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Greenhouse Gas Emission Monitoring: Technologies, Challenges and Future Development

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ABSTRACT

Greenhouse gas (GHG) emission monitoring is a core link in global carbon neutrality and climate change response, which provides accurate data support for emission accounting, policy formulation and emission reduction effect evaluation. This paper systematically elaborates the main technical systems of greenhouse gas emission monitoring, including ground-based in-situ monitoring, remote sensing monitoring and mobile monitoring technologies, and analyzes the technical characteristics, application scope and accuracy of different monitoring methods. On this basis, the key challenges faced by current GHG emission monitoring are discussed, such as the low monitoring accuracy of small and medium-sized emission sources, the high cost of long-term continuous monitoring, the insufficient integration of multi-source monitoring data and the lack of unified global monitoring standards. Finally, the future development trends of GHG emission monitoring technology are prospected, including the miniaturization and intellectualization of monitoring equipment, the networking of monitoring stations, the high precision of remote sensing monitoring and the construction of global unified monitoring data platforms. This study aims to provide theoretical and technical references for the optimization and improvement of greenhouse gas emission monitoring systems in various countries.

KEYWORDS

Greenhouse gas emission; Emission monitoring; Monitoring technology; Carbon neutrality; Climate change.

1. INTRODUCTION

Greenhouse gas emissions, dominated by carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are the primary driving factors of global climate change and extreme weather events [1]. In response to the severe challenges of climate change, more than 190 countries and regions have signed the Paris Agreement, committing to controlling the global average temperature rise within 2℃ compared with the pre-industrial period, and striving to limit the temperature rise to 1.5℃ [2]. To achieve this goal, accurate, real-time and comprehensive greenhouse gas emission monitoring is an indispensable prerequisite. It not only provides reliable data for national greenhouse gas inventory accounting, but also is the basis for verifying the effectiveness of emission reduction measures and carrying out international carbon emission trading.

With the continuous advancement of global carbon neutrality goals, the demand for greenhouse gas emission monitoring is increasing, and the requirements for monitoring accuracy and coverage are also constantly improved. However, the current greenhouse gas emission monitoring system still has many deficiencies, especially for the monitoring of scattered small and medium-sized emission sources and mobile emission sources, the technical means are relatively backward. This paper combs the current mainstream greenhouse gas emission monitoring technologies, analyzes the existing problems, and looks forward to the future development direction, hoping to promote the innovation and application of greenhouse gas emission monitoring technology.

2. MAIN TECHNOLOGIES OF GREENHOUSE GAS EMISSION MONITORING

Greenhouse gas emission monitoring technology has formed a multi-level system including ground-based in-situ monitoring, remote sensing monitoring and mobile monitoring after decades of development. Each monitoring technology has its own technical characteristics and application scenarios, and they complement each other to form a comprehensive greenhouse gas emission monitoring network, the diagram of system framework is shown in Fig. 1.

