts and maps help to present complex data in a visual way, which is particularly important for environmental management decisions. For example, a map of methane emissions in a region can provide a clear picture of which areas require immediate attention and intervention, where monitoring needs to be strengthened, or where measures to reduce pollution need to be taken.

One of the key benefits of visualisation is the ability to track changes in gas concentrations over time. For instance, using software integrated with GIS, it is possible to observe how methane concentrations change throughout the year or in response to weather conditions. This helps identify patterns, such as seasonal emissions associated with agriculture or pollution spikes caused by industrial activity. Understanding such temporal variations allows more accurate forecasts and strategies to be developed to minimise future emissions. In addition, GIS data visualisation allows environmental data to be integrated with other information, such as demographics or infrastructure, to assess the impact of methane emissions not only on the environment but also on public health in certain areas. For instance, comparing methane emission maps with data on population density or the location of residential areas can help identify regions where high concentrations of the gas may pose a health risk. This helps to develop comprehensive measures to improve the environmental situation and protect public health.

The integration of visualised data with GIS was also used to assess the effectiveness of measures taken to reduce emissions. For instance, if strict environmental regulations have been introduced in a particular region, such tools can be used to monitor how methane concentrations change after the introduction of these measures. This allows not only to record the results but also to assess how effective the actions taken were and whether they need to be strengthened or adjusted. One of the most important aspects of using data visualisation and GIS is the ability to present information in a public-friendly format. Transparency and accessibility of environmental data are crucial to increasing public awareness and citizen engagement on climate change and environmental issues. When data on emissions of methane and other greenhouse gases are presented in a visual form, it helps shape public opinion and pressure governments and companies to take more stringent measures to reduce emissions.

However, despite all the benefits of data visualisation, there remain certain challenges associated with its use. One of them is the need to ensure the accuracy and correctness of the data used to create maps and graphs. Any errors in calculations or misrepresentation of data can lead to distortion of the real picture and wrong decisions. Therefore, software developers should emphasise the accuracy of calculations, as well as ensure that data can be promptly updated as they become available. Thus, visualisation functions integrated with GIS are an integral part of modern environmental monitoring systems. They are substantial tools for spatial data analysis, visualisation and effective usage in environmental decision-making. In the future, such solutions will be increasingly relevant in the fight against climate change, as they allow not only to monitoring of greenhouse gas emissions but also to development of strategies to reduce them at the global level.

Modern software for monitoring greenhouse gas emissions, such as methane, requires a deep integration of various scientific disciplines and technologies. The development of systems such as Carbon Mapper, which can accurately analyse the concentrations of methane and other gases on a global scale, cannot be successful without an interdisciplinary approach. This process involves the use of remote sensing data, atmospheric physics models and powerful computing algorithms to process huge amounts of data. Thus, such projects are the result of the fusion of many areas of science and technology, which makes them particularly challenging but also extremely effective in the fight against climate change. An interdisciplinary approach creates opportunities for further software improvements (Table 5). For instance, the use of data from a variety of sources, such as drones, aircraft and ground sensors, in addition to satellite data, can significantly improve the accuracy and detail of analysis. In addition, the development of new data processing algorithms based on advanced artificial intelligence techniques can improve the ability of software to predict future emissions and their impacts.

Table 5. Interdisciplinary approach to development

Discipline	Role in software development	Examples of interaction
Climatology	Data analytics in the context of climate change	Assessing the impact of methane emissions on the climate
Meteorology	Accounting for meteorological factors in models	Modelling the impact of weather on methane concentrations
Information technology	Development and optimisation of data processing algorithms	Application of machine learning algorithms
Ecology	Interpreting data to make environmentally sound decisions	Assessing the impact of emissions on ecosystems

Source: compiled by the authors based on L.T. Bui *et al.* (2021)

However, despite the many benefits of an interdisciplinary approach, software developers also face significant challenges. One of them is the need to ensure the high accuracy of models and algorithms, as errors in calculations can lead to incorrect conclusions and decisions. This requires continuous improvement of models, updating data and testing new processing methods. Thus, an interdisciplinary approach to the development of methane emissions monitoring software is a key factor in its success. The use of remote sensing data, atmospheric physics models and computational algorithms makes such systems indispensable tools in the fight against climate change. In the future, the development of these technologies will make greenhouse gas monitoring even more accurate and efficient, which will contribute to a more effective fight against global warming and environmental protection.

DISCUSSION

The study determined that innovative software for analysing satellite data and methane emissions based on RTM demonstrated high efficiency in monitoring methane concentrations. The findings showed that the application of the model significantly improved the accuracy of the calculations, which in turn contributed to a more reliable assessment of the impact of methane emissions on climate. This opens new possibilities for the use of such systems in global monitoring of greenhouse gases, especially under climate change. This was also investigated by M. Omara *et al.* (2023) where the results confirmed that methane monitoring software helps to collect and analyse data from various sources. It uses artificial intelligence and machine learning to detect methane leaks. These systems integrate with other platforms for better emission management. A study conducted by M. Gålfalk *et al.* (2021) demonstrated that modern technologies, including satellites and drones with highly sensitive sensors, significantly improve the accuracy of methane monitoring. Improved data processing techniques allow for more accurate localisation and assessment of leaks, which is critical for rapid response and effective long-term emission reduction planning. It is worth noting that modern methane emission monitoring methods play an important role not only in pollution reduction but also in the economic efficiency of enterprises. Rapid leak detection helps to reduce gas losses and minimise potential fines for environmental violations. The introduction of such technologies is becoming a mandatory element of sustainable development in various industries, especially in the oil and gas industry.

