Monitoring greenhouse gases (GHGs) in China: status and perspective

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Abstract

In order to establish a creditable greenhouse gases (GHGs) monitoring network to support the goals of carbon peak/neutrality, it is necessary to know what we have done and what we have to do in the future. In this study, we summarize an overview to the status and perspective of GHGs monitoring in China. With decades of effort, China has made a great breakthrough in GHGs monitoring capacity and steadily improved the performance of homemade GHGs monitoring instruments. However, most GHGs monitoring studies are hitherto research-oriented, temporal, sparse, and uncoordinated.

It is suggested to take full advantages of various monitoring technologies, monitoring platforms, numerical simulations, and inventory compilation techniques to form a creditable GHGs stereoscopic monitoring and assessment system at an operational level. We envisage that this system can routinely quantify GHGs on national, provincial, regional and even individual scales with high spatiotemporal resolution and wide coverage to support low-carbon policy in China.

Keywords:
Carbon peak; Carbon neutrality; Greenhouse gases; Carbon monitoring

1. Introduction

Climate change is one of the great challenges facing humankind around the globe (Tian et al., 2017; Sun et al., 2021; Liu et al., 2022). According to the United Nations Intergovernmental Panel on Climate Change (IPCC) estimates, in order to achieve the 1.5° target of the Paris Agreement, the integrated Earth system must achieve net zero carbon dioxide (CO_2) emissions (also known as "neutrality") by 2050, i.e., the annual CO_2 emissions are equal to the amount of CO_2 reductions through strategies that can either increase carbon sinks or reduce carbon sources, e.g., decarbonization, carbon offset, energy consumption reduction, tree-planting, carbon capture and storage (CCS), and carbon sequestration (Zheng et al., 2020a). Carbon neutrality is an important strategy to tackle global climate change (IPCC, 2019). Currently, there are 137 countries around the globe have proposed carbon neutrality deadlines through policy announcements or legislation. Most of these countries such as the ones from the European Union, the United States, Japan, the Great Britain, Australia, Canada, New Zealand, South Africa, have committed to achieve carbon neutrality by 2050 (IPCC, 2019). A few countries such as Germany have brought forward their carbon neutrality deadline to 2045 (IPCC, 2019). Since most developed countries have already achieved carbon peak, they only need to continue their previous greenhouse gases (GHGs) reduction strategies for achieving their carbon neutrality goals, and thus their carbon reduction tasks are relatively easy to realize (IPCC, 2019). Although the total carbon emissions are still increasing, China is committed to achieving the goals of carbon peak by 2030 and carbon neutrality by 2060 (Liu et al., 2022). Considering much of China's economic growths in current stage still rely on the high-carbon energy previously implemented by the developed countries, the next 30 years will be a critical period for

China to balance its economic development with industrial transformation. During the 14th Five-Year Plan stage, China's ecological civilization construction will step into a critical stage for upgrading its ecological environment quality (Zhao et al., 2021). In addition to continuing current pollution control policies, this stage will promulgate a series of carbon reduction measures to achieve an initial low-carbon transformation for economic and social development (Yang et al., 2021a).

To tackle climate change, it is critical to have creditable information on GHGs with respect to who, which emission sector and how much quantity are responsible for the emissions (Boesch et al., 2021). This information allows assessment of the effectiveness of GHGs mitigation initiatives, strategies, and policies. Especially it allows assessment of how much GHGs reductions are being met at global, national, sector, or even individual point source. It also allows GHGs trading schemes to be functional since such schemes would have no integrity without credible trading units. This credibility determines if buyers and sellers will have confidence in such trading schemes (Boesch et al., 2021). Accurate GHGs information is also crucial for investigating the relationship between global warming and GHGs (Wunch et al., 2010; Wunch et al., 2011). By accurately capturing the diurnal, monthly, seasonal, and inter-annual variabilities of key GHGs, we can speculate their sources and sinks, reveal the physical and chemical mechanisms that drive their variabilities, predict their future trends, and understand how GHGs emissions interact with the atmosphere and how the climate responds to both natural and anthropogenic GHGs emissions (Wunch et al., 2011b). In addition, a creditable GHGs monitoring system could not only promote the investigation of carbon cycle, but also support the development of chemical transport models (CTMs) and emission inventory compilation technology around the globe (MacFaul, 2007; Yang et al., 2020).

In order to establish a creditable GHGs monitoring network to support the goals of carbon peak/neutrality in China, it is necessary to know what we have done and what we have to do in the future. In this study, we summarize an overview to the status and perspective of GHGs monitoring in China. There is a very large number of topics and literature related to GHGs, this work cannot be capable to summarize all of them, but will attempt to condense the major information in the field of GHGs monitoring capacity in China. In section 2, we briefly introduce the history of GHGs monitoring around the globe. Section 3 and section 4 summarize the status and typical advances of GHGs monitoring in China. Section 5 discusses main challenges that need to be addressed for developing creditable GHGs stereoscopic monitoring network in China. In section 6, we present a perspective for future development of GHGs monitoring in China. Section 7 gives the conclusions.

