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EDITORIAL

Focus on atmospheric remote sensing and environmental change

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1. Introduction

Atmospheric remote sensing enables comprehensive and quantitative analysis of atmospheric composition and the Earth' energy balance (Lenton *et al* 2024). It provides critical insights into global issues such as air pollution, climate change, energy security, and natural disasters, capturing spatial and temporal variations (Krishnamurthy *et al* 2022, Casagli *et al* 2023, Lelli *et al* 2023, Walshaw *et al* 2024). Advances in remote sensing technologies enhance the accuracy of monitoring gases, aerosols, hydrometeors, and dust, supporting verification of environmental regulations and climate treaties (Anenberg *et al* 2020, Dube and Musasa 2024, Variath and Taori 2024). This knowledge improves understanding of direct and indirect impacts on the climate system and air quality (Quaas *et al* 2020, Kahn *et al* 2023), aiding in policy development, mitigation strategies, and adaptation to changes in atmospheric concentrations of greenhouse gases (GHGs), trace gases and aerosols and in radiative forcing (Sorek-Hamer *et al* 2020, Holloway *et al* 2021, Wooster *et al* 2021, Gao and Yuan 2022).

Several common objectives are generally accepted by the scientific community focusing on atmospheric remote sensing studies. The first aim of using remote sensing observations is to better understand the conditions occurring in the real world, with a particular emphasis on the Global South and developing nations, areas which have fewer resources and access to high-quality observations (Mhawish *et al* 2020, Anjum *et al* 2021). The second aim is to address the rapid and immense ongoing changes in terms of development, emissions, and climate (Woodcock *et al* 2020, Halder *et al* 2021, Jiao *et al* 2021). The third aim is that these observations lead to more inclusive and higher quality solutions to understand the *in-situ* situation, allowing action across borders and of a more open nature to be made (Lin *et al* 2020, Sorek-Hamer *et al* 2020).

To achieve these goals, the Atmospheric Environmental Remote Sensing Society (AERSS) held its 1st international annual conference in Wuhan, China, in 2024. Over 500 participants presented studies on diverse topics, including satellite and ground-based remote sensing using active and passive techniques across various wavelengths and *in situ* measurements from aircraft and drones. Research ranged from monitoring trace gases, aerosols, GHGs, and clouds to broader themes like environmental changes, climate impacts on atmospheric composition, emission inversion, mitigation strategies, and health effects. New techniques for analyzing environmental changes were also highlighted. This Focus Issue features 10 contributions selected from the AERSS annual conference.

2. Trace gases and GHGs

Trace gases and GHG play crucial roles in the atmospheric environment. The evolution of trace gases and GHG in the atmosphere involves primary emission, production and removal by chemical reactions, and dynamical processes such as transport and deposition. A good understanding of atmospheric environmental changes requires accurate quantification of both the sources of trace gases and GHG and their evolution mechanisms. This Focus Issue includes several papers that demonstrate the application of remote sensing to quantify the emissions of nitrogen oxides (NO_x) (Mao *et al* 2024), which is a major precursor of ozone (O_3), the temporal and spatial distributions of surface O_3 (Gao *et al* 2024a) and the impacts of dynamical processes on O_3 (Hong *et al*

2024) and methane (CH_4) (Tao *et al* 2024). These papers illustrate the advantages of remote sensing in studies of trace gases and GHG as well as the importance to improve our understanding of environmental changes.

Mao *et al* (2024) report on the analysis of anthropogenic NO_x emissions in China, the United States and Europe, using nitrogen dioxide (NO_2) observations from the TROPOMI sensor on board the Sentinel-5 satellite for the years 2019–2022. During this period, the COVID-19 epidemic resulted in a dramatic change in anthropogenic activity globally, with effects on NO_x emissions which are still uncertain. Mao *et al* investigated NO_x emission changes associated with the outbreak and recovery of the COVID-19 epidemic. Their results show a reduction in NO_x emissions in 2020 and a rebound in 2021 in all three regions. The rebound of NO_x emissions was faster in China than in the United States and Europe, surpassing its levels in 2019 by July 2020. The TROPOMI-derived NO_x emissions show another decline in all three regions in 2022, in response to a COVID-induced lockdown period and ensuing economic consequences. With NO_2 being a major precursor of O_3, the changes in NO_x emissions are expected to have a significant impact on O_3 concentrations.

