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Application of Remote Sensing Technology in Monitoring the Carbon Dioxide Content in the Atmosphere

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Abstract. Monitoring the carbon dioxide (CO2) concentration in the atmosphere is crucial for reducing carbon emissions. Compared to traditional ground-based monitoring, remote sensing measurements have a wider coverage and stronger continuous monitoring capabilities. This paper introduces the types and characteristics of remote sensing satellites used for CO_2 detection, describes the detection process and main technologies, and takes the remote sensing satellite carrying AIRS (Atmospheric Infrared Sounder) as an example to analyze its application in CO_2 detection. The results indicate that the current remote sensing satellites have TIROS-N series TOVS sensors, AIRS, IASI, SCIAMACHY, GOSAT, and OCO. The remote sensing technology process includes mission planning and sensor selection, data acquisition, data preprocessing, spectral analysis, inversion algorithm for extracting CO_2 concentration information, spatial resolution optimization, data quality control and validation, spatiotemporal analysis and data fusion, generation of visual reports, and data dissemination. The data obtained from the AIRS remote sensing satellite for detecting CO_2 concentration has been validated through comparison with ground station and aircraft measurement data. In addition, by analyzing the spatial and temporal distribution of CO_2 and analyzing the intensity and seasonal variations of carbon sources and sinks in different regions, high carbon emission areas can be identified. Remote sensing technology also has some challenges and uncertainties, such as limitations caused by atmospheric turbulence, cloud cover, and lower accuracy. Therefore, future research needs to optimize remote sensing data processing methods further, develop more accurate inversion models, and consider integrating multiple remote sensing data sources.

Keywords: Atmospheric Carbon Dioxide Content Monitoring; Satellite Remote Sensing; Application; Carbon Reduction; Carbon Sinks.

1. Introduction

In recent years, the rapid economic and technological development in various regions of the world has led to a continuous increase in carbon emissions, resulting in rising temperatures, glacier melting, and changes in precipitation patterns. Therefore, detecting carbon dioxide (CO_2) levels in the atmosphere has become a key issue in balancing economic development and environmental protection. China strives to peak its CO_2 emissions before 2030 and achieve carbon neutrality before 2060. As China approaches the dual carbon targets and carbon neutrality, it will significantly impact the ecological balance, climate stability, sustainable resource utilization, and human health of the earth. Therefore, monitoring of CO_2 emissions has become of utmost importance. Gas analysers commonly monitor the real-time CO_2 content in the atmosphere by setting up monitoring stations in urban and industrial areas. Additionally, gas analyzers are used to monitor the CO_2 content in the atmosphere by setting up meteorological stations on the ground. In the field of remote sensing, compared to traditional ground monitoring, remote sensing measurements have a wider coverage and stronger continuous monitoring capability. Its role is mainly reflected in the monitoring of greenhouse gas emissions in different regions and types, providing important technical means and data support for accurately assessing CO_2 emissions and absorption. By obtaining wide-ranging, real-time, high-resolution Earth observation data, remote sensing helps scientists to more comprehensively and accurately monitor the dynamic changes in the concentration of CO_2 in the atmosphere and its influencing factors. Remote sensing technology can assess the carbon sequestration capacity of ecosystems such as forests, grasslands, and wetlands by monitoring vegetation cover and growth conditions [1], thereby aiding scientists in accurately determining the CO_2 levels in these areas.

With the continuous advancement of scientific and technological capabilities, significant progress has been made in remote sensing research for monitoring CO_2 concentrations. By integrating satellite remote sensing technology with ground-based monitoring data, researchers can now measure CO_2 emissions and absorptions more accurately. Emerging remote sensing technologies, such as lidar and hyperspectral imaging [1], can provide more detailed and precise data for monitoring CO_2 concentrations. These technologies enable global-scale monitoring, facilitating researchers' understanding of CO_2 emissions and absorptions across different regions, thereby offering critical support for global climate change research. This paper examines the primary types of remote sensing technologies used for CO_2 monitoring and discusses specific case studies related to their application.