2. History of GHGs monitoring around the globe

The first continuous monitoring of atmospheric GHGs was started at Mauna Loa (155.6°W, 19.5°N) in Hawaii in 1957 (MacFaul, 2007). In situ GHGs measurements at this station were based on nondispersive infrared (NDIR) spectroscopic technology, and were conducted by the National Oceanic and Atmospheric Administration (NOAA), the United States. Subsequently, NOAA expanded such continuous routine monitoring of atmospheric GHGs to Barrow (156.6°W, 71.3°N), American Samoa (170.6°W, 14.2°S), and the South Pole (59.0°E, 90.0°S) (MacFaul, 2007). Long-term time series of GHGs measurements at the four observatories show that global atmospheric CO_2 concentration increased year by year in the past 50 years (Fig. 1). Furthermore, the Global Atmosphere Watch (GAW) network organized by the World Meteorological Organization (WMO) measures atmospheric GHGs from several ground-based and tower-based stations around the globe (Fig. 2). Currently, the GAW only operates one global station (Mt. Waliguan (100.9°E, 36.3°N)) and three regional stations (Lin'an (119.7°E, 30.3°N), Longfengshan (127.6°E, 44.7°N), and Shangdianzi (117.2°E, 40.7°N)) within China (Fang et al., 2014; Fang et al., 2015a; Fang et al., 2015b; Fang et al., 2016). Most GAW ground-based and tower-based stations use commercially available cavity ring-down spectroscopic (CRDS) instruments to achieve high-precision measurements of GHGs (Gomez-Pelaez et al., 2019). Furthermore, GAW also operates many airborne in situ monitoring instrumentations for atmospheric GHGs monitoring around the globe (Fig. 2). These airborne measurement campaigns include the Intercontinental Chemical Transport Experiment–North America campaign (INTEX-NA) and the CO_2 Budget and Rectification Airborne – Maine experiment (COBRA-ME) over the United States during 2004–2005 (Gerbig et al., 2003; Lin et al., 2006; Singh et al., 2006); the Tropical Warm Pool International Cloud Experiment (TWP-ICE) over Australia in 2006; the HIAPER aircraft campaign following the START-08 and HIPPO campaigns in 2008 and 2009; the Beechcraft King Air aircraft campaign over Tsukuba, Japan in 2009, and Learjet overflights over Lamont, the United States in 2009 (Wunch et al., 2010).

Optical remote sensing techniques sampling the total atmospheric column have been developed throughout the last two decades and have been found to be very useful for monitoring atmospheric GHGs (Wunch et al., 2011b). A series of state-of-the-art satellites with different spatiotemporal resolutions, including SCIAMACHY (Schneising et al., 2012; Dils et al., 2014; Houweling et al., 2014; Buchwitz et al., 2015; Heymann et al., 2015; Kulawik et al., 2016) and TROPOMI (Butz et al., 2012; Veefkind et al., 2012; Pandey et al., 2019; Wang et al., 2020a; Zhang et al., 2020b; Barre et al., 2021; Pandey et al., 2021; Park et al., 2021; Qu et al., 2021; Sha et al., 2021; Shen et al., 2021) by European Space Agency (ESA), GOSAT and GOSAT-2 by Japan (Butz et al., 2011; Morino et al., 2011; Cogan et al., 2012; Yoshida et al., 2013; Deng et al., 2014; Parker et al., 2020; Boesch et al., 2021), OCO-2 and OCO-3 by the United States (Thompson et al., 2012; Frankenberg et al., 2015; Eldering et al., 2017; Nassar et al., 2017; Patra et al., 2017; Wunch et al., 2017; Wang et al., 2020a; Zheng et al., 2020a; Zheng et al., 2020b; Hu and Shi, 2021; Kiel et al., 2021), TanSat (Liu et al., 2013; Liu et al., 2014; Liu et al., 2018; Yang et al., 2018a; Yang et al., 2018b, c; Zhang et al., 2019; Yang et al., 2020d; Bao et al., 2020; Wang et al., 2020c; Yang et al., 2020a; Yang et al., 2021a; Yang et al., 2021b) and Gaofen-5 (GF-5) series satellites by China (Li et al., 2016; Wu et al., 2018; Zhang et al., 2020a; Zhao et al., 2021), GHGSat by Canada (Varon et al., 2019; Jervis et al., 2021), etc., have been launched to derive the global distributions of GHGs. These satellites mainly measure total columns of GHGs by means of infrared grating or Fourier transform infrared (FTIR) spectrometers through atmospheric limb or nadir observations. SCIAMACHY, GOSAT, OCO-2, and TanSat have XCO_2 precisions of 2.5ppmv, 1–2 ppmv, ~1 ppmv, and 1–4 ppmv, respectively (Reuter et al., 2011; Nassar et al., 2017; Boesch et al., 2021; Yang et al., 2020a). Studies with satellite data have yielded anthropogenic CO_2 flux estimates at the scale of megacities or larger regions (Eldering et al., 2017), and recently have extended CO_2 emissions estimate at the scale of an individual facility, such as a single power plant (Nassar et al., 2017; Zheng et al., 2020a). Jacob et al. (2022) have summarized the capability of current and scheduled satellite observations of atmospheric methane in the shortwave infrared (SWIR) to quantify CH_4 emissions from the global scale down to point sources, where XCH_4 precisions of various satellites were presented.

Ground-based high resolution FTIR spectrometers are powerful tools for deriving total columns and profiles of GHGs (Wunch et al., 2011a). Both the Total Carbon Column Observing Network (TCCON) and the Network for Detection of Atmospheric

Composition Change-Infrared working group (NDACC-IRWG) use high resolution FTIR spectrometers (mainly IFS120HR/IFS125HR series spectrometers manufactured by Bruker, Germany) to observe total columns and profiles of GHGs and atmospheric pollutants (Chevallier et al., 2011; Messerschmidt et al., 2011; Saito et al., 2012; Kuai et al., 2012; Connor et al., 2016; Kiel et al., 2016; Belikov et al., 2017). The TCCON/NDACC-IRWG networks were operating since 2004/1992 and provided time series of many atmospheric constituents, including GHGs such as H_2O, HDO, CO_2, CH_4, CH_3D, N_2O, SF_6, O_3, C_2H_6, CCl_3F, CCl_2F_2, and $CHClF_2$. For solar zenith angles (SZAs) of less than 80°, the total errors of X_{CO2}, X_{CH4}, and X_{N2O} are less than 0.25% (~1ppmv), 0.5% (~5ppbv), and 1% (~3 ppbv), respectively (Wunch et al., 2011b). These observations have been extensively used in investigations of carbon cycle, carbon source and transport, satellite validation, development of remote sensing algorithm, and evaluation of atmospheric CTMs. Currently, there are only ~30 TCCON/NDACC-IRWG joint stations around the globe, most of them distributed in Europe and Northern America, and the number of stations in other parts of the globe is sparse (Fig. 3). Currently, only two TCCON stations have been set up in China, the Hefei station (117.2°E, 32.0°N) and the Xianghe station (116.96°E, 39.75°N) (Tian et al., 2017; Wang et al., 2017; Yang et al., 2020c).