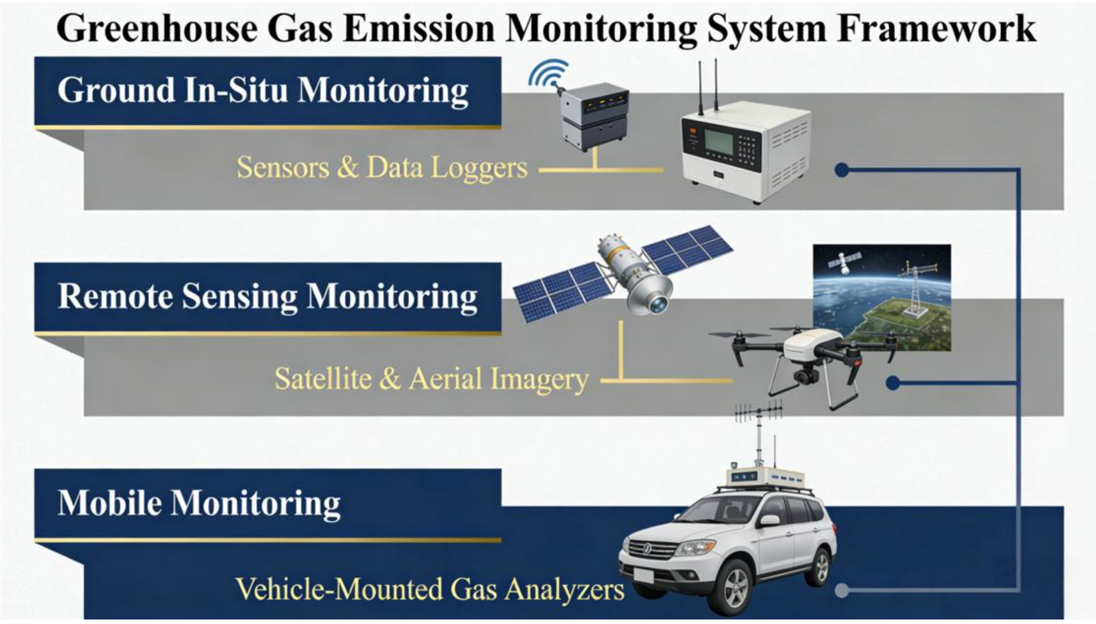

Fig. 1. Greenhouse Gas Emission Monitoring System Framework

2.1. Ground-based In-situ Monitoring Technology

Ground-based in-situ monitoring is the most traditional and mature greenhouse gas emission monitoring technology, which realizes the real-time monitoring of greenhouse gas concentration and emission flux by setting fixed monitoring stations at key emission sources (such as power plants, steel plants, chemical plants and landfills) [3]. The core equipment of this technology includes gas analyzers based on non-dispersive infrared spectroscopy (NDIR), cavity ring-down spectroscopy (CRDS) and tunable diode laser absorption spectroscopy (TDLAS). Among them, TDLAS technology has the advantages of high detection accuracy, fast response speed and strong anti-interference ability, and is widely used in the continuous monitoring of high-concentration greenhouse gas emission sources.

Ground-based in-situ monitoring can obtain continuous and high-precision monitoring data of fixed emission sources, and is the main technical means for the accounting of large-scale greenhouse gas emission sources at present. However, this technology has high construction and operation costs, and it is difficult to carry out large-scale layout for scattered small and medium-sized emission sources, resulting in monitoring blind areas.

2.2. Remote Sensing Monitoring Technology

Remote sensing monitoring technology realizes the large-scale and regional greenhouse gas emission monitoring by detecting the greenhouse gas concentration in the atmosphere through satellites, aircraft and other remote sensing platforms, and inversing the emission flux combined with meteorological data [4]. Satellite remote sensing monitoring has the advantages of wide coverage, global scale and long-term continuous observation, and is the main technical means for global greenhouse gas emission monitoring and regional emission source positioning. The typical satellite systems include NASA's Orbiting Carbon Observatory (OCO-2), the European Space Agency's Sentinel-5P and China's Gaofen-5 satellite. The Fig. 2. visualizes their orbital coverage and the corresponding spatial pattern of atmospheric CO_2 concentration.

Airborne remote sensing monitoring makes up for the deficiency of satellite remote sensing in spatial resolution, and is suitable for the fine monitoring of regional greenhouse gas emission sources (such as urban agglomerations and industrial parks). However, remote sensing monitoring technology is easily affected by meteorological conditions (such as clouds, fog and rain), and the inversion accuracy of emission flux needs to be further improved, especially for the small and medium-sized emission sources with low emission intensity.

