

Gaseous pollutants and greenhouse gases are significantly synergistic and homologous (Brink et al., 2001; Bytnerowicz et al., 2007; Nam et al., 2013; Agee et al., 2014; Thompson et al., 2014; Monjardino et al., 2021; Bodor et al., 2022; Bian et al., 2023; Monforti-Ferrario et al., 2024). Although they are in small quantities, they are very harmful. Monjardino et al. (2021) reported that decarbonization efforts were found to have strong co-benefits for reducing air pollutant emissions. Transport and power generation are the greatest potential to reduce greenhouse gas emissions, providing the most significant reductions of air pollutants. To improve the air quality, the Chinese government has consecutively carried out a series of program measures, such as “Action Plan for Air Pollution Prevention and Control” and “Three-Year Action Plan to Win the Blue Sky Defense War,” since 2013. Concentrations of primary emission pollutants (e.g., PM_{2.5} and SO₂) have declined significantly, but O₃ and its precursors (NO_x and VOCs) have declined slowly or continued to increase (Feng et al., 2019; Maji et al., 2020; Jiang et al., 2021). Synergistic control of PM_{2.5} and O₃ has become a major task in air pollution control in recent years. Moreover, China has clearly set out the goals of “carbon peaking” by 2030 and “carbon neutrality” by 2060 in 2020, and carbon monitoring and emission reduction have been given high priority (Wang et al., 2021a; Zhao et al., 2022; Yang et al., 2023). However, with the continuous promotion of China’s “reduction of pollution and carbon emissions” strategy, there have been significant changes in the sources of pollution/greenhouse gases, emission components and emission concentrations (Song et al., 2017; Dong et al., 2018; Jiang et al., 2019; Zheng et al., 2019; Li et al., 2023a), which have put forward higher requirements for the development of monitoring technologies, such as high spatiotemporal resolution, rapid response, highly adaptable to complex environments, automated intelligence, etc. (Marc et al., 2015; Motlagh et al., 2020; Wang et al., 2023).

The multi-platform optical monitoring technology plays an important role in the monitoring of air pollution/greenhouse gases and the improvement of atmospheric environment. For satellite remote sensing, the National Aeronautics and Space Administration of the United States of America (NASA) and the European Space Agency (ESA) have successively launched several hyperspectral satellite payloads, such as GOME, SCIAMACHY, OMI, TROPOMI, OCO-2, etc., since 1990s. These satellite payloads can be used to monitor the spatiotemporal distributions of pollutants (O₃, NO₂, SO₂, HCHO, CHOCHO, etc.) and greenhouse gases (CO₂ and CH₄) at a global scale (Burrows et al., 1999; Boersma et al., 2007; Gebhardt et al., 2014; Sun et al., 2017; De Smedt et al., 2018). To enhance our autonomy and controllability in the field of hyperspectral satellite remote sensing, China launched the Gaofen-5 satellite in 2018. It carried