Despite their outstanding capabilities such as high precision and stability, the high-resolution IFS120/125HR FTIR spectrometers also have their limitations. They are expensive and ponderous spectrometers; their operation relies on a large number of infrastructure and the maintenance for their optical alignments are difficult and time consuming. In order to address these issues, the usage of cheaper, smaller, and more transportable FTIR spectrometers has been investigated in recent few years. These FTIR spectrometers including EM27/SUN and VERTEX-80/SUN manufactured by Bruker, Germany have been verified to have comparable capacity as the IFS125HR with respect to GHGs monitoring. The transportability of the EM27/SUN and VERTEX-80/SUN spectrometers favor campaign use, and many successful campaigns were conducted by various scientists (Hase et al., 2015; Hedelius et al., 2016; Frey et al., 2019; Vogel et al., 2019; Ars et al., 2020; Jacobs et al., 2020; Tu et al., 2020; Frey et al., 2021; Mermigkas et al., 2021). Generally, scientists first use high accuracy of high resolution FTIR dataset to calibrate the EM27/SUN and VERTEX-80/SUN spectrometers, and then use the transportable spectrometers to derive the emission rate of a city, an industrial facility or a landfill. With the transportable EM27/SUN spectrometers, the COllaborative Carbon Column Observing Network (COCCON) has been built to derive column-averaged abundances of GHGs over the world (Hase et al., 2015; Frey et al., 2019). The EM27/SUN and VERTEX-80/SUN observations can complement the high-resolution FTIR observations around the globe (Table S2).

In addition to the network-based routine observations, there are also many research-oriented GHGs campaigns around the globe, and these uncoordinated behaviors are too numerous to count accurately (Gerbig et al., 2003; Lin et al., 2006; Zellweger et al., 2016; Gomez-Pelaez et al., 2019; Liu et al., 2021a; Liu et al., 2021b). These GHGs measurements are proceeded using by either CRDS, NDIR spectroscopy, off-axis integrated cavity output spectroscopy (OA-ICOS), gas chromatography with flame ionisation detection (GC/FID) technique, FTIR spectroscopy or differential absorption LIDAR (DIAL) implemented on different platforms (Krings et al., 2011; Krings et al., 2013; Zellweger et al., 2016; Krautwurst et al., 2017; Krings et al., 2018; Krautwurst et al., 2021). For example, the airborne MAMAP (Methane Airborne Mapper) spectrometer developed by University of Bremen can be used to derive point source rates of CH_4 and CO_2 (Krings et al., 2011; Krings et al., 2013; Krings et al., 2018). Japanese scientists have developed a grating based optical spectrum analyzer (OSA) and an optical fiber Fabry-Perot interferometer (FFPI) to measure atmospheric CO_2 and CH_4 total columns (Kobayashi et al., 2010).

Overall, the international community has established a series of monitoring networks to measure GHGs on different spatiotemporal scales. Taking the advantage that all GHGs have spectral absorptions in the infrared waveband, most of these networks are established by means of various spectroscopic instruments. These stereoscopic monitoring networks combining the emission inventory compilation and CTMs have formed the state-of-the-art GHGs monitoring and assessment system (Zellweger et al., 2016; Krautwurst et al., 2021), which is extensively used by the United Nations Framework Convention on Climate Change (UNFCCC) to assess GHGs emissions on global, national and regional scales, and identify who, which emission sector and how much quantity are responsible for respective GHGs emissions (IPCC, 2019).

3. Status of GHGs monitoring in China

The global energy consumption data discloses that China has overtaken the United

States in 2006 as the world's top CO_2 producer, i.e., the biggest anthropogenic contributor to global warming (IPCC, 2019). The severity, extension, complexity, and the need-to-cut scale of GHGs emissions in China are unrivaled compared to other countries (Liu et al., 2022). Facing one of the most serious climate change problems around the globe, China has to address a series of scientific, technical, and management issues to achieve the goals of carbon peak/neutrality. As China pays more and more attention to climate change, Chinese government has put a large effort into the development of GHGs monitoring capacity. Although efforts to monitor GHGs in China have hitherto been largely uncoordinated with the established international networks, the GHGs monitoring capacity has been steadily improved. Chinese scientists have conducted many GHGs monitoring studies in urban agglomerations or typical industrial parks in different city clusters such as the Yangtze River Delta (YRD), North China Plain (NCP), Pearl River Delta (PRD) (Tian et al., 2017; Tian et al., 2018; Wang et al., 2019; Li et al., 2021; Liu et al., 2021b), in background areas such as Waliguan in Qinghai Province and Longfengshan in Heilongjiang Province (Fang et al., 2014; Fang et al., 2015a; Fang et al., 2016), and in offshore areas such as the South China Sea, Yellow Sea, and Bohai Bay (Gerbig et al., 2003; Liu et al., 2021a; Liu et al., 2021b). Research institutions, monitoring technologies, monitoring platforms, monitoring scales, monitoring applications, and typical advances can be summarized in Table 1. We elaborate this as follows.

1. Monitoring technologies include a variety of active and passive measurement technologies, which mainly include Electrochemical (EC) sensing technology, Tunable Diode Laser Absorption Spectroscopy (TDLAS), Differential Optical Absorption Spectroscopy (DOAS), FTIR, NDIR, GC/FID, LIDAR, CRDS, OA-ICOS, Photoacoustic Spectroscopy (PAS), etc. All these techniques can be classified as spectroscopic technique except EC technology, which uses capacitive readout cantilevers to detect an absorbed signal (Zellweger et al., 2016; Liu et al., 2022). In most cases, the EC, TDLAS, NDIR, GC/FID, LIDAR, CRDS, OA-ICOS, PAS techniques are commonly used for active measurement platforms, while DOAS and FTIR techniques are extensively used for both active and passive measurement platforms. Fig.4 illustrates the principles of spectroscopic techniques for GHGs monitoring. The active measurement techniques (a, f) use artificial light source and the passive measurement techniques (b, c, d, e) use natural light sources such as sunlight to monitor GHGs. For both active and passive measurement techniques, the absorbed

signals can be detected from direct transmission (a, b), surface reflection (e) or atmospheric scattering (c, d, f). Currently, spectroscopic technique is the only technology that can be used to observe global GHGs from space.