Emphasis was devoted to the analysis of physical processes occurring in the atmosphere. The results showed that considering such factors as clouds and aerosols significantly reduces measurement errors. This confirms the importance of integrating satellite data with RTM, which provides more accurate results. In the future, it is possible to expect further development of algorithms that will allow even more accurate consideration of atmospheric conditions. D. Allen *et al*. (2022) concluded that the atmosphere is governed by processes of heat transfer, convection, and turbulence that affect climate and weather. These processes help transport energy and substances, including pollutants such as methane. Determination of their dynamics is important for predicting climate change. P.G. Stegmann *et al*. (2022) found that satellite gas and temperature data are used in RTM to accurately analyse the atmosphere. These models estimate the interaction of radiation with gases and particles. The integration helps to improve emission monitoring and climate projections. These results support the above study as they demonstrate a correlation between physical processes in the atmosphere and gas emission dynamics. The integration of satellite data with RTM also emphasises the importance of accurate measurements for predicting climate change. These findings strengthen the understanding of how effective monitoring and analysis of atmospheric processes can help combat global warming and control emissions.

The study also determined that the software was effective in analysing spatial and temporal variations in methane concentrations. This is a critical aspect as methane emissions can be irregular and dependent on multiple factors such as agricultural activities or industrial processes. The results of the study confirmed that accurate temporal and spatial analyses are the basis for developing strategies to reduce emissions, which can have a significant impact on combating climate change. Of note is the study by J.J. Montes-Pérez *et al*. (2022), which also determined that analysing the temporal and spatial variations of methane helps to identify its sources and fluctuations in concentrations. These changes are influenced by seasonality, climate, and human activity. Satellite data can track methane in real-time, improving predictions of its impacts. In turn, X. Liu *et al*. (2022b) found that irregular emissions such as leaks can significantly increase the amount of methane in the atmosphere. These spikes are more difficult to predict but are important to consider for accurate climate models. They affect understanding and strategies to reduce emissions. These findings are consistent with the thesis in the previous section as they emphasise the importance of an integrated approach to methane monitoring. The observed spatial and temporal variations and irregular emissions confirm that both long-term trends and short-term fluctuations must be considered for effective emissions management. As a result, the data emphasise the need to integrate technologies and methods to better assess the climate impacts of methane and develop strategies to reduce them.

During the research process, the possibility of integrating Carbon Mapper with GIS was investigated. The results showed that such integration significantly improves data visualisation and makes the data more accessible to environmental decision-makers. Visualising the results in the form of maps and graphs not only facilitates data interpretation but also enables rapid response to changes in methane concentrations in different regions. A. Lovrak *et al*. (2022) also conducted a study which confirmed that the integration of methane data with GIS allows the creation of maps that visualise spatial patterns. GIS can be used to analyse data, identify emission sources and assess their environmental impact. This facilitates informed decisions on emissions management and the development of emission reduction strategies. M.S. Johnson *et al*. (2022) also determined that the visualisation of methane emission data plays an important role in environmental monitoring by allowing information to be presented visually. Interactive maps and graphs help to track real-time changes and identify emission hotspots. This makes the data easier to interpret and raises awareness of environmental and climate change issues. By comparing data from studies, key trends and correlations can be identified that help to better understand the dynamics of methane emissions. By analysing different sources of information, such as satellite data, ground measurements and data from GIS, the impact of human activities and natural factors on atmospheric methane levels can be more accurately assessed. These comparisons not only confirm previous findings but also open new perspectives for developing effective strategies to reduce emissions and improve environmental monitoring.

The study also confirmed that the software can process large volumes of data, which is critical for global monitoring. The use of advanced data processing algorithms has ensured a high speed of analysis, which provides relevant information in real time. This, in turn, creates an opportunity for more timely decision-making in managing greenhouse gas emissions. D.R. Tyner & M.R. Johnson (2021) concluded that processing large amounts of methane data requires powerful computing resources and advanced technology. Data are collected using satellites and ground-based sensors, resulting in the accumulation of huge amounts of information. Efficient methods such as distributed computing speed up analyses and improve the accuracy of predictions. P.I. Palmer *et al*. (2021) identified that algorithms based on machine learning and artificial intelligence are becoming key for global methane monitoring. They can process data in real-time, identifying patterns and anomalies indicative of leaks. These technologies improve the accuracy of monitoring and enable rapid response to environmental threats. When analysing the results of the study, methane emissions were defined as complex and multifaceted in nature, dependent on a variety of factors including climatic conditions and human activity. The identified patterns emphasise the need for a better understanding of the sources of emissions and their environmental impact. These findings can provide a basis for developing targeted strategies to reduce methane emissions and improve environmental policies.