Chinese first ultraviolet-visible hyperspectral payload Environment Monitoring Instrument (EMI) for pollution monitoring and a Greenhouse gas Monitoring Instrument (GMI) for greenhouse gas monitoring, developed by the Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. In addition, China has previously launched their first carbon remote sensing satellite, TanSat, in 2016. The retrieval of the spatiotemporal distributions of NO₂, SO₂, HCHO, O₃, and CO₂ has also been realized on the basis of above satellite payloads developed in China (Zhang et al., 2020a; Hong et al., 2021; Xia et al., 2021a; Zhao et al., 2021; Su et al., 2022a). Ground-based optical monitoring technologies mainly include differential optical absorption spectroscopy (DOAS) and cavity ring-down spectroscopy (CRDS) developed for pollutants such as aerosols, NO₂, HONO, SO₂, HCHO, CHOCHO, and greenhouse gases such as CO₂ and CH₄ based on their molecular “fingerprint” absorptions; light detection and ranging (LIDAR) developed for aerosol, O₃ and H₂O based on their laser absorption/scattering properties; fourier transform infrared spectroscopy (FTIR) for VOCs and greenhouse gases such as CO₂, CO, and CH₄ based on their absorption and emission of infrared spectra; tunable diode laser absorption spectroscopy (TDLAS) for CO₂, CH₄, N₂O, CO, NO, NH₃ based on their narrow-band absorption characteristics; laser heterodyne spectroscopy (LHS) developed for mobile observation of CO₂ and CH₄ column concentrations/vertical profiles; and fluorescence assay by gas expansion (FAGE) developed for atmospheric radicals (HO_x) based on their electronically excited state fluorescence properties (Kukui et al., 2008; Rodin et al., 2014; Kou et al., 2018; Prasad et al., 2019; Lan et al., 2020; Xu et al., 2020). Among them, multi-axis differential optical absorption spectroscopy (MAX-DOAS), LIDAR and FTIR technologies have been widely used in stereoscopic detection of atmospheric components due to their obvious advantages in vertical detection. Mobile remote sensing monitoring platforms, mainly including vehicle platform, ship platform, and aircraft platform, and they have assisted in supporting pollution control and carbon emission accounting. Xi et al. (2021) successfully captured the emission and diffusion processes of NO₂ plume in an industrial park based on a self-developed UV-Vis hyperspectral airborne DOAS. Fujinawa et al. (2021) explored the spatial distribution of CO₂ in industrial parks based on airborne infrared hyperspectral equipment, along with the carbon-nitrogen emission ratio. However, most of the above techniques are limited by the lack of stereoscopic detection capabilities, and still have significant drawbacks in quantifying the emissions and diffusion/transport of pollution/greenhouse gases. Optical monitoring technology for atmospheric environment needs to be developed toward higher accuracy, more components, greater range and more intelligence.

In this study, we first reviewed the current status of the development of optical technologies for atmospheric environment. Moreover, we put new perspectives on the bottlenecks and outlook of optical monitoring techniques for atmospheric environment. This research will deepen the understanding of the development of atmospheric monitoring technology and help to achieve the scientific goal of “reduction of pollution and carbon emissions”.

Appendix A lists the abbreviations used within this study (Table A1).

2 Status of optical monitoring technology for atmospheric components

As shown in Fig. 1, a system of environmental optical monitoring technology with differential optical absorption spectroscopy (DOAS), cavity ring-down spectroscopy (CRDS), light detection and ranging (LIDAR), laser heterodyne spectroscopy (LHS), tunable diode laser absorption spectroscopy (TDLAS), Fourier transform infrared spectroscopy (FTIR) and fluorescence assay by gas expansion (FAGE) as the main body has been formed at present. The development of these optical monitoring techniques has driven advances in atmospheric sciences

such as atmospheric physics, atmospheric chemistry, climate, and meteorology.

2.1 Hyperspectral satellite remote sensing

The advantage of hyperspectral (wavelength resolution < 0.5 nm) satellite remote sensing is that it can capture the horizontal distribution of pollution and greenhouse gases on a global or regional scale. The history of the development of hyperspectral remote sensing satellites for pollutants and greenhouse gases can be found in Fig. 2. China started late in the field of hyperspectral satellite remote sensing, being about 23 years behind Europe and the United States of America. The Gaofen-5 satellite launched in 2018 carries China’s first hyperspectral payload developed by Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences to detect O₃, NO₂, SO₂, HCHO, etc. (Zhang et al., 2020a; Xia et al., 2021a; Liu et al., 2022a; 2022b; Su et al., 2022a; Zhao et al., 2023). The spectral quality of the EMI payload is much worse than that of the S5P payload due to deficiencies in the performance of the key components of payloads, such as gratings and detectors. Given the hardware shortcomings, researchers have developed a series of calibration and retrieval correction algorithms. A



Fig. 1 Environmental optical monitoring system.



Fig. 2 History of the development of hyperspectral remote sensing satellites for pollutants and greenhouse gases.