2. Monitoring platforms include manual sampling analysis, surface in-situ measurement sites (e.g., laboratory measurement or surface monitoring network), ground-based remote sensing platforms (such as ground-based FTIR, LIDAR, and DOAS observatories), tower-based, airborne, space-based (e.g., GF-5 series, TanSat satellites, and space-borne LIDAR), ship-borne, vehicle-borne, unmanned aerial vehicle (UAV), balloon, tethered balloon and other monitoring platforms. Since any of a single monitoring platform cannot fully meet the requirements of stereoscopic monitoring of GHGs emissions due to its limited coverage or spatial resolution, scientists usually integrate a suite of observation platforms to form a stereoscopic monitoring system (Fig. 5). However, most stereoscopic GHGs monitoring activities in China are hitherto research-oriented, temporal, sparse, and uncoordinated with the established international networks (Fang et al., 2014; Tian et al., 2017; Wang et al., 2017; Tian et al., 2018; Yang et al., 2020c; Liu et al., 2021a; Liu et al., 2021b; Sun et al., 2021).

3. Monitoring spatial scale ranges from single point source, single constituent, small scale, regional scale to multi-point sources clustered, multi-constituent, large scale, global scale (Zellweger et al., 2016). Depending on monitoring technologies, constituents and platforms, monitoring temporal resolution ranges from second, minute, hour to day levels. Monitoring spatial resolution ranges from meter, dozens of meters, kilometer to dozens of kilometers. Monitoring accuracy ranges from thousandth level to percent level, and monitoring sensitivity ranges from ppbv to ppmv level. Usually the more abundant GHGs tend to produce stronger spectroscopic absorptions, which makes them easier to be separated from background, and thus can be monitored with high sensitivity. Although traditional EC or manual sampling analysis techniques are capable to measure many GHGs with satisfactory accuracy, they usually have limited coverage and can only measure one constituent at a time. In comparison, spectroscopic technology can have a larger coverage, wider monitoring range, more sensitivity, and can continuous real-time monitoring of multi-constituents at a time. Particularly, a single spectroscopic instrument can simultaneously monitor several GHGs without disturbing the samples, i.e., the monitoring process can be completely unattended. As long as an appropriate waveband is selected, the volume mixing ratio (VMR)

concentrations of some GHGs can be measured with a sensitivity of less than 1 ppmv. The coverage can be extended from several meters to several kilometers without multi-point sampling.

4. Monitoring targets include H_2O, HDO, CO_2, CH_4, CH_3D, N_2O, SF_6, O_3, C_2H_6, CCl_3F, CCl_2F_2, and $CHClF_2$ (Sun et al., 2018b). Monitoring regions include typical industrial zones, industrial stack emissions, urban atmosphere, ambient atmosphere, remote background regions, offshore regions, wetlands, etc. These GHGs measurements with different spatiotemporal scales have been extensively used in investigations of global carbon cycle, GHGs trends, regional GHGs sources and transport, ecological GHGs flux estimate, urban or industrial GHGs emissions estimates, validations of CTMs and emission inventory, multi-platform cross calibration, and algorithm improvement, etc (De Maziere et al., 2018; Tian et al., 2018; Sun et al., 2021).

4. Advances in GHGs monitoring in China

With decades of effort, China has made a great breakthrough in GHGs monitoring capacity and steadily improved the performance of homemade GHGs monitoring instruments. Typical advances in GHGs monitoring in China include, but are not limited to, the following aspects.

1. The TanSat and GF-5 series GHGs satellite payloads developed by China have successfully obtained high precision of global CO_2 distributions (Li et al., 2016; Wu et al., 2018; Zhang et al., 2020a; Zhao et al., 2021; Cai et al., 2022). The comparisons with the TCCON, GOSAT, and OCO-2 data show that some key performance indicators such as accuracy, precision, and spatiotemporal resolution of these Chinese GHGs satellites have reached the envisaged requirements (Liu et al., 2013; Liu et al., 2014; Cai et al., 2014; Du et al., 2018; Liu et al., 2018; Yang et al., 2018a; Yang et al., 2018b, c; Li et al., 2019; Zhang et al., 2019; Zhao et al., 2019; Bao et al., 2020; Wang et al., 2020c; Yang et al., 2020a, b; Yang et al., 2020d; Boesch et al., 2021;Yang et al., 2021a; Yang et al., 2021b). Both TanSat and GF-5 series GHGs payloads use passive remote sensing technology to derive global CO_2 distributions from scattered sunlight. As a result, they can only work in the daytime and are also seriously influenced by clouds and aerosols. The first Chinese space-borne CO_2 LIDAR onboard the atmospheric environment monitoring satellite launched on April 16, 2022 used active remote sensing technology

to derive global CO_2 distributions. Its operation does not rely on sunlight and is less influenced by clouds and aerosols, which will greatly improve the global CO_2 mapping capacity.

2. A series of in situ online, ground-based, and airborne instruments have been developed by Chinese scientists to investigate the diurnal, monthly, seasonal, and inter-annual variabilities and spatial distributions of key GHGs (Tang et al., 2006), speculate their sources and sinks, and reveal the physical and chemical mechanisms that drive their variabilities. For example, Chinese scientists have developed a suite of in situ spectroscopic instruments to measure surface VMRs and isotope ratios of GHGs in background atmosphere, sea-air CO_2 flux in coastal ocean boundary layer, and soil-air CO_2 flux in farmland (Gerbig et al., 2003; Liu et al., 2021a; Liu et al., 2021b). They have also developed a suite of ground-based spectroscopic instruments for measuring total columns of GHGs (Tian et al., 2018), vehicle-based spectroscopic instruments for industrial GHGs emissions, and airborne spectroscopic instruments for deriving the spatial distributions of CO_2 in the North China Plain (Wang et al., 2019; Shi et al., 2021).