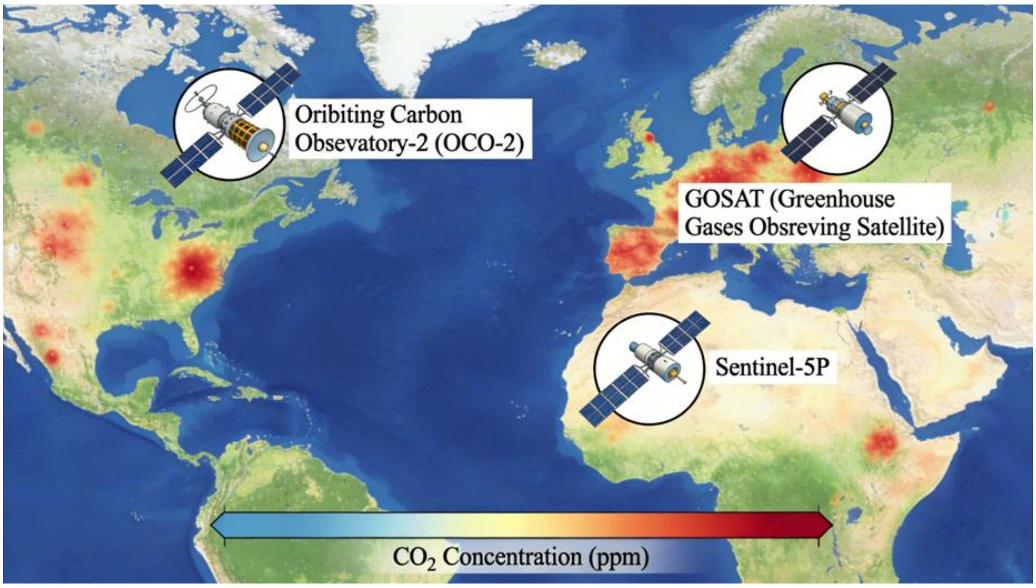

Fig. 2. Global Distribution of Greenhouse Gas Monitoring Satellites and the atmospheric CO_2 Concentration

2.3. Mobile Monitoring Technology

Mobile monitoring technology is a new type of greenhouse gas emission monitoring technology developed in recent years, which loads greenhouse gas detection equipment on vehicles, ships and drones to realize the mobile monitoring of scattered emission sources and unknown emission sources [5]. Drone mobile monitoring has the advantages of flexible operation, high spatial resolution and low cost, and is especially suitable for the monitoring of greenhouse gas emission sources in complex terrain areas (such as mountainous areas, coastal areas) and inaccessible areas (such as high-altitude industrial pipelines and remote landfills).

Vehicle-mounted mobile monitoring can realize the continuous monitoring of greenhouse gas concentration in urban roads and industrial zones, and quickly locate the abnormal emission sources. Mobile monitoring technology has become an important supplement to ground-based in-situ monitoring and remote sensing monitoring, effectively reducing the monitoring blind areas of greenhouse gas emission sources.

3. TECHNICAL CHARACTERISTICS AND APPLICATION COMPARISON OF GHG MONITORING METHODS

Different greenhouse gas emission monitoring methods have obvious differences in technical characteristics, monitoring accuracy, application scope and operation cost. The rational selection of monitoring methods according to the characteristics of emission sources is the key to improving the efficiency and accuracy of greenhouse gas emission monitoring.

3.1. Comparative Analysis of Monitoring Technologies

The table 1 shows the comprehensive comparison of the main greenhouse gas emission monitoring technologies, including the core technical principles and monitoring accuracy . This table can provide a clear reference for the selection of greenhouse gas emission monitoring methods in different scenarios.

Table 1. Comparison of different GHG monitoring technologies

Monitoring Technology	Core Principle	Monitoring Accuracy	Main Advantages
Ground-based In-situ	TDLAS spectroscopy	CO_2: ±1 ppm; CH_4: ±0.1 ppm	High precision, real-time data
Satellite Remote Sensing	Infrared spectroscopy	CO_2: ±2 ppm; CH_4: ±0.3 ppm	Wide coverage, global scale
Drone Mobile Monitoring	NDIR/CRDS spectroscopy	CO_2: ±1.2 ppm; CH_4: ±0.15 ppm	Flexible, low cost, high resolution

3.2. Selection Principle of Monitoring Methods

The selection of greenhouse gas emission monitoring methods should follow the principles of source adaptation, accuracy matching and cost optimization. For large fixed emission sources with high emission intensity (such as thermal power plants with annual CO_2 emissions of more than 1 million tons), ground-based in-situ monitoring technology with high precision and continuous monitoring should be selected to ensure the accuracy of emission data accounting. For global and regional greenhouse gas emission monitoring and regional emission source positioning, satellite remote sensing monitoring technology should be the main method, supplemented by airborne remote sensing monitoring.