2. Background of Remote Sensing Technology

Remote sensing technology identifies and quantifies CO_2 in the atmosphere by utilizing its spectral characteristics, which are detected and analyzed through radiation information from the atmosphere. CO_2 in the atmosphere exhibits distinct spectral absorption features, with its absorption peaks detectable within the infrared spectrum. By employing infrared spectrometric instruments to observe atmospheric radiation, remote sensing technology can detect these absorption peaks, thereby enabling the identification and quantification of CO_2 concentrations in the atmosphere. This study integrates the latest advancements in international remote sensing research focused on CO_2 concentration monitoring, encompassing methodologies for carbon emissions monitoring as well as remote sensing technologies for detecting carbon gas concentrations. (Including thermal infrared, solar spectrum, active remote sensing monitoring technology [2]), Currently, several satellite sensors that are actively in use and projected for future adoption to monitor key carbon emission gases include [3]: the TIROS-N series TOVS sensors, AIRS, IASI, SCIAMACHY, GOSAT, and OCO are included in this category. Table 1 presents the revisit periods, spatial resolutions, spectral ranges, and uncertainties associated with CO_2 measurements of various satellites, along with specific applications for monitoring CO_2 (Table 1).

Table 1. Performance data from different satellite sensors [3, 4]

Apparatus	Satellite	Description	Repeat Cycle	Spatial Resolution	Spectral Range	CO_2 uncertainty	Application scenarios
AIRS	AQUA	High spectral resolution infrared detector	1 day	50×50	3.7~15.4	1.5	Meteorological temperature and water vapor profile acquisition
SCIAMACHY	ENVISAT	Atmospheric mapping scanning imaging absorption spectrometer mounted by an environmental	6 days	30×60	0.24~2.4	14	Ultraviolet, visible, and near-infrared observations

		monitoring satellite					
-	AURA	The main mission is to study the chemical composition and dynamics of the Earth's atmosphere, in particular global observations of the ozone layer, air quality and key climate parameters.	2 days	5.3×8.5	3.2~15.4	-	Monitoring the ozone layer, assessing air quality, researching climate change, supporting weather forecasting, developing environmental policies, protecting public health, and optimizing agricultural production.
-	METOP - A	A hyperspectral infrared detector on board the Metop satellite launched by the European Space Agency	0.5 days	50×50	3.6~15.5	2	Meteorological temperature and water vapor profile acquisition
-	GOSAT	A satellite launched by Japan specifically for observing CO and CH4	3 days	10×10	0.76~14.3	4	Accurate observation of CO_2 and CH4 column data
	GOSAT-2		6 days	10×10	0.76~14.3	0.5	
-	OCO-2	United States planned launch of a satellite dedicated to detecting atmospheric CO_2 concentrations (launch failed)	16 days	1.29×2.25	0.76~2.08	<1	Global atmospheric CO_2 mean column concentration
	OCO-3		-	1.6×2.2	0.76~2.08	<1	

ACGS	TANSAT A	China's first scientific experiment satellite for high-precision global atmospheric CO_2 monitoring is equipped with a hyperspectral CO_2 detector and a cloud and aerosol polarization imager	16 days	2×2	0.76~2.08	4	The dynamic monitoring of CO_2 concentration in the global atmosphere, which in turn provides global carbon distribution data, plays an important role in understanding the global carbon cycle process and its impact on climate change

3. Remote Sensing Technology in the Process and Technology of CO_2 Detection

3.1. Inspection Process

The complete CO_2 detection process by remote sensing technology usually includes the following main steps (Figure 1).