3. The ground-based high-resolution FTIR observatory at Hefei has continuously observed the total columns or profiles of H_2O, HDO, CO_2, CH_4, CH_3D, N_2O, SF_6, O_3, C_2H_6, CCl_3F, CCl_2F_2, and $CHClF_2$ in eastern China since 2014, and has become a national infrastructure for ground-based validation of GF-5 series GHGs satellites and other space-borne instruments (Sun et al., 2018a; Sun et al., 2018b). The ground-based FTIR measurements at the Hefei observatory meet the TCCON quality requirements and this station has been formally accepted as a TCCON site in 2018. Ground-based FTIR CO_2 measurements at the Hefei observatory showed an increasing change rate of (2.71 ± 0.32) % per year between 2015 and 2019 (Fig. 6). A similar ground-based high-resolution FTIR observatory at Xianghe has also passed the TCCON quality inspection and joined the TCCON network in 2021 (Yang et al., 2020c). Furthermore, a few affiliations started to operate the portable EM27/SUN FTIR spectrometers and became COCCON members in recent three years (Frey et al., 2019; Liu et al., 2022; Che et al., 2022a; Che et al.,2022b; Cai et al., et al.,2021).

4. Some Chinese scientists have used the commercial in situ instruments such as Picarro or Licor series GHGs analyzers to investigate the spatiotemporal variabilities and emission flux of GHGs in different regions of China (Lin et al., 2006; Tang et al., 2006; Fang et al., 2016; Tian et al., 2018; Yi et al., 2019; Li et al., 2021; Liu et al.,

2021b). With the public accessible OCO-2 satellite data, Chinese scientists have estimated CO_2 anthropogenic emissions of cities and industrial regions in China. The satellite-based CO_2 emissions are generally in good agreement with the MEIC emission inventory values but are more different from the global gridded EDGAR and ODIAC emission datasets (Zheng et al., 2020a; Zheng et al., 2020b). Most recently, Chinese scientists have used the public accessible OCO-2 satellite observations to quantify CO_2 emissions down to individual point sources such as middle- to large-size coal power plants over China (Zheng et al., 2020a; Hu and Shi, 2021).

5. Challenges

Governments around the globe are committed to providing credible data to support global carbon budget, which promoted the emergence of the state-of-the-art GHGs monitoring technology in developed countries. As the world's top CO_2 producer, China faces both challenges and opportunities. One of the major challenges is how we can accurately monitor GHGs emissions under the complex carbon emission scenarios over China. GHGs emissions in China are complex and diverse (Liu et al., 2022). GHGs concentrations measured at a specific place include both local generation and long-range transport, which occurs not only near the surface but also in upper atmosphere. In addition, China has a complex ecological environment characterized as high aerosol levels, high variability, and compound pollution mixed with many constituents, which poses unprecedented challenges (i.e., increase monitoring uncertainty) to the establishment of GHGs stereoscopic monitoring network in China. Fortunately, China can learn experience from other countries (IPCC, 2019). Through in-depth cooperation with international community, China is possible to establish a reliable GHGs monitoring network with international credibility.

Accurate knowledge of regional GHGs emissions requires accurate measurements of GHGs variabilities on different spatial scales, including the in-situ "point" concentration reflecting small-scale level, the "column" concentration reflecting mesoscale level, and more importantly, the "profile" concentration reflecting vertical distribution of GHGs. In order to develop creditable GHGs stereoscopic monitoring network in China, some key technical questions need to be solved, which are summarized as follows.

1. In terms of specific in situ monitoring and remote sensing technologies, how can

different monitoring technologies and monitoring platforms learn from and complement each other by means of intensive comparison, verification and optimization?

2. In terms of organization and implementation, how to take full advantages of various monitoring platforms and technologies, make full use of their strengths and avoid their weaknesses, and make concerted efforts to achieve stereoscopic GHGs monitoring for specific carbon source and carbon sink scenarios?

3. In terms of data fusion, how to assimilate multiple datasets collected from different platforms and technologies to generate a new uniform dataset that have better coverage than the original dataset without reducing their accuracy, which would improve our understanding for carbon cycle mechanism and promote the development of GHGs forecasting model?

6. Future perspectives

Although much of China's economic growths in current stage still rely on the high-carbon energy previously implemented by the developed countries, China is committed to achieving the goals of carbon peak by 2030 and carbon neutrality by 2060. In order to support the formulation of low-carbon policies for achieving the goals of carbon peak/neutrality, China should improve its GHGs monitoring capability as soon as possible. It is suggested to take full advantages of various monitoring technologies, monitoring platforms, numerical simulations, and inventory compilation techniques to form a creditable GHGs stereoscopic monitoring and assessment (M&A) system. Implementation of this M&A system should be coordinated with the established international networks, and routinely quantify GHGs on global, national, provincial, regional, and individual point scales with high spatiotemporal resolution and wide coverage. Improved knowledge of carbon emissions on different scales is very useful for adjustment of low-carbon policy in China. In view of status, advances, and challenges of China's GHGs monitoring, future developments are expected to focus on the following aspects.

1. The development of high-end GHGs monitoring technology, instrument and core components should be strengthened to improve GHGs monitoring capacity in China. Development priorities include intelligent and miniaturized instruments dedicated for profile and flux of GHGs within multi-sphere ecological environment,

and key optical components such as high-resolution spectrometer, light source, solid laser, high-reflectivity mirror, narrow-band filter, detector, etc. It is expected that homemade GHGs monitoring instruments can meet routine GHGs monitoring demands in China in near future.

2. It is suggested to routinely monitor GHGs over typical GHGs sources and atmospheric background regions, which favors the verification of GHGs emission inventory and the implement of nationwide carbon trading. At present, the number of GHGs monitoring sites in China remains sparse. The rural regions are rarely covered and there are only few monitoring stations located in western China. GHGs are not included in the atmospheric constituents routinely monitored by the China National Environmental Monitoring Center (CNEMC) network. It is suggested to include key GHGs into China's surface environmental quality monitoring network, which will improve China’s GHGs monitoring capacity.