For scattered small and medium-sized emission sources (such as small chemical plants, rural biogas plants) and emission sources in complex terrain areas, mobile monitoring technology (drone or vehicle-mounted) with low cost and flexible operation should be selected to reduce monitoring blind areas. In practical applications, it is necessary to combine multiple monitoring technologies to form a multi-source and multi-scale greenhouse gas emission monitoring system, so as to realize the full coverage and high precision of monitoring.

4. KEY CHALLENGES FACED BY GREENHOUSE GAS EMISSION MONITORING

Although greenhouse gas emission monitoring technology has made great progress, with the continuous improvement of global carbon neutrality requirements, the current monitoring system still faces many key challenges in technical application, data integration and standardization construction, which restrict the improvement of monitoring efficiency and accuracy.

4.1. Low Monitoring Accuracy of Small and Medium-sized Emission Sources

Most of the current greenhouse gas emission monitoring technologies are developed for large fixed emission sources, and the monitoring accuracy and sensitivity for small and medium-sized emission sources with low emission intensity are insufficient [6]. Scattered small and medium-sized emission sources are widely distributed, with large total emissions, and have become an important part of greenhouse gas emissions in various countries. However, due to the limitations of monitoring technology and cost, it is difficult to carry out large-scale and high-precision monitoring for such emission sources, resulting in large errors in greenhouse gas inventory accounting.

4.2. High Cost of Long-term Continuous Monitoring

The construction and operation cost of high-precision greenhouse gas emission monitoring system is relatively high, especially for ground-based in-situ monitoring stations and satellite remote sensing systems[7]. For developing countries with relatively weak economic strength, it is difficult to carry out large-scale layout of high-precision monitoring stations, resulting in the incompleteness of greenhouse gas emission monitoring network. At the same time, the long-term operation and maintenance of monitoring equipment also requires a lot of financial and human resources, which restricts the long-term continuous monitoring of greenhouse gas emissions.

4.3. Insufficient Integration of Multi-source Monitoring Data

At present, greenhouse gas emission monitoring data are mainly from ground-based in-situ monitoring, remote sensing monitoring and mobile monitoring, and the data formats, spatial and temporal resolutions of different monitoring methods are quite different. There is a lack of a unified data integration and processing platform, which makes it difficult to realize the mutual verification and fusion of multi-source monitoring data, and the data utilization efficiency is low. In addition, the isolation of monitoring data between different departments and regions also leads to the disconnection of greenhouse gas emission monitoring data, which cannot form a comprehensive and unified emission data map.

4.4. Lack of Unified Global Monitoring Standards

The greenhouse gas emission monitoring standards and technical specifications of various countries are not unified, and there are great differences in monitoring methods, emission flux calculation models and data quality control standards. This leads to the poor comparability of greenhouse gas emission data between different countries, which is not conducive to the formulation of global climate change policies and the development of international carbon emission trading. In addition, the lack of unified data sharing mechanisms and platforms also restricts the global exchange and application of greenhouse gas emission monitoring data.

5. FUTURE DEVELOPMENT TRENDS OF GREENHOUSE GAS EMISSION MONITORING

In order to solve the key challenges faced by current greenhouse gas emission monitoring, combined with the development of emerging technologies such as artificial intelligence, Internet of Things and remote sensing, the future greenhouse gas emission monitoring technology will show the development trends of miniaturization, intellectualization, networking, high precision and standardization.

5.1. Miniaturization and Intellectualization of Monitoring Equipment

With the development of micro-nano manufacturing and sensor technology, the miniaturization of greenhouse gas detection equipment will become an important development trend [8]. The miniaturized monitoring equipment has the advantages of small size, low cost, easy portability and simple operation, which can realize the large-scale layout of monitoring points for small and medium-sized emission sources, and effectively reduce the monitoring blind areas. At the same time, the integration of artificial intelligence technology into monitoring equipment will realize the intellectualization of data collection, processing and analysis, and the automatic identification and early warning of abnormal emission sources.