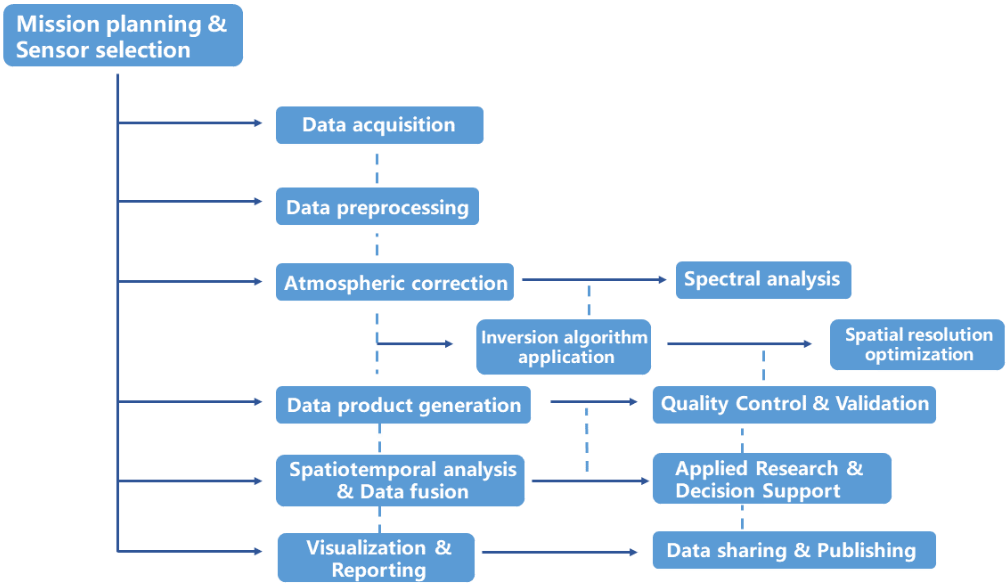

Figure 1. CO2 detection process using remote sensing technology

The first step involves task planning and sensor selection, which primarily entails identifying monitoring objectives and requirements and choosing appropriate remote sensing platforms (such as satellites or aircraft) and sensor types. Subsequently, data collection is conducted by utilizing the sensors mounted on the selected remote sensing platforms to acquire spectral data of the atmosphere, which will reflect the absorption characteristics of CO_2 present in the atmosphere. Following this, data preprocessing is performed, which includes radiometric calibration, spectral calibration, and geometric correction, to ensure the quality of the data. To mitigate the influence of other atmospheric constituents (such as water vapor and ozone) on the spectral data, atmospheric correction models should be applied. Following this, spectral analysis is carried out to examine the spectral data within specific wavelength ranges and to identify the absorption characteristics of CO_2 molecules. Subsequently, inversion algorithms, such as optimal estimation and radiative transfer models, are employed to extract CO_2 concentration information from the spectral data. Furthermore, spatial resolution optimization should be conducted to enhance the spatial resolution of the data through data processing techniques, thereby enabling precise monitoring of specific regions. Subsequently, the processed spectral data will be transformed into various levels of data products, accompanied by quality control and validation measures. This involves conducting quality control of the data products and comparing them with ground station data to ensure accuracy. Next, spatiotemporal analysis and data fusion will be performed, integrating Geographic Information Systems (GIS) and other remote sensing data to explore the spatiotemporal distribution characteristics of CO_2 and support application research and decision-making. Finally, a visual report and data sharing and publication will be generated.

The entire process encompasses multiple disciplines and technological domains, necessitating the integration of expertise from remote sensing technology, atmospheric science, data processing, and GIS. Through this workflow, it is possible to effectively monitor and assess changes in CO_2 concentrations on a global or regional scale, providing a scientific basis for climate change research and carbon emission policies.

3.2. Main Detection Technologies

The key technologies used in remote sensing technology in CO_2 detection mainly include the following aspects:

(1) Utilizing hyperspectral resolution instruments, such as the Atmospheric CO_2 Detector (ACDS) aboard China's first carbon satellite, TanSat, this technology employs near-infrared/shortwave infrared solar radiation reflected from the Earth to detect the concentration of CO_2 in the atmosphere, thereby obtaining high-precision atmospheric absorption spectra [1].

(2) Multispectral and hyperspectral detection technologies, such as the TANSO-FST sensor onboard Japan's GOSAT satellite, utilize a Michelson interferometer to acquire absorption spectral data at specific wavelength bands. This data is subsequently inverted to derive the XCO_2 product in the atmosphere.

(3) Solar-Induced Chlorophyll Fluorescence (SIF) technology has become prevalent in the detection of forest vegetation. By capturing the SIF signals emitted by vegetation, it is possible to estimate the photosynthetic productivity of the plants, which can subsequently be applied to monitor carbon sources and sinks.

(4) After monitoring atmospheric retrieval data, atmospheric correction and inversion algorithms are employed for processing. Inversion algorithms, such as the optimal estimation method, are utilized in conjunction with atmospheric correction models to extract CO_2 concentration information from the spectral data.

(5) Data fusion techniques, such as integrating CO_2 and NO2 data, enhance the accuracy of estimations regarding anthropogenic emissions [5].

(6) Thermal infrared remote sensing technology is employed to study the properties of Earth's materials using thermal infrared wavelengths. This technology facilitates the inversion of surface temperature data, thereby enabling monitoring of global climate warming.

(7) Satellite design and orbital deployment, exemplified by the sun-synchronous orbit configuration of the TanSat satellite, allow for continuous global coverage [1].