3. Since roughly 70% of the Earth is shrouded by clouds at any given moment and GHGs monitoring from space is prone to cloud interference, a single satellite can only provide a small number of observations per year suitable for emission estimates for any given GHGs source. It is necessary to routinely monitor GHGs over China with satellite constellation, which can offer better spatiotemporal resolution and coverage compared to a single satellite alone. Only with high spatiotemporal resolution and coverage, we can routinely quantify GHGs on global, national, provincial, regional, and individual point scales to support adjustment of low-carbon policy.

4. Monitoring data quality control, multi-source data fusion, and data sharing platforms should be systematized and standardized. By standardizing data quality control and data fusion technology of multi-source GHGs metadata and establishing a systematic data sharing mechanism, the metadata can be eventually applied in carbon reduction governance and decision-making by management departments.

5. It is suggested to establish an inter-departmental management agency for GHGs monitoring in China, where the government serves as the leader, and the technology holders and expert communities are participating. Furthermore, it is of great significance to unite environmental protection industry association of China, Chinese association of environmental science, research institutions, universities, enterprises and other professional communities to build a uniform verification standard for GHGs monitoring, which should be in cooperation with international networks/partners to achieve common global criteria. This verification standard can not only standardize

GHGs monitoring technology but also disclose its verification criteria and process, which can promote the implementation of new GHGs monitoring technology in China.

7. Conclusions

GHGs monitoring capability in China has achieved rapid improvement in recent years. Relying on homemade technologies and instruments, combined with public accessible space-borne observation instruments and open source remote sensing algorithms, China has conducted a suite of GHGs stereoscopic monitoring studies in different regions of China, but most of them are hitherto research-oriented, temporal, sparse, and uncoordinated with the established international networks. Some key technical indicators such as spatiotemporal resolution, coverage and accuracy need to be further improved. Furthermore, monitoring data quality control, multi-source data fusion, and data sharing platform have not been standardized.

In order to support the formulation of green economic policies for achieving the goals of carbon peak/neutrality, China should improve its GHGs monitoring capability as soon. It is suggested to take full advantages of various monitoring technologies, monitoring platforms, numerical simulations, and inventory compilation techniques to form a creditable GHGs stereoscopic monitoring and assessment (M&A) system. Implementation of this M&A system should be coordinated with the established international networks, and routinely quantify GHGs on global, national, provincial, regional, and individual point scales with high spatiotemporal resolution and wide coverage. Improved knowledge of carbon emissions on different scales is very useful for adjustment of low-carbon policy in China.

Data availability. The geolocations of all sites coordinated by NOAA and WMO, and all FTIR sites coordinated by TCCON, NDACC-IRWG, and COCCON are summarized in the supplement. All other data are available on request of YS (ywsun@aiofm.ac.cn).

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Figures

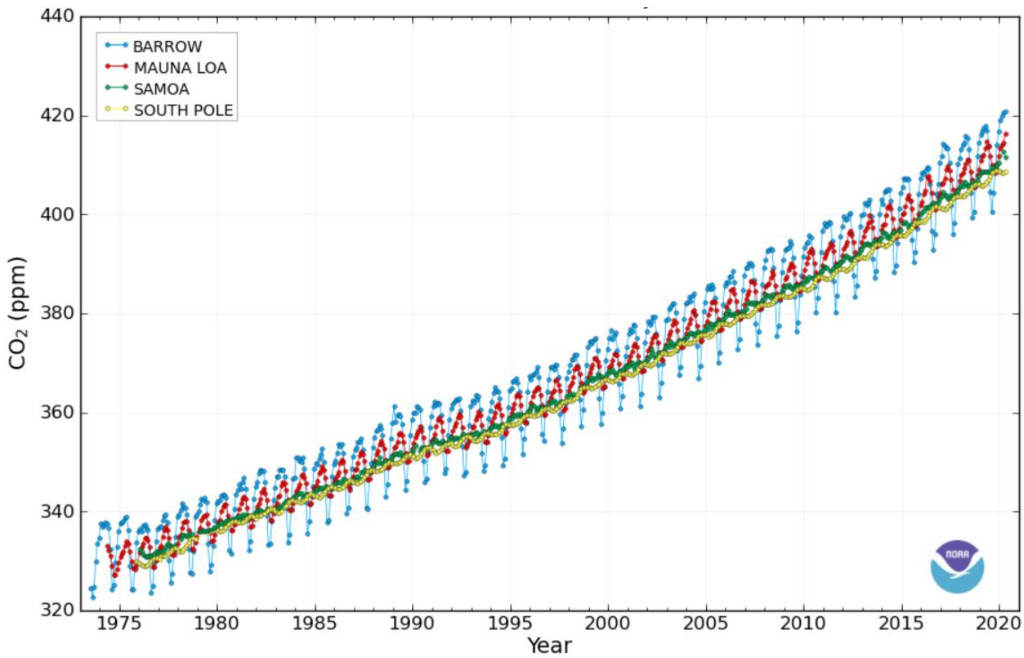

Fig. 1 Long-term time series of CO_2 at the Mauna Loa, Barrow, American Samoa, and South Pole observatories (adapted from https://gml.noaa.gov/)