5.2. Networking and Integration of Monitoring Stations

The construction of a global unified greenhouse gas emission monitoring station network is the key to realizing full coverage of greenhouse gas emission monitoring. Based on the existing ground-based in-situ monitoring stations, combined with mobile monitoring points and remote sensing monitoring platforms, a multi-scale and multi-source greenhouse gas emission monitoring network will be constructed, and the seamless connection of monitoring data between different regions and different monitoring methods will be realized through the Internet of Things technology [9]. The networking of monitoring stations will realize the real-time transmission and sharing of monitoring data, and improve the timeliness and comprehensiveness of greenhouse gas emission monitoring.

5.3. High Precision and Refinement of Remote Sensing Monitoring

The high precision and refinement of remote sensing monitoring technology is an important development direction to improve the monitoring accuracy of small and medium-sized greenhouse gas emission sources. Through the optimization of remote sensing sensor technology and the improvement of emission flux inversion model, the spatial and spectral resolution of satellite and airborne remote sensing monitoring will be greatly improved, and the fine monitoring of small and medium-sized emission sources with low emission intensity will be realized [10-12]. At the same time, the combination of remote sensing monitoring and ground-based verification will further improve the inversion accuracy of greenhouse gas emission flux, and realize the mutual verification of multi-source monitoring data.

5.4. Construction of Global Unified Monitoring Data Platform

The construction of a global unified greenhouse gas emission monitoring data platform is the basis for realizing the standardization and sharing of monitoring data. Based on cloud computing and big data technology, the platform will integrate multi-source greenhouse gas emission monitoring data from all over the world, unify data formats and calculation standards, and realize the mutual verification, fusion and sharing of monitoring data. At the same time, the platform will provide open data interfaces for governments, research institutions and enterprises, and provide data support for global climate change research, policy formulation and emission reduction effect evaluation.

5.5. Formulation of Global Unified Monitoring Standards

The formulation of global unified greenhouse gas emission monitoring standards and technical specifications is an inevitable requirement for the development of global climate change response. Under the framework of the United Nations Framework Convention on Climate Change (UNFCCC), all countries will jointly formulate unified monitoring methods, emission flux calculation models, data quality control standards and data sharing mechanisms, so as to improve the comparability and credibility of greenhouse gas emission data between different countries. The unification of monitoring standards will also promote the development and application of greenhouse gas emission monitoring technology in a standardized direction, and reduce the technical and economic barriers of international carbon emission trading.

6. CONCLUSION

Greenhouse gas emission monitoring is an important technical support for global carbon neutrality and climate change response, and its technical level and monitoring efficiency are directly related to the realization of global climate goals. This paper systematically expounds the three main technical systems of greenhouse gas emission monitoring: ground-based in-situ monitoring, remote sensing monitoring and mobile monitoring, and compares their technical characteristics, application scope and operation cost in detail. The current greenhouse gas emission monitoring is facing key challenges such as low monitoring accuracy of small and medium-sized emission sources, high long-term monitoring cost, insufficient multi-source data integration and lack of unified global monitoring standards.

In the future, with the development of micro-nano sensor, artificial intelligence, Internet of Things and remote sensing technology, greenhouse gas emission monitoring technology will develop towards miniaturization, intellectualization, networking, high precision and standardization. The miniaturization of monitoring equipment will solve the monitoring problem of small and medium-sized emission sources. The networking of monitoring stations will realize the full coverage of monitoring. The construction of global unified data platform and the formulation of monitoring standards will realize the sharing and comparability of monitoring data.

All countries should strengthen the research and development of greenhouse gas emission monitoring technology, increase the investment in monitoring system construction, and strengthen international technical cooperation and data sharing, so as to jointly build a global unified, full coverage and high-precision greenhouse gas emission monitoring system, and provide solid data support for the global response to climate change and the realization of carbon neutrality goals. With the joint efforts of all countries, greenhouse gas emission monitoring technology will be continuously optimized and improved, and will play a more important role in the global climate change response.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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