laboratory calibration device and an on-orbit real-time calibration algorithm for EMI load have been developed to correct the wavelength drift, spectral deformation and irradiance distortion in the space environment (Zhang et al., 2018). A solar reference spectrum reconstruction algorithm has been developed, and a high-precision real-time reference spectrum for EMI load has been obtained (Zhang et al., 2020a; Xia et al., 2021a). An iterative algorithm for adaptive inversion configuration has been developed to maximally remove the interference of other gases absorbed in the same wavelength band and realize trace gas retrieval at the condition of low signal-to-noise ratio (Zhao et al., 2023). The algorithm for estimating air mass factors under multiple scattering has been developed, which greatly improves the observation accuracy of satellite remote sensing under the background of high aerosol loads in China. This algorithm corrects the serious overestimation of SO₂ in China, and significantly improves the observation accuracy of NO₂ and HCHO (Su et al., 2020; Xia et al., 2020; Liu et al., 2022). China launched its first hyperspectral satellite (TanSat) for greenhouse gas monitoring in 2016. The lack of hardware performance results in poor spectral quality of the TanSat. Under this background, Chinese researchers have developed a hyperspectral high-precision CO₂ retrieval algorithm, which realizes high-precision CO₂ observations by TanSat in both nadir and sun-glint modes (Hong et al., 2022a; 2023a; 2023b). The correlation coefficients between CO₂ measured by TCCON and CO₂ observed by TanSat in nadir and sun-glint modes reached 0.92 and 0.93, respectively. The DQ-1 satellite launched in 2022 carries two main hyperspectral payloads, EMI II and

aerosol and carbon dioxide detection lidar (ACDL), to detect pollutants and CO₂, respectively. The spatial resolution significantly improved for EMI II than EMI I, reaching 13 km × 24 km (Li et al., 2023b; Qian et al., 2023a). ACDL is the first international satellite-mounted CO₂ detection lidar to obtain global CO₂ column densities with an accuracy better than 1 ppm (Shi et al., 2023).

The limitations of hyperspectral satellite remote sensing are mainly as following: (1) spectral signals can be shielded by clouds, and the retrievals of pollutants and greenhouse gases can be disturbed; (2) for low cloud coverage scenarios, satellite remote sensing algorithms use radiative transfer doing corrections based on retrieved cloud parameters. However, it is limited by the isotropic, fixed-constant approximation of cloud albedo, which ultimately transfers errors to the retrieved trace gas products.

2.2 Differential optical absorption spectroscopy (DOAS)

After decades of development and application, DOAS has become an important and powerful tool for environmental monitoring, atmospheric detection, atmospheric chemical cycling, and the study on gas chemical reaction mechanisms (Lin et al., 2022a; Hong et al., 2022a; Song et al., 2023; Xing et al., 2023; 2024). Based on the difference in light source, DOAS can be divided into active and passive systems.

Multi-axis differential optical absorption spectroscopy (MAX-DOAS), a kind of passive DOAS, is widely used to detect the vertical distributions of aerosol, O₃ and their precursors (NO₂, SO₂, HONO, HCHO, CHOCHO, H₂O

etc.) (Xing et al., 2017; 2019; 2020; 2021; Lin et al., 2020; Ren et al., 2021; Liu et al., 2022; Ji et al., 2023; Qian et al., 2023b). Its development is due to the advances in retrieval algorithms. At present, there are three main kinds of vertical profile algorithms: parametric algorithm, optimal estimation algorithm and look-up table algorithm (Vlemmix et al., 2011; Bösch et al., 2018; Beirle et al., 2019). The disadvantage of parametric algorithm is that the high nonlinearity of the forward model can lead to the appearance of retrieval singularities. The disadvantages of optimal estimation algorithm are the retrieval results being overly dependent on a priori information, and the algorithm itself being insensitive at high altitudes. The look-up table algorithm, as a newly developed vertical profile retrieval algorithm, has significantly improved its retrieval speed and is more sensitive to the distribution of pollutions at higher altitudes. In addition, a new method for retrieval and prediction of vertical profiles of air pollutants based on deep learning algorithms fusing multiple-source data, such as solar scattering spectra and meteorological parameters, is proposed (Zhang et al., 2022; Tian et al., 2024). Up now, several MAX-DOAS networks were established to learn the stereoscopic evolution of atmospheric pollutants in regional scale. The university of Bremen established a network, named Bremen DOAS network for atmospheric measurements (BREDOM) (Richter et al., 2002). The Japan agency for marine earth science and technology and Europe union established the MAX-DOAS network over Russia and Asia (MADRAS) and the network for observation of volcanic and atmospheric change (NOVAC), respectively (Galle et al., 2010; Kanaya et al., 2014). The university of science and technology of China (USTC) also established a MAX-DOAS network within 34 stations in China (Liu et al., 2022).