Besides quantification of precursor emissions, many studies focus on the estimation of ground-level O_3 concentrations using satellite observations. As an example, Gao *et al* (2024a) proposed an innovative method for the estimation of hourly full-coverage ground-level O_3 concentrations using machine learning (ML). In their study, the light Gradient Boosting Machine (lightGBM) model was trained with multiple data sets including ground-based O_3 observations together with satellite observations of O_3 from the Chinese Advanced Geosynchronous Radiation Imager (AGRI) on board the geostationary Fengyun-4A satellite and the Dutch/Finnish Ozone Monitoring Instrument (OMI) on board NASA's Aura satellite. The model was then applied to hourly full-coverage high-resolution (4 km) surface O_3 concentrations in China for the year 2022. Gao *et al* (2024a) demonstrate high consistency between the diurnal variation of ML-derived-O_3 concentrations and ground-based observations for both clear and cloudy days. Their study highlights the advantage of remote sensing for the extension of spatial coverage of sparse ground-level observations, which is critical for a comprehensive understanding of the evolution of O_3 concentrations, in particular over background areas where *in-situ* observations are lacking.

Stratosphere-to-troposphere transport (STT) has been recognized as an important natural source of tropospheric O_3 in western, northeastern, and eastern China. However, the influence of STT on tropospheric O_3 in southeastern China is still uncertain. Hong *et al* (2024) analyzed a 1 year data-set of ozonesonde observations from the Shaowu observation station, located in Nanping City, Fujian Province, in south-eastern China, during the period from November 2021 to November 2022. These authors concluded that STT contributes significantly to the increase of tropospheric and surface O_3 in southeastern China. Hong *et al* (2024) highlight the large influence of STT on the anomalous ozone profile observed on 4 May 2022. STT plays a substantial role in shaping tropospheric O_3 during spring, accounting for over 30% of O_3 concentrations above 4 km in the atmosphere.

In addition to trace gases, the emission and evolution of GHGs can also be investigated by using remote sensing techniques. As an example, Tao *et al* (2024) analyzed the seasonal enhancement of CH_4 in the upper troposphere over the Asian Summer Monsoon (ASM) region using CH_4 observations from the Atmospheric Infrared Sounder (AIRS) on board NASA Aqua satellite together with simulations using the GEOS-Chem atmospheric chemistry transport model. Their results show the effect of the ASM on the vertical transport of CH_4 concentrations in the upper troposphere within the active monsoon region were enhanced by up to 3%, with respect to the zonal means, and by up to 6% relative to the pre-monsoon season. The spatial distribution of the CH_4 plume shows a southwest ward shift in the AIRS retrievals, in contrast to a broader enhancement in the model simulations.

Gao *et al* (2024b) studied the spatiotemporal variations of ground surface temperature in China, providing a crucial indicator to understand the land–atmosphere interaction and flux transfer processes.

The above papers published in this Focus Issue present different examples of the applications of remote sensing in atmospheric studies, showing the utility of the various techniques to obtain information on the occurrence and concentrations of atmospheric constituents, processes and the power of using a suite of different techniques to improve our understanding of the atmosphere.

3. Remote sensing of aerosols

Ambient exposure to fine particulate matter ($PM_{2.5}$) is the largest contributor to the air pollution's burden of disease worldwide. In addition, aerosol particles have a large effect on climate and pose one of the largest uncertainties in climate change assessment. Remote sensing of aerosols primarily relies on detecting the radiance received by a satellite sensor at the top of atmosphere due to scattering of solar radiation by aerosol particles. However, this requires an effective separation of the aerosol contribution to the radiance received by the sensor from other contributions, in particular from the Earth' surface. This requires accurate models or assumptions for the surface reflectance, or methods to eliminate surface effects such as using multiple viewing angles. In addition, accurate aerosol models are need to describe how aerosol particles interact with sunlight, i.e. how they scatter and/or absorb solar radiation and how these properties vary with height above the Earth' surface and with the sun-satellite observation geometry. The aerosol optical depth (AOD) measured by a satellite sensor is the integral of the aerosol extinction (the sum of scattering and absorption) along the light path and needs to corrected to a vertical column. Therefore, the AOD is a good indicator of the abundance of aerosols in the atmosphere. However, using satellite AOD to predict $PM_{2.5}$ has been challenging due to retrieval uncertainties, unrevealed mechanisms (Martin 2008, Van Donkelaar *et al* 2012, Zhang and Li 2015), missing data related to presence of clouds and over highly reflecting surfaces (ice/snow) (Gupta and Christopher 2008, Levy *et al* 2009). In addition, relationship between AOD and $PM_{2.5}$, is non-linear and varies in space and time due to variations in their vertical distributions, including variations in chemical composition which determines aerosol optical properties and hygroscopicity (Chin *et al* 2002, Jin *et al* 2019).