(8) Active laser radar technology utilizes single-photon detection in free-space spectral remote sensing to achieve atmospheric spectral analysis with distance resolution [6].

These technologies collectively establish a technical framework for remote sensing applications in CO_2 detection, providing robust data support for scientific research and policy formulation.

4. Application of Remote Sensing Technology in CO2 Detection

Remote sensing technology for monitoring CO_2 concentrations primarily encompasses various types, including atmospheric remote sensing, vegetation remote sensing, and surface remote sensing. Atmospheric remote sensing mainly utilizes satellite and aircraft platforms to acquire data on CO_2 concentrations in the atmosphere. Key techniques employed in this domain include infrared spectroscopy, lidar (light detection and ranging), and Doppler radar, which facilitate monitoring the vertical distribution and spatiotemporal variations of CO_2 in the atmosphere. Vegetation remote sensing utilizes platforms such as satellites to acquire data on the absorption and release of CO_2 during plant growth processes. The primary techniques in this field include multispectral and hyperspectral remote sensing, which enable monitoring of CO_2 absorption and release within vegetation ecosystems. Surface remote sensing, on the other hand, employs satellites and other platforms to gather data on CO_2 absorption and release from terrestrial and oceanic surfaces. Key techniques in this area include microwave remote sensing and optical remote sensing, which facilitate monitoring CO2 distribution and variations in terrestrial and marine environments.

The importance of remote sensing technology in monitoring the spatiotemporal distribution of CO_2 and assessing carbon sources and sinks lies in its ability to provide continuous and extensive observational data, which is crucial for understanding the global carbon cycle and climate change. Data obtained from satellite remote sensing, specifically the column-averaged dry air volume mixing ratio of CO_2, allows for the analysis of the intensity and seasonal variations of carbon sources and sinks in different regions, enabling the identification of areas with elevated carbon emissions. This information serves as a scientific basis for policymaking and emission reduction measures. Furthermore, advancements in remote sensing technology have deepened the understanding and management of ecosystem carbon sink functions. For instance, forests, as a primary carbon sink in terrestrial ecosystems, can effectively monitor and assess their carbon sequestration capacity through remote sensing data. This is of significant importance for implementing nature-based solutions, such as afforestation and ecological restoration projects, aimed at enhancing terrestrial carbon sink functions and advancing towards achieving carbon neutrality goals. Moreover, the application of remote sensing technology has extended to studying carbon cycles in inland water bodies such as lakes, enhancing the understanding of these ecosystems' role in the global carbon cycle. As remote sensing technology continues to advance, its applications in global carbon verification and carbon cycle research will become even more widespread, providing robust technical support for addressing global climate change. Therefore, this chapter discusses the application of satellite remote sensing data equipped with the AIRS instrument as a case study, focusing on its use in monitoring the spatiotemporal distribution of CO_2 and the processes of carbon sources and sinks.

4.1. Data Sources

Satellite remote sensing data from the Atmospheric Infrared Sounder (AIRS) instrument have been utilized to collect information on CO_2 concentrations in the mid-troposphere over China. These data span from January 2003 to December 2008, providing a long-term and continuous observational record. The accuracy and reliability of the AIRS data have been validated through comparisons with ground station and aircraft measurement data. Table 2 compares ground and satellite measurements from 2003 to 2008. According to the data in Table 2, the monthly average bias is maintained within 3 ppmv, thereby providing a solid data foundation for subsequent analyses.

Table 2. Comparison of ground and satellite measurements from 2003 to 2008 [7]

Ground-base Station	Annual growth rate (ppmv/a)		Mean (ppmv)		Average deviation (ppmv)	Monthly average standard deviation (ppmv)	R
	Ground	Satellite	Ground	Satellite			
Assekerm	1.995	2.076	380.734	379.822	0.912	1.609	0.922
Mauna Loa	1.992	2.034	380.786	379.286	1.500	1.598	0.915
Niwot Ridge	2.018	2.149	381.293	380.811	0.482	2.614	0.806
Plateau Rosa	1.935	2.040	380.729	381.007	-0.278	2.976	0.771
Waliguan	1.977	2.100	381.209	380.730	0.479	2.692	0.806
Average	1.983	2.080	380.950	380.331	0.619	2.298	-