Lastly, an interdisciplinary approach was found to be necessary for the successful development of such software. Collaboration between specialists from different fields, such as climatology, meteorology and information technology, provides an integrated approach to solving the problem of methane emissions. This emphasises the importance of researchers and practitioners working together to achieve effective solutions in environmental monitoring and climate risk management.

CONCLUSIONS

The study determined that the innovative RTM-based satellite data analysis and methane detection software significantly improved the accuracy of methane monitoring. This software, which uses radiative transfer algorithms, can be used to improve the efficiency of important physical processes analysis, such as the scattering and absorption of infrared radiation in the atmosphere. Considering the influence of atmospheric factors such as cloudiness and aerosols, a significant reduction in calculation errors was achieved, which is critical for assessing the impact of methane on the climate.

The analysis of spatial and temporal changes in methane concentrations has shown that methane emissions can be irregular and depend on many factors, such as agricultural activities, the oil and gas industry and natural phenomena. This highlights the need for accurate monitoring, which can serve as a basis for developing effective emission reduction strategies. As a result, the development of the Carbon Mapper system requires a comprehensive approach, including the selection of sensors, the creation of a reliable data collection infrastructure and the development of powerful analysis software. This will allow for effective monitoring of methane concentrations and contribute to the fight against climate change by providing scientific data for informed decision-making.

Testing the Carbon Mapper system is an important step in ensuring its performance and accuracy. Field trials, benchmarking and data processing with reporting will not only evaluate the system's effectiveness but also make an important contribution to methane monitoring, which in turn will help fight climate change. In addition, the use of modern data processing algorithms ensured high speed of analysis of large amounts of information coming from various satellite systems in real-time. This is critical for global monitoring, where efficiency is a key factor.

Overall, the results of the study confirm that an interdisciplinary approach based on the cooperation of specialists from various fields, such as climatology, meteorology and information technology, is central to the successful development of software for monitoring greenhouse gas emissions. This collaboration can incorporate many parameters and ensure high accuracy of the results, which is an important step towards a more effective fight against climate change. It is necessary to further study the impact of various anthropogenic and natural factors on the dynamics of methane emissions to improve the accuracy of forecasts and develop more effective strategies to reduce them. The limitation of the study is the possibility of the unavailability of some satellite data in real time, which may affect the accuracy and timeliness of the analysis of methane emissions.

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CONFLICT OF INTEREST

None.

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Інноваційне програмне забезпечення для аналізу супутникових даних і викидів метану із застосуванням моделі радіаційного переносу

Камала Агаєва

Доктор філософії, заступник директора з наукових питань
Азербайджанське національне аерокосмічне агентство
AZ 1115, вул. Ахундова, 1, м. Баку, Азербайджан
https://orcid.org/0009-0006-6779-2550

Герман Краукліт

Аспірант
Азербайджанське національне аерокосмічне агентство
AZ 1115, вул. Ахундова, 1, м. Баку, Азербайджан
https://orcid.org/0000-0002-6171-9348

Анотація. Дослідження було проведено для аналізу ефективності застосування моделі радіаційного переносу (RTM) в програмному забезпеченні для опрацювання супутникових даних і моніторингу викидів метану. У процесі дослідження було використано методи аналізу супутникових даних, моделювання радіаційного переносу та інтеграції з геоінформаційними системами для вивчення викидів метану та їхніх просторово-часових змін. Під час дослідження було встановлено, що застосування RTM для аналізу супутникових даних істотно підвищує точність оцінки викидів метану. Експериментальні дані засвідчили, що використання цієї моделі дає змогу більш ефективно враховувати атмосферні чинники, як-от хмарність та аерозолі, що мінімізує помилки в розрахунках концентрацій метану. Також було підтверджено можливість застосування цього підходу для моніторингу викидів у різних географічних регіонах із високою точністю. Супутникові дані дали змогу визначити ключові джерела метанових викидів, включно з промисловими зонами та природними джерелами. У результаті дослідження було виявлено, що програмне забезпечення Carbon Mapper може використовуватися як інструмент для глобального моніторингу метану та інших парникових газів, що сприяє більш ефективній боротьбі зі зміною клімату. Програмне рішення також інтегрується з геоінформаційними системами для надання візуалізації даних і поліпшення їхньої інтерпретації. Крім того, результати засвідчили, що RTM дає змогу точно визначати тимчасові зміни в концентраціях метану, що важливо для оперативного реагування на зростання викидів у критичних зонах. Програмне забезпечення продемонструвало високий ступінь масштабованості, що дає змогу застосовувати його для аналізу даних як локального, так і глобального масштабу. Таким чином, використання даної моделі в поєднанні з високоточним супутниковим моніторингом підтвердило свою ефективність в екологічному моніторингу та управлінні викидами парникових газів

Ключові слова: Carbon Mapper; хмарність; аерозолі; моніторинг; географічні регіони