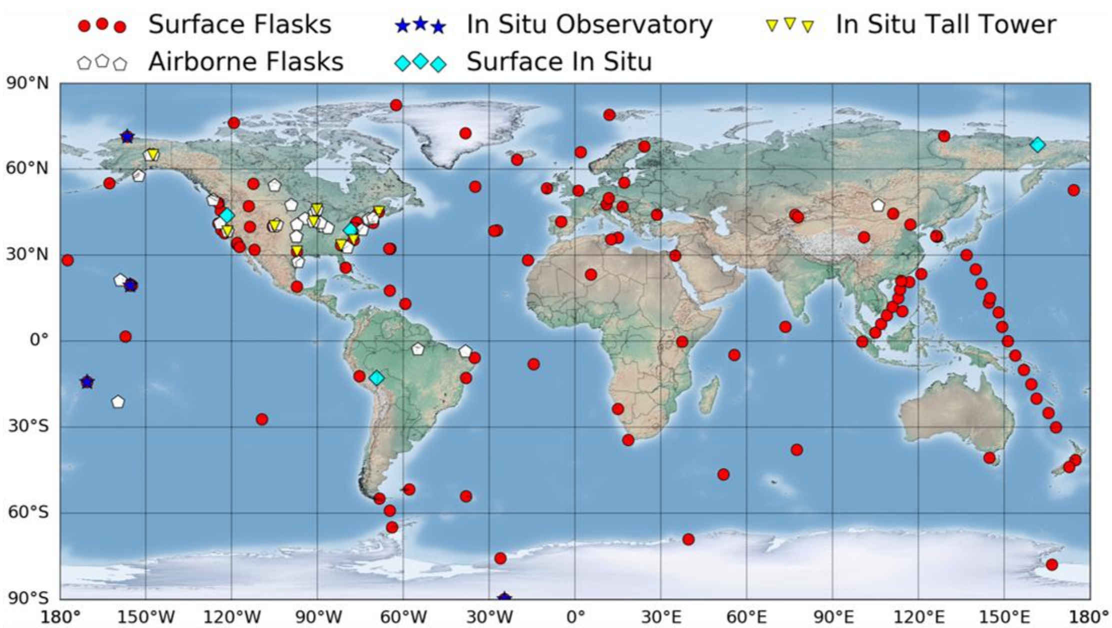

Fig. 2 Global GHGs monitoring network coordinated by NOAA and WMO. Geolocations of all sites are listed in Table S1. Base map of this figure is from the Basemap package of Python.

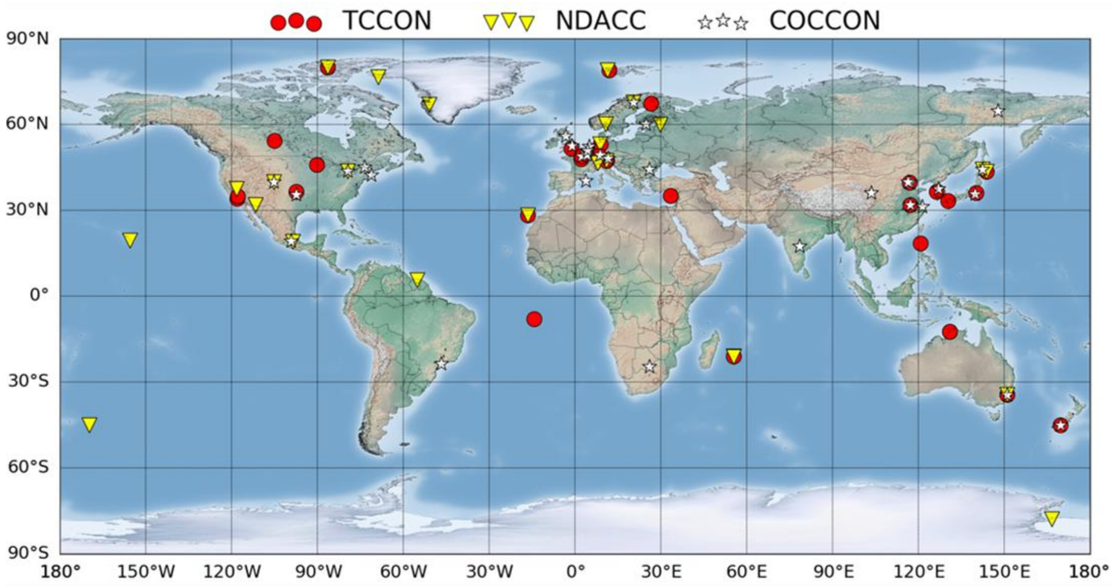

Fig. 3 Global FTIR observation networks, including TCCON, NDACC-IRWG, and COCCON networks. Geolocations of all sites are listed in Table S2. Base map of this figure is from the Basemap package of Python.

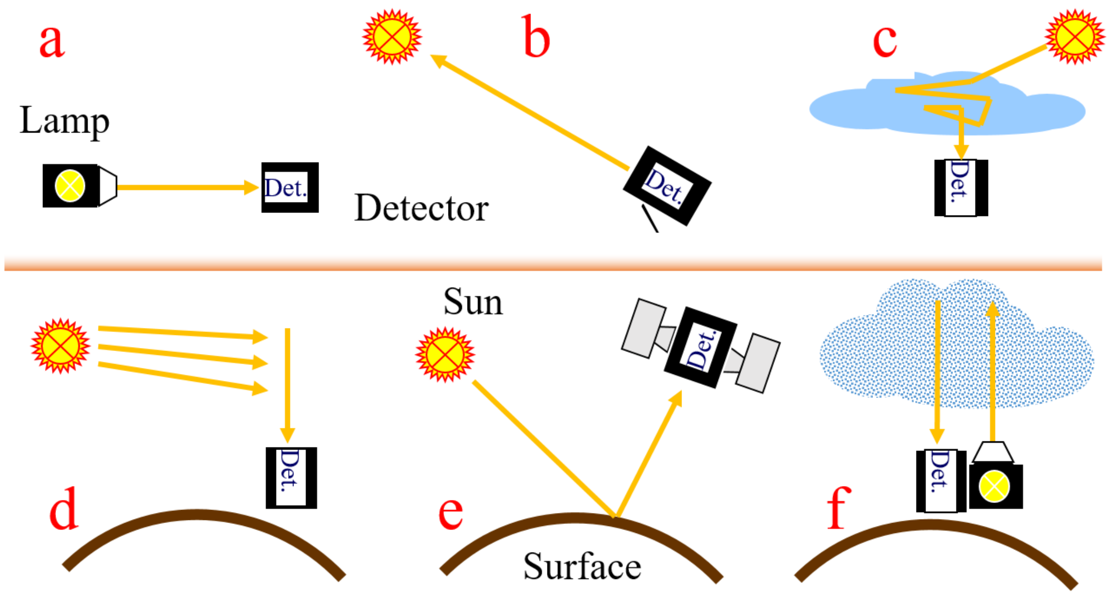

Fig. 4 Principles of spectroscopic techniques for GHGs monitoring. Active measurement techniques (a, f) use artificial light source and passive measurement techniques (b, c, d, e) use natural light sources such as sun to monitor GHGs.