4.2. Research Methodology

The AIRS instrument covers a spectral range of 3.7 to 15.4 micrometres and comprises 2,378 spectral channels, enabling the generation of global profiles for temperature, water vapor, CO_2, and other trace gases based on the measured data. This study employed the mid-tropospheric CO_2 retrieval product from AIRS, which utilizes cloud-cleared radiance for retrieval and implements quality control under cloudy conditions. Data quality is assured by assessing the root mean square (RMS) of adjacent 2x2 pixel points. To validate the mid-tropospheric CO_2 product from AIRS, data from five ground and aircraft CO_2 measurement stations were compared with the satellite data. Among these, the Assekrem, Mauna Loa, Niwot Ridge, and Waliguan stations employed discrete sampling methods using canisters for air collection, while the Plateau Rosa station utilized a continuous sampling approach.

4.3. Research Results

Figure 2 illustrates the average global CO2 concentration in the mid-troposphere from 2003 to 2008. The results indicate that the average CO_2 concentration in the Northern Hemisphere is generally higher than that in the Southern Hemisphere. Taking China as an example, the northern regions exhibit consistently elevated CO_2 concentrations compared to the south, particularly in areas within the latitude range of 35° to 45°N, such as the Northeast Plain, Inner Mongolia, the Taklamakan Desert, and the Tarim Basin. These areas have become significant sources of CO_2 emissions due to concentrated industrial activities and variations in natural conditions. In contrast, Yunnan Province, characterized by its abundant vegetation and tropical monsoon climate, is identified as an area with relatively low CO_2 concentration, displaying the characteristics of a carbon sink.

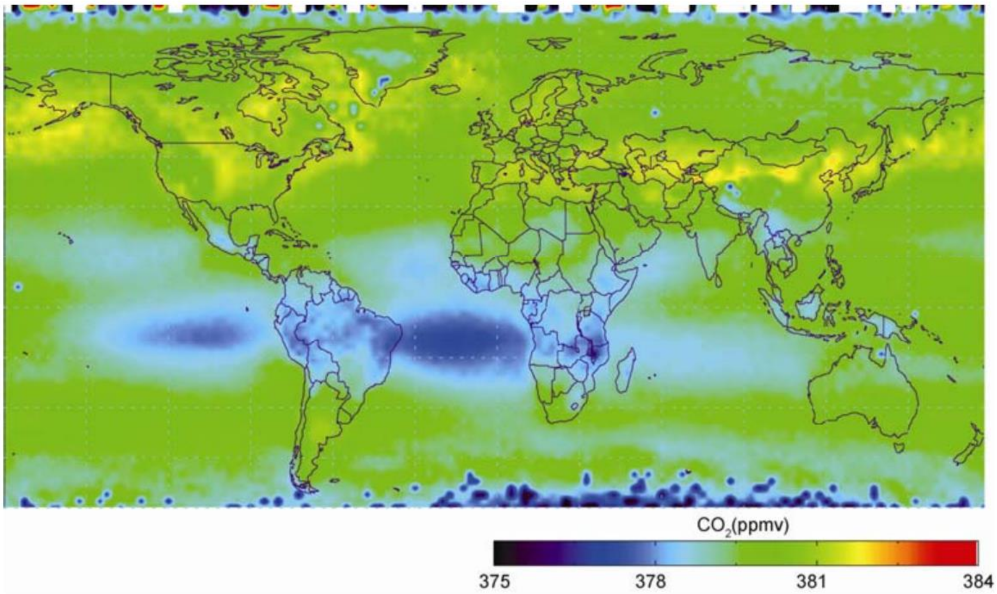

Figure 2. Average Mid-Tropospheric CO_2 Concentrations Globally from 2003 to 2008 [7]

Furthermore, global CO_2 concentrations increased yearly from 2003 to 2008, averaging 2.14 ppmv per year. For instance, Russia exhibited the highest annual growth rate globally, reaching 2.32 ppmv, while India recorded the lowest growth rate among the countries, at 2.03 ppmv.

The analysis of seasonal variations is beneficial for understanding the processes of CO_2 sources and sinks. Figure 3 illustrates the distribution of mid-tropospheric CO_2 concentrations in China during different seasons from 2003 to 2008. The results indicate that CO_2 concentrations peak in spring, which is associated with intensified respiration by plants and soil, coupled with relatively weaker photosynthetic activity. Conversely, in autumn, CO_2 concentrations decline to their lowest levels due to maximum photosynthetic activity, reflecting the significant impact of seasonal biological activity on atmospheric CO_2 concentrations.