This Focus Issue features five studies that advance the application of satellite remote sensing measurements to infer $PM_{2.5}$ concentrations near the surface (Chen *et al* 2024, Itahashi and Uno 2024) and in the upper troposphere (Wu *et al* 2024a), at various spatial scales, including urban roadside (Wu *et al* 2024b), regional scale (Chen *et al* 2024), national scale (Hang *et al* 2023), over the ocean (Itahashi and Uno 2024) and the globe (Wu *et al* 2024a). These studies demonstrate the value of remote sensing for filling the spatial gaps of ground-based monitoring.

Itahashi and Uno (2024) used satellite-derived AOD data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) to track the change of fine mode AOD (AOD_f) over the East Asia Ocean, a region without ground-based monitoring. They found a gradual decrease of AOD_f from 2010 to 2021, which agrees with the observed decreasing $PM_{2.5}$ trend over Japan. Itahashi and Uno (2024) also showed the impact of reduced transboundary pollution on air quality improvement over Japan, in particular due to the decreasing emissions in China.

$PM_{2.5}$ is the total mass of dry aerosol particles with a diameter smaller than 2.5 μm and includes a wide variety of chemical constituents. The elemental carbon (EC) is a human carcinogen, which has shown to be potentially more toxic than other major $PM_{2.5}$ components (Janssen *et al* 2011). Meng *et al* (2018) developed the generalized additive models that use data from the multiangle imaging spectroradiometer (MISR) on board NASA's Terra satellite to provide ground-level concentrations of four $PM_{2.5}$ components, including EC. In their contribution to this Focus Issue, Hang *et al* (2023) describe the use of MISR-derived EC data together with MODIS-derived vegetation data (NDVI: Normalized Difference Vegetation Index) and cloud fraction from the Clouds and the Earth's Radiant Energy System (CERES) belonging to NASA's Earth Observing Systems (EOS), ground-based EC observations and atmospheric re-analysis data with a Random Forest model to map EC concentrations across China with a spatial resolution of 10 km. The application of this method for the years 2005–2018 shows that the national mean EC concentration remained relatively stable over China from 2005 to 2018, even though the total $PM_{2.5}$ concentration had declined (Hang *et al* 2023). The results were used to assess health impacts of EC in China and the authors calculated all-cause non-accidental deaths over the 2005–2018 period in each province of China attributable to long-term EC exposure based on concentrations derived from their work.

Studies of air pollution in urban areas, in particular along roads, require information on $PM_{2.5}$ with higher resolution than provided by satellites such as MODIS and MISR. Wu *et al* (2024b) developed an ultra-high-resolution $PM_{2.5}$ retrieval algorithm using 30-m Landsat-8 L1 data. They applied the dark target method in a two-step algorithm, accounting for land cover, to retrieve AOD. The AOD results were used to train a support vector machine model to estimate AOD over urban surfaces. In the second step, a Random Forest model was used to analyze the AOD/$PM_{2.5}$ relationship. Ground-based $PM_{2.5}$ observations were used for training the models, together with a large suite of auxiliary data. The model was used to analyze roadside $PM_{2.5}$ pollution and population exposure in 11 cities in the Pearl River Delta of China. The results show different $PM_{2.5}$ pollution levels between these 11 cities, consistent with their traffic volume data, and illustrate weekend effects.