Long path differential optical absorption spectroscopy (LP-DOAS), a kind of active DOAS, is more advantageous for accurate measurements of pollutants due to its known air mass factors. In particular, it shows significant advantages in the measurement of atmospheric oxidation radicals and VOCs components due to the application of active light source (Nan et al., 2017; Gao et al., 2021; Yan et al., 2021; Lu et al., 2022; Sun et al., 2023). The most commonly used light sources for LP-DOAS include xenon lamps, deuterium lamps, and laser-driven plasma-emitting light sources. The advantage of these light sources is the wide range of excitation wavelengths, while the disadvantages are limited operating life, high price, and insufficient optical power at the target single wavelength. In recent years, light-emitting diodes (LEDs) have been widely used for atmospheric monitoring due to their high optical power and low price. However, short wavelength, wavelength drift due to heat generation, and poor quasi-quality have become important factors limiting their functions. Therefore, stable temperature-

controlled, multi-band efficiently coupled LEDs will be important driving factors for the further development of LP-DOAS.

2.3 Fourier transform infrared spectroscopy (FTIR)

The core component of fourier transform infrared spectroscopy (FTIR) is an infrared interferometer. The light beams interfere after passing through different optical paths inside the interferometer first. Then, the infrared detector collects the interference signals. Finally, the interference signals in the time domain are converted into signals in the frequency domain, so as to realize acquisition of highly efficient infrared spectra. FTIR allows non-contact detection of most infrared-active gases such as greenhouse gases and volatile organic compounds. Signal-to-noise ratio and wavelength resolution determine the spectral quality. Internationally, the signal-to-noise ratio of FTIR usually can reach 35000–40000:1, and the optimum wavelength resolution can reach 0.001 cm^{-1} . In China, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences has developed a series of localized FTIR instruments. According to the light source, these instruments can be classified as active FTIR and passive FTIR. Active FTIR uses artificial infrared light sources and is commonly used for analyzing of gas samples and for local surface atmospheric monitoring, such as open path FTIR and Extractive FTIR (Xu et al., 2007a; 2007b; Cheng et al., 2021; Qu et al., 2021a; 2021b; Wang et al., 2021b; Cheng et al., 2022). Passive FTIR uses natural light sources such as solar radiation and infrared radiation sources, and can be used for whole atmosphere monitoring and gas leakage detection, such as the sun occultation flux FTIR and the imaging FTIR for gas clouds (Qu et al., 2019; Hu et al., 2021a; 2022; Deng et al., 2023). To better understand global climate change and to validate current and future satellite measurements, total column carbon observing network (TCCON) all over the world based on FTIR technique was established (Toon et al., 2009).

There are still some technical bottlenecks for the development of FTIR: 1) the need to develop new types of infrared light sources and more sensitive detectors to improve the performance and applicability of FTIR instruments; 2) improved retrieval algorithms to resolve the absorption interferences of H_2O and CO_2 ; 3) the need to develop faster data-processing methods to accommodate dynamic processes and rapid monitoring of small targets; 4) the development of portable FTIR needing to address the balance between instrument size and performance to adapt to a wider range of application scenarios.

2.4 Light detection and ranging (LIDAR)

Light detection and ranging (LIDAR) enables real-time

continuous detection of the vertical profiles of aerosol, O_3 , temperature, humidity, H_2O , NO_2 , SO_2 , CO_2 , and CH_4 over a full time period. In recent years, through overcoming key technologies such as laser light source, transient recording of radar signals and active calibration of transceiver optical system, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences has independently developed multi-platform and multi-model aerosol and ozone LIDARs that can be flexibly applied to ground-based, vehicle-mounted or airborne-mounted applications, which provide technical support for monitoring of air pollutants. Lv et al. (2017) proposed a vehicle-mounted LIDAR detection technique applicable to detect particulate matter in urban areas. Liu et al. (2020) first presented an ozone differential absorption LIDAR system based on an all-solid-state tuning-free laser light source, which greatly improved LIDAR's stability. In addition, several LIDAR networks in different regions all over the world were established to monitor the regional distribution and transport characteristics of aerosol, dust etc., such as the Raman and polarization lidar network (Polly^{NET}), Micro pulse lidar network (MPLNET) and Asian dust and aerosol lidar observation network (AD-Net) (Sugimoto et al., 2014; Baars et al., 2016; Welton et al., 2018). Chinese aerosol and ozone LIDAR observation network was established and a corresponding stereoscopic assimilation system was developed from 2014. Based on the self-developed vehicle-mounted LIDAR and above LIDAR observation network Lv et al. (2020) identified and analyzed the transport paths and transport characteristics of particulate matter in the Beijing-Tianjin-Hebei region. Xiang et al. (2021) revealed the stereoscopic dynamic evolution of particulate matter pollution in the North China Plain based on long-term observation data from above LIDAR observation network and data assimilation techniques. Wang et al. (2021c) also analyzed the seasonal characteristics, local formation, regional transport and potential sources of ozone pollution in the Pearl River Delta region based on above LIDAR observation network. Finally, the ground surface *in situ* measurement methods for O_3 are unable to characterize the spatiotemporal distribution and evolution of O_3 , making the development of the world's first satellite-based LIDAR payload for coordinated observation of O_3 and $PM_{2.5}$ a promising monitoring technology in the future.