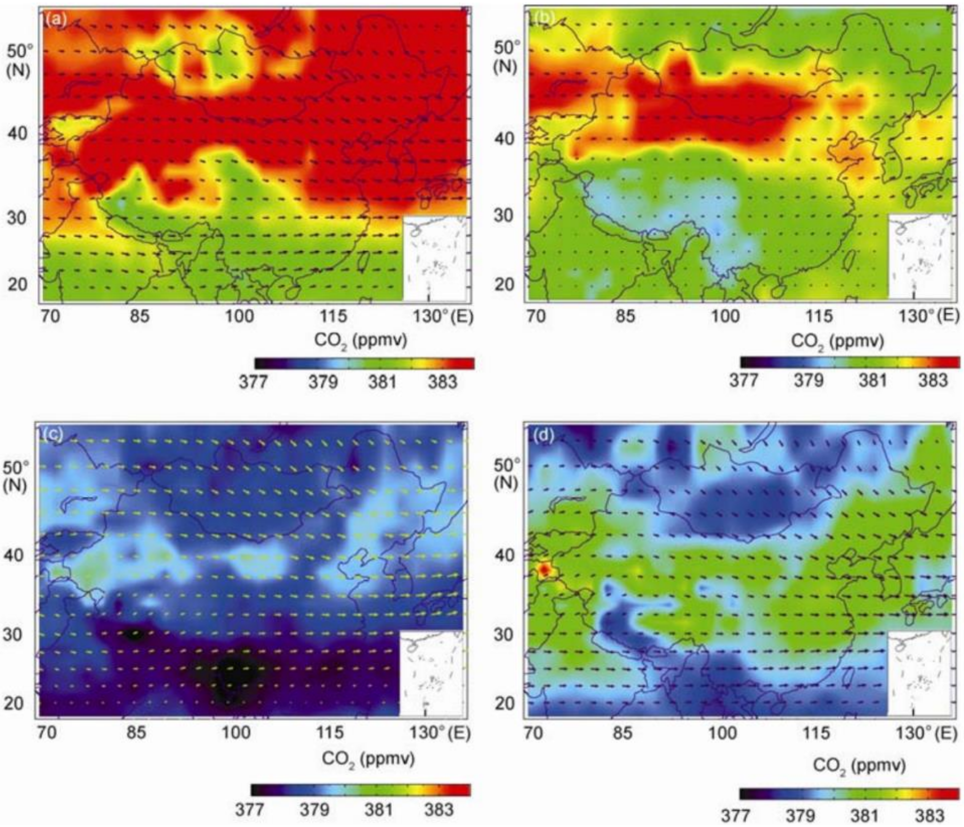

Figure 3. Seasonal Variations of CO_2 in the Mid-Troposphere over China from 2003 to 2008(a) spring, (b) summer, (c) autumn, (d) winter [7]

In summary, the application of remote sensing data offers a macro perspective on the spatiotemporal distribution of CO2 and reveals the dynamic changes in source-sink processes through long-term observation. This provides valuable information and scientific evidence for global climate change research and policy formulation.

5. Challenges and Future Trends

The accuracy level of current remote sensing monitoring of CO_2 concentrations is continuously improving; however, several challenges remain. Firstly, there are inherent limitations associated with remote sensing technologies themselves. Commonly utilized methods for CO_2 monitoring include satellite remote sensing and ground-based lidar technologies. While satellite remote sensing can cover extensive areas, its accuracy is constrained by atmospheric disturbances and cloud cover, leading to lower precision. In contrast, ground-based lidar can provide more accurate concentration data but is limited to localized monitoring. Secondly, the processing and interpretation of observational data present challenges. The raw data obtained from remote sensing monitoring requires complex data processing and model analysis to yield accurate CO_2 concentration results. Additionally, it is essential to consider the influence of environmental factors such as meteorological conditions and topography on the data. Furthermore, ensuring the consistency between ground-based measurements and remote sensing data poses another challenge. Ground monitoring can provide accurate point data, but its coverage is limited; conversely, remote sensing can offer extensive area data, yet the consistency with ground-based monitoring data requires further validation and adjustment [8].