The abovementioned satellite-based sensors are passive instruments, which measure upwelling reflected solar or emitted Earth radiation. These sensors have limited capability to capture vertical variation of aerosol, trace gas and GHG concentrations. LiDARs (light detection and ranging) consist of an optical system that emits pulsed laser light into the atmosphere and a receiver system consisting of a telescope, optical detector and dedicated electronics. The intensity of laser light backscattered by aerosol particles in the direction of the telescope is measured. The time between emission of the laser pulse and detection of the backscattered light is a measure for the distance from the lidar system. After correction, calibration and processing, a series of consecutive lidar pulses provides the aerosol profile information. Lidars can be used on board satellites, such as the Cloud Aerosol LIdar with Orthogonal Polarization (CALIOP) on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), on aircraft and at the ground. Chen *et al* (2024) used a ground-based lidar together with a wind lidar to measure wind profiles, a microwave radiometer to extract relative humidity (RH) and temperature profiles and MODIS AOD data to study a 6 d haze event in the Beijing–Tianjin–Hebei area in China, in November 2022. The study focused on the role of downdrafts in trapping pollutants and exacerbating $PM_{2.5}$ concentrations.

Wu *et al* (2024a) studied upper-tropospheric carbonaceous aerosol layers (TCALs) over Asia, South America, and Africa. The formation of TCAL involves atmospheric dynamics and emission of surface pollutants, i.e. deep convection and strong updrafts during an anticyclonic system transporting pollutants from the surface into the upper troposphere and lower stratosphere. Wu *et al* (2024a) used multiple data sources to study this phenomenon, including Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) reanalysis, models of the Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations and retrieval results from the Ozone Mapping and Profiler Suite (OMPS) Limb Profiler (LP) aboard the Suomi National Polar-orbiting Partnership satellite. CALIOP AOD data, MODIS land cover and fire monitoring products and outgoing longwave radiation from CERES on NOAA satellites were used for comparison. TCALs in Asia occur in July–August, in South America in October–December and in Africa in November–December. Two TCAL centers were observed over Asia, which are due to anthropogenic pollution and cause a net warming radiative effect. Over both South America and Africa, one TCAL center was observed, due to wildfire emissions, causing a net cooling radiative effect. The opposing radiative effects are due to different carbonaceous aerosol composition when originating from anthropogenic emissions (over Asia) than from natural emissions (over Africa and South America).

4. Conclusions

Focusing on gases and aerosols, the 10 papers in this Focus Issue represent a tip of the iceberg of scientific studies and applications using remote sensing to learn and address changes in the Earth environment. Current remote sensing studies still face a large number of challenges, such as the spatiotemporal coverage and resolution of satellite remote sensing measurements; the limited amount of observation platforms and instruments; the uncertainties of calibration and algorithms converting from radiation to columnar abundance, surface concentration, and emission; and the integration between remote sensing and the wider environmental and climate change community, such as the use of remote sensing products in general environmental research, monitoring and management. These challenges are particularly outstanding for the 'global south' which includes China. Within the remote sensing regime, studies of radiation, gases, aerosols, clouds, and surface properties and their interactions could also be better integrated to provide a more complete picture of the environmental changes. These issues are highly interdisciplinary in nature and will require substantially improved coordination between stakeholders at different aspects.

Remote sensing products are expected to become more capable and provide additional knowledge on more aspects of the atmosphere and environment, become more reliable, frequent, accessible, and relevant. This new knowledge and improved quality will allow deeper and more exciting science to be done, to advance our understanding of the atmosphere, air pollution, climate change and ecosystem impacts. It is expected that through remote sensing, economic, environmental, policy and other gains will continue to be made. The ability to impact people's lives and address issues facing our present and future society will be improved.

However, remote sensing has still severe limitations, such as the spatial and temporal resolution and, in particular, the number of degrees of freedom which limit the number of parameters that can be retrieved independently. In addition, the accuracy with which the information can be retrieved is less than that from dedicated instrumentation for *in situ* measurements, designed for a certain purpose. However, *in situ* measurements and ground-based remote sensing provide information for a limited area around the measurement location, whereas satellite measurements provide information on local, regional and global scales. On the other hand, *in situ* measurements can often be made continuously where satellite observations rely on their overpass time, varying from daily to a few days, except for geostationary satellites. Physical models are often needed for the interpretation of satellite observations and, vice versa, satellite data are often needed to evaluate model results. For all these reasons, remote sensing is complementary to other observation techniques and modelling, which should be used together to develop our knowledge of the Earth Atmosphere system. Examples of the complementary use of different information source have been presented as described above.

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