2.5 Tunable diode laser absorption spectroscopy (TDLAS)

Tunable diode laser absorption spectroscopy (TDLAS) is a laser absorption spectroscopy technique with the advantages of non-contact, high selectivity, high sensitivity, fast response and simple structure. TDLAS can detect atmospheric CO_2 , CH_4 , H_2O , NH_3 , NO_x , etc. The detection sensitivity of TDLAS is usually in the range of 10^{-3} – 10^{-4} cm^{-1} . The accuracy of the

measurement can be further improved by choosing a light source with a higher intensity of absorbed spectral lines, increasing the distance between the laser and the gas to be measured, reducing the electronic noise in the system. Higher detection sensitivity can be achieved using mid-infrared lasers as source of TDLAS. The use of multiple reflection cells, such as White cell, Heriot cell, annular cell, etc., allows the distance between the laser and the gas to be measured to increase more than 100 m and increases the signal intensity by one or two orders of magnitude. The reduction of the system electronic noise is achieved by high frequency modulation. High frequency modulation mainly includes wavelength modulation and frequency modulation (Chen et al., 2019; Wang et al., 2022). Although the above three methods improve the detection sensitivity of the TDLAS, they also increase the cost and size of this system. Li et al. (2019) developed a set of sensors with small size, low power consumption and high sensitivity based on TDLAS technique to detect the dissolved CO_2 in seawater. The linear correlation coefficient of this system compared to a commercial instrument (Picarro, G2301) for CO_2 observations was 1.005 ± 0.003 . Li et al. (2020a) developed open-range CO_2 and H_2O sensors by combining the first-harmonic phase angle method and wavelength modulation spectroscopy. The system has a higher temporal resolution (500 Hz) compared to a commercial instrument (LICOR, 7500A) with a 20 Hz temporal resolution. Li et al. (2020b) developed an online open path CO_2 detection instrument based on direct and derivative absorption spectroscopy, with the measurement distance on the order of kilometres. Residual amplitude modulation effects in high-frequency modulation techniques and intensity fluctuation noise in lasers limit further improvements in TDLAS detection sensitivity (Wong and Hall, 1985).

2.6 Cavity ring-down spectroscopy (CRDS)

Cavity ring-down spectroscopy (CRDS) has the advantage of being immune to laser intensity fluctuations. CRDS is often used for trace gas detection, such as CO_2 , CH_4 , H_2O , NH_3 , NO_x and atmospheric radicals, due to its high accuracy and sensitivity. Yuan et al. (2020) reported a small-scale real-time detection system for dissolved CH_4 in seawater based on CRDS technique. The detection sensitivity of this system is 0.4 ppbv, and it has the noise of 1.3 ppbv smaller than the commercial instrument (Picarro, G2131-i) with the noise of 8.5 ppbv. Hu et al. (2021b) built a fiber-optic integrated CRDS system with a detection limit of 1.8 ppm to detect CO_2 dissolved in seawater. The maximum deviation between this system and a commercial instrument (Picarro, G2201-i) is just 1.3%. Li et al. (2018a; 2018b) reported a NO_3/N_2O_5 -CRDS system with detection limits for NO_3 and N_2O_5 being 0.5 ppt and 0.7 ppt (1 σ , 30 s), respectively.