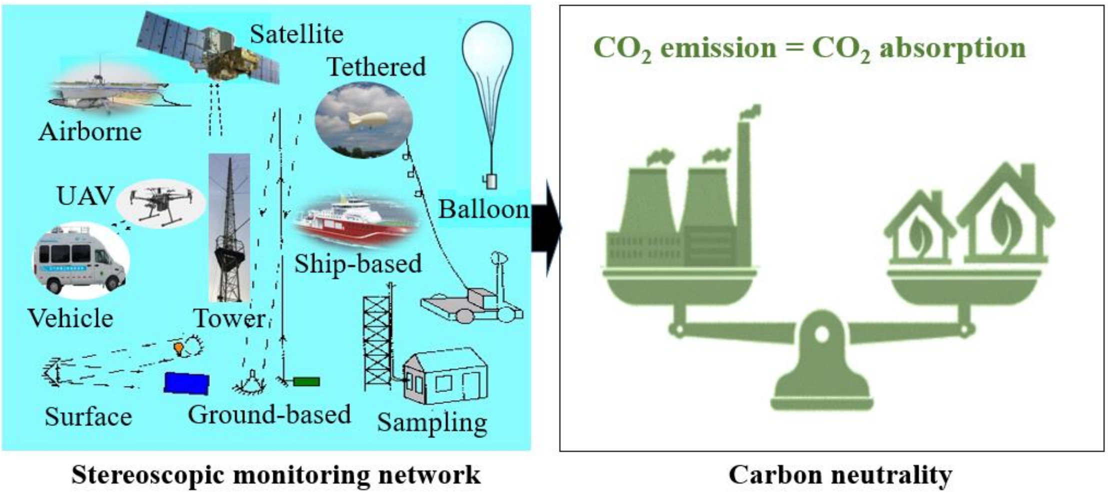

Fig. 5 Stereoscopic GHGs monitoring network to support carbon peak/neutrality in China

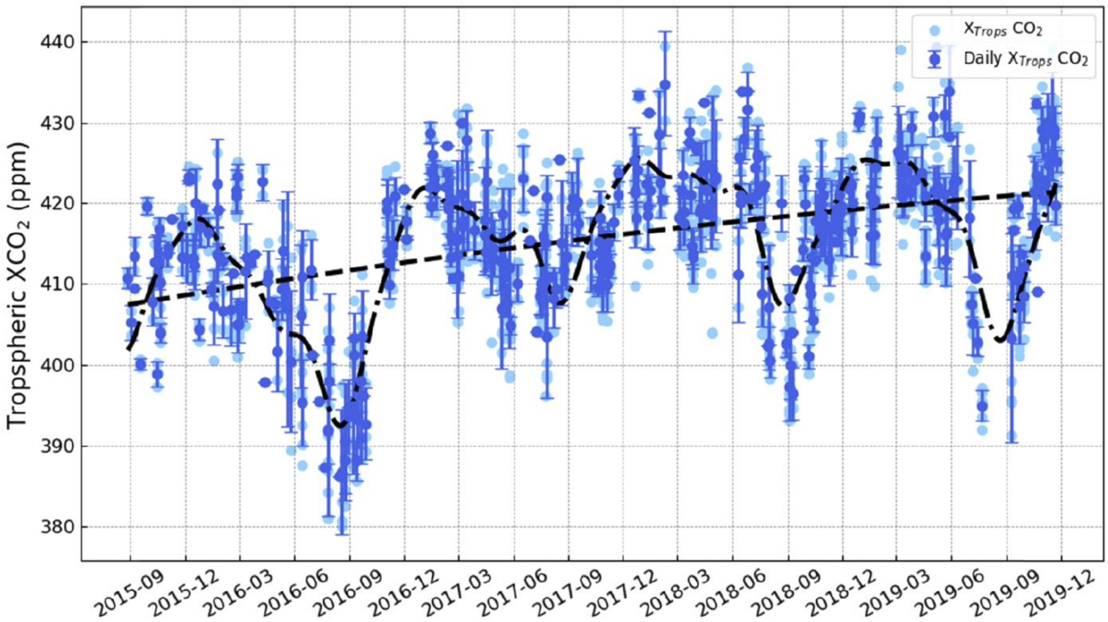

Fig. 6 Ground-based FTIR CO_2 measurements at the Hefei observatory (Shan et al., 2021). The seasonality and interannual variability are represented by black dashed curve and black dashed line, respectively, which are fitted by using a bootstrap resampling model with a 3rd Fourier series plus a linear function.

Tables

Table 1 Status of GHGs monitoring

Institutions	institutes of Chinese academy of sciences, universities, business units, and enterprises
Technologies	EC, DOAS, TDLAS, FTIR, NDIR, GC/FID, LIDAR, CRDS, OA-ICOS, PAS
Platforms	manual sampling, surface in-situ, ground-based, tower-based, airborne, space-based, ship-borne, vehicle-borne, UAV, balloon, and tethered balloon
Working mode	active, passive, single constituent, and multi-constituent
Target	H_2O, HDO, CO_2, CH_4, CH_3D, N_2O, SF_6, O_3, C_2H_6, CCl_3F, CCl_2F_2, and $CHClF_2$
Coverage	single point, small scale, regional scale, large scale, and global scale
Sensitivity	ppbv to ppmv level
Accuracy	thousandth to percent level
Temporal resolution	second, minute, hour to day levels
Spatial resolution	meter, dozens of meters, kilometer to dozens of kilometers
Monitoring regions	typical industrial zones, industrial stack emissions, urban atmosphere, ambient atmosphere, remote background regions, offshore regions, wetlands
Applications	investigations of global carbon cycle, GHGs evolution trends, regional GHGs sources and transport, ecological GHGs flux estimate, urban or industrial GHGs emissions estimates, validations of CTMs and emission inventory, cross calibration, and algorithm improvement
Advances	TanSat and GF-5 series GHGs satellites, space-borne CO_2 LIDAR, ground-based high resolution remote sensing, the performance for homemade GHGs monitoring instruments have been steadily improved