To address the existing challenges associated with current technologies, the following improvements can be proposed:

Technological Improvements: With the continuous advancement of technology, monitoring equipment and techniques are also being updated and enhanced. The adoption of more advanced sensors and monitoring devices can improve measurement accuracy while expanding the monitoring range and frequency. For instance, utilizing satellite remote sensing technology and high-tech equipment such as drones can facilitate the coverage of broader areas and enable real-time data monitoring [9].

Data Analysis and Processing: The adoption of advanced data analysis and processing techniques can enhance the accuracy of interpreting monitoring data, thereby improving measurement precision. Utilizing artificial intelligence and big data analytics can uncover hidden patterns and trends within the data, providing more valuable information for monitoring efforts.

Diversified Monitoring Approaches: Employing various monitoring methods for cross-validation can enhance the reliability and accuracy of measurements. For example, integrating ground-based monitoring, satellite monitoring, and meteorological radar monitoring can provide a more comprehensive understanding of the conditions of the monitored subject [10].

Integrated Monitoring Systems: Establishing a comprehensive integrated monitoring system can consolidate various monitoring devices and technologies, facilitating the sharing and interaction of monitoring data. This approach will enhance the comprehensiveness and timeliness of the monitoring efforts.

Strengthening Monitoring Network Development: Increasing investment in monitoring facilities and continuing to improve the monitoring network infrastructure is essential. This includes enhancing the density and coverage of monitoring stations to achieve more extensive monitoring and observation of additional regions and subjects.

In the future, remote sensing technologies for monitoring CO_2 concentrations may evolve in the following directions. Higher Precision: With the continuous advancement and improvement of technology, the accuracy of remote sensing for monitoring CO_2 concentrations is expected to increase, allowing for more precise detection and monitoring of changes in atmospheric CO_2 levels. Wider Coverage: Future remote sensing technologies may expand their monitoring range to comprehensively observe CO_2 concentrations on a global scale, thereby enhancing our understanding of global climate change. Multivariable Monitoring: In addition to CO_2 concentrations, future technologies might enable the monitoring of other atmospheric parameters, such as temperature and humidity, facilitating a comprehensive understanding of atmospheric environment changes. Data Fusion and Intelligent Analysis: Future remote sensing technologies may integrate various data sources, including satellite remote sensing data and ground monitoring data, employing technologies such as artificial intelligence for data fusion and intelligent analysis. This approach would enhance data utilization efficiency and monitoring capabilities.

6. Conclusion

Currently, several spaceborne sensors for monitoring major carbon emissions, which are already in use or are expected to be adopted in the future, include the TIROS-N series TOVS sensors, AIRS, IASI, SCIAMACHY, GOSAT, and OCO, among others. The remote sensing technical process encompasses task planning and sensor selection, data collection, data preprocessing, spectral analysis, the extraction of CO_2 concentration information using inversion algorithms, spatial resolution optimization, data quality control and validation, spatiotemporal analysis and data fusion, the creation of visual reports, and the publication of data. The primary objective is to monitor CO_2 concentrations in the atmosphere, analyze and apply remote sensing data, and support decision-making processes.

Remote sensing technology demonstrates significant applicability in monitoring and analyzing the spatiotemporal distribution of CO_2 in the atmosphere and its source-sink dynamics. Through satellite sensors such as AIRS, continuous CO_2 concentration data can be collected over extensive areas, which is crucial for understanding the global carbon cycle, assessing the impact of human activities on the atmosphere, and identifying trends in climate change. Additionally, remote sensing technology aids in identifying CO_2 sources and sinks; for instance, areas with concentrated industrial activities serve as sources of CO_2 emissions, while regions with high vegetation cover act as CO_2 sinks. Despite the valuable perspectives and data that remote sensing technology offers for CO_2 research, long-term trend analysis requires more extensive continuous data to reduce uncertainty. This will enable more accurate assessments of climate change impacts and the formulation of corresponding policy measures.

Challenges faced by remote sensing technology in monitoring CO_2 concentrations include data quality and resolution issues, the effects of meteorological conditions and surface characteristics, and the accuracy and reliability of algorithms. In the future, the development directions for remote sensing technology in monitoring CO_2 concentrations are expected to include enhancing the resolution and spatiotemporal coverage of data acquisition, improving monitoring algorithms and models, strengthening the integration of remote sensing data with ground-based observational data, and applying new technologies such as deep learning and artificial intelligence. These advancements aim to comprehensively monitor CO_2 concentrations in response to global change.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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