Moreover, nighttime observations of NO_3 and N_2O_5 using this system in different regions, such as Yangtze River Delta region and Beijing-Tianjin-Hebei region, were carried out to understand the concentration levels and change patterns of tropospheric NO_3 and N_2O_5 (Lin et al., 2022b).

For CRDS technique, the linewidth of the laser is usually on the order of MHz, while the linewidth of the optical resonant cavity mode is usually on the order of kHz. The difference in the linewidth reduces the coupling efficiency and coupling accuracy. In addition, the coupling state of laser and cavity mode is easily broken by the fluctuation of external environment. Therefore, the efficient and stable coupling of laser and cavity mode is the unremitting pursuit of CRDS development.

2.7 Laser heterodyne spectroscopy (LHS)

Laser heterodyne spectroscopy (LHS) is a high-resolution coherent spectroscopy measurement technique. Its working principle is as following: first, the laser and broadband light source are used to beat frequency in the photosensitive surface of the photodetector; then the obtained differential frequency signal is processed and detected by the radio frequency device; then it is demodulated by the lock-in amplifier, so as to obtain the target signal. The LHS technique combines the advantages of high spectral resolution and small system size. It is mainly applied to detect the column density and vertical profiles of CO_2 , CH_4 , H_2O , O_3 , N_2O , etc. At present, NASA has developed LHS mounted on CubSat to detect stratospheric CO_2 , CH_4 , H_2O (Wilson et al., 2017). The Rutherford Laboratory at the University of Oxford has developed a ground-based mid-infrared (MIR) LHS to detect the vertical profiles of CO_2 and H_2O , and it has been combined with mid-infrared air-core optical waveguide technology to further develop a satellite based mid-infrared LHS to detect CH_4 isotope (Weidmann et al., 2011; 2017). China's first research work on LHS was carried out in 2015 by Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences (Tan et al., 2015). Deng et al. (2022) integrated semiconductor optical amplification into the LHS, substantially improving the signal-to-noise ratio of the heterodyne signal. LHS technology has the problem of signal loss caused by signal light intensity modulation and the difficulty in improving signal-to-noise ratio of the heterodyne signal caused by the theoretical limitation of optical antenna. Moreover, the development of intrinsic vibration light modulation technique significantly improved the detection performance of LHS (Deng et al., 2020a; 2021; Li et al., 2023c).

The improvement of the performance of the heterodyne system and the accuracy of the atmospheric a priori parameters are the key factors for accurate retrieval of the vertical profiles of greenhouse gases. Therefore, there is

still a need to develop signal-to-noise ratio enhancement techniques and improve the retrieval algorithm to get rid of the a priori atmospheric parameters, with a view to further improving the accuracy of greenhouse gas detection.

2.8 Fluorescence assay by gas expansion (FAGE)

Considering the high activity, short lifetime and low concentration of HO_x radicals, the sensitivity of the measuring instrument is extremely demanding. Gas-expanded laser-induced fluorescence (FAGE-LIF) technology has the advantages in high sensitivity and low interference. Based on the ultrasonic jet sampling technique, the ambient atmosphere is sampled by millimeter-level nozzles into a low-pressure fluorescence cell, where the sampled gas stream is rapidly expanded to meet the 308 nm laser beam, and then excites to OH radical resonance fluorescence. By injecting NO into the cell, the chemical conversion of $\text{HO}_2 \rightarrow \text{OH}$ is accomplished with a fixed efficiency, which in turn completes the indirect measurement of HO_2 radical. Marno et al. (2020) provided a detailed account of the application of the FAGE technique for measuring OH and HO_2 under varying pressure, humidity, internal air density, and internal quenching conditions. Through the development of the all pressure altitude-based calibrator for HO_x experimentation (APACHE) system, airborne LIF-FAGE accurately measured OH and HO_2 across a wide range of variations encountered. Bottorff et al. (2021) developed a novel instrument based on laser photolysis and LIF for detecting OH radicals. This method, akin to the traditional FAGE technique, incorporates a laser photolysis step to enhance measurement sensitivity and accuracy for HONO and OH. Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences has developed an online detection system for atmospheric HO_x (OH, HO_2) radicals (HO_x -FAGE) with independent intellectual property rights, which realizes highly sensitive detection of HO_x radicals (Wang et al., 2019). The detection limits of OH and HO_2 radicals were $3.3 \times 10^5 \text{ cm}^{-3}$ and $1.1 \times 10^5 \text{ cm}^{-3}$, respectively, at 60 s time resolution. Moreover, the comparison campaign was carried out with peking university laser-induced fluorescence system (PKU-LIF) developed by peking university and Jülich Research Centre, which validates the applicability of our system in complex atmospheric environments (Zhang et al., 2022). In recent years, in response to the need for coordinated control of O_3 and $\text{PM}_{2.5}$, the HO_x -FAGE online system has been used to carry out radical outfield measurements in urban, suburban and background environments in China (including Beijing, Shanghai, Shenzhen, Chengdu, Nanjing, Hefei, Xizang, etc.) (Wang et al., 2019; 2021d; Zhang et al., 2022a; 2022b; 2023).

HO_x -FAGE system has the technical advantages of high sensitivity, low detection limit and fast response, but its

complex composition limits the further expansion of its application scenarios. Therefore, the research on miniaturization and integration of HO_x-FAGE system can help to extend the radical detection to other platforms, such as airborne and vehicle. It will further enhance Chinese research level in the field of HO_x radical detection.

3 Perspectives and outlook

At present, much improvement has been achieved for China's independent research and development of equipment and technology in terms of remoteness, intelligence, support for scientific decision-making and precise supervision (Liu et al., 2022). However, ion sources, ultraviolet lasers, mid-infrared lasers, photodetectors, highly sensitive imaging detectors, ultraviolet wavelength multiple reflection cell, quadrupole and other key stranglehold components need to make further breakthroughs. In the context of coordinated control of O₃ and PM_{2.5} as well as carbon peaking and carbon neutral, the following fields of atmospheric environmental science should be given more emphasis.

3.1 The new optical monitoring techniques and the construction of stereoscopic monitoring system

The need to upgrade monitoring technology is becoming increasingly urgent. About satellite remote sensing, the development of domestically produced high-orbit geostationary satellite payloads and algorithms should be focused on, in order to meet the needs for large-scale, higher spatiotemporal resolution, and more pollutants and greenhouse gas components. About air-based monitoring, unmanned aerial vehicle (UAV) remote sensing technology and the corresponding new type of UAV remote sensing payloads should be developed, facing the demand for higher monitoring spatiotemporal resolution and accurate localization at a meter level. About ground-based monitoring, new optical *in situ* detection technologies, new optical stereoscopic detection technologies (horizontal and vertical detection) and new optical imaging detection technologies should be developed to meet the needs for higher precision quantification of concentrations, stronger detection of new components and more accurate transport/diffusion evaluation. In addition, environmentally friendly monitoring technologies should also be vigorously developed, such as solar-powered monitoring instruments.

It is difficult to meet the multiple requirements of pollutants and greenhouse gases monitoring using a single technology, and different monitoring platforms have their own advantages and disadvantages. Therefore, multi-platform and multi-technology joint observation has become an important means of monitoring atmospheric

pollutants and greenhouse gases. Effective monitoring of pollutant and greenhouse gases on multiple spatial scales and time scales can be achieved through the construction of a full-time, full-scale, full-spectrum, full-element satellite remote sensing observation network and a ground-based stereoscopic remote sensing monitoring network.

3.2 Increased focus on interdisciplinarity

The atmosphere plays a key role in the earth-climate system and is closely linked to the biosphere, pedosphere, hydrosphere and cryosphere. Multi-circle cross-study is bound to become an important direction and an inevitable trend in geoscientific research. Research in atmospheric science must make full use of modern scientific means, such as advanced detection means (satellite remote sensing, etc.) and advanced computational tools (artificial intelligence and supercomputers, etc.). Moreover, the development of atmospheric science should use results and methods from disciplines such as advanced mathematics, physics, chemistry and biology, as well as advanced 5G communication technology, GPS technology, etc.

In addition, with the advent of the big data era and the development of supercomputer and processor technology, the development of machine learning technology in the earth discipline should be accelerated. The key development directions include the construction of a multi-component-driven machine learning network architecture and the development of machine learning-based prediction techniques. Artificial intelligence can drive the development of numerical forecasting in the future. First, it can play a role in parts that require big data and statistical computation, such as in ensemble forecasting, data assimilation, and statistical post-processing of forecast products. The second is to play a role in accelerating computation, such as artificial intelligence agent algorithms (accelerated computation) for some computational modules with large computational time consuming, artificial intelligence solvers for partial differential equations, etc. Third, it may play a role in improving the performance of the model, such as parameterisation of parts of the computation that cannot be resolved after numerical discretisation.

3.3 Increased emphasis on monitoring of greenhouse gases and research on atmospheric chemistry

As the increase of greenhouse gases, such as CO₂ and CH₄, is contributing to global warming, which will have many adverse effects on the climate and the environment. Therefore, we should pay more attention to the monitoring of greenhouse gases and the study of atmospheric chemistry. The sources of carbon emissions in China are complex and diverse. Greenhouse gases are not only

emitted locally, but also transported from external regions. Moreover, transport occurs not only near the ground surface, but also at high altitudes. Together with the interference of the complex environment in China, such as high aerosol and compound pollution, this has posed an unprecedented challenge to the monitoring and evaluation of carbon source and carbon sink. The key issues that need to be urgently resolved in developing China's independently controllable and internationally credible carbon source/sink monitoring and evaluation system are: 1) How to accurately monitor anthropogenic carbon emissions to reduce the uncertainty of regional carbon source and sink accounting under the complex interaction of multi-circle ecological environments? 2) How to integrate stereoscopic observation and multi-circle earth models to predict the evolution of carbon sources and sinks? The main technical needs to address above issues are: 1) to independently develop high-end carbon source/sink monitoring technology and equipment as well as core components; 2) to deploy networks for monitoring pollution sources and background greenhouse gases; 3) to establish autonomous and controllable systems and algorithmic software for global carbon monitoring and evaluation; 4) to establish a well-functioning, open and efficient platform for verification and evaluation of carbon source/sink monitoring technologies.

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Appendix A

Table 1A Abbreviations used in text, sored alphabetically

Abbreviation	Meaning
ACDL	Aerosol and carbon dioxide detection lidar
AD-Net	Asian dust and aerosol lidar observation network
APACHE	All pressure altitude-based calibrator for HO _x experimentation
BREDOM	Bremen DOAS network for atmospheric measurements
CRDS	Cavity ring-down spectroscopy
DOAS	Differential optical absorption spectroscopy
EMI	Environment Monitoring Instrument
ESA	European space agency
FAGE	Fluorescence assay by gas expansion
FTIR	Fourier transform infrared spectroscopy
GMI	Greenhouse gas monitoring Instrument
LEDs	Light-emitting diodes
LHS	Laser heterodyne spectroscopy
LIDAR	Light detection and ranging
LIF	Laser-induced fluorescence
LP-DOAS	Long path differential optical absorption spectroscopy
MADRAS	MAX-DOAS network over Russia and Asia
MAX-DOAS	Multi-axis differential optical absorption spectroscopy
MIR-LHS	Mid-infrared laser heterodyne spectroscopy
MPLNET	Micro pulse lidar network
NASA	National aeronautics and space administration of the United States of America
NOVAC	Netwok for observation of volcanic and atmospheric change
Polly ^{NET}	Raman and polarization lidar network
TCCON	Total column carbon observing network
TDLAS	Tunable diode laser absorption spectroscopy
UAV	Unmanned aerial vehicle
USTC	University of science and technology of China

Author Biography



Wenqing Liu, Professor, is the director of the academic committee of Hefei Institutes of Physical Science, Chinese Academy of Sciences, and the academic director of Anhui Institute of Optics and Fine Mechanics. He is also the vice chairman of Chinese Society for Environmental Sciences, the Vice Chairman of the Chinese Optical Society, and the Vice Chairman of China Instrument and Control Society.

He is mainly engaged in the research of environmental monitoring technology and application, developed new methods of environmental optical monitoring, developed a series of environmental monitoring equipment and being industrialized, and integrated a comprehensive stereoscopic monitoring system for air pollutants. He developed a new field of environmental optical monitoring technology in China. His research achievements have won 3 times second prize of National Scientific and Technological Progress in 2007, 2011 and 2015, and 5 provincial and ministerial first-class scientific and technological awards. He was honored with the Anhui Province major scientific and technological achievement award in 2012, the science and technology achievement award by Ho Leung Ho Lee foundation in 2016, and the worker “National Advanced Worker” in 2020. He was elected as an academicians of the Chinese Academy of Engineering in 2013.