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Key Points:

- Geostationary ultraviolet (UV)/visible air quality missions omit Africa and South America, where pollution can be severe and in situ measurements are few
- Measurements at UV through infrared wavelengths are needed for comprehensive space-based measurements of atmospheric composition
- International coordination is needed for a sustainable and equitable satellite-based global observing system

Supporting Information:

Supporting Information may be found in the online version of this article.

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Coordinated Geostationary, Multispectral Satellite Observations Are Critical for Climate and Air Quality Progress

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Abstract Satellite observations are critical for air quality and climate monitoring, and for developing the process understanding needed for reliable planning and predictions. Our current space-based observing system stands at a crossroads with the early missions approaching their end-of-life. We articulate the challenges and needs to sustain and develop these environmental records into the future, focusing specifically on observations of gas-phase atmospheric composition.

Plain Language Summary We describe challenges and needs for developing a globally comprehensive and equitable satellite-based observing system for air quality and climate pollution.

1. Introduction

Air pollution emissions kill millions of people every year, with disproportionate impacts on lower-income and disadvantaged communities (Rentschler & Leonova, 2023). Many air pollutants are also direct or indirect climate forcers (Szopa et al., 2021) contributing to impacts that include heat waves and altered precipitation patterns (Capua & Rahmstorf, 2023; Wang et al., 2023). Meanwhile, oxidizing and nitrogen-containing air pollutants degrade ecosystems, lower crop yields, and perturb the global N cycle (Groffman et al., 2021; Liu et al., 2013; Peñuelas et al., 2013). Atmospheric composition thus underlies several of the Earth system boundaries that define a safe and equitable planetary environment (Richardson et al., 2023). However, few of the relevant pollutants are routinely monitored in situ, and those measurement sites are skewed to affluent countries in northern midlatitudes. This observational gap limits our understanding of the Southern Hemisphere atmosphere (Paton-Walsh et al., 2022), an untenable situation given dramatic projected growth in population, urbanization, pollutant emissions, and associated mortality—particularly in Africa (Kaudia & Feresu, 2023).

Satellite observations of tropospheric gas-phase composition have been available since the turn of the century, and have revolutionized our understanding of Earth's atmosphere and its environmental challenges (Burrows et al., 2011). Unlike in situ observations, satellites monitor the atmosphere across local-to-global scales—irrespective of political boundaries or economic status—and therefore offer a representative and equitable measurement of the state of our planet. However, our satellite-based observing system stands at a crossroads. The early, science-led pathfinder missions are rapidly approaching end-of-life, creating an urgent need to sustain and develop these critical environmental records over the long term. Our options for doing so come with opportunities and challenges for the atmospheric and climate communities, which we discuss below. We concentrate discussion on observational needs for tracking the gas-phase composition of our atmosphere; satellite-based measurements of aerosol optical properties are also important but not the focus here.

2. Challenges

Our first challenge is to provide comprehensive observations that monitor planetary boundaries and map atmospheric pollution around the world. We are beginning to benefit from groundbreaking air quality-focused missions that make measurements at ultraviolet (UV) through visible (Vis) wavelengths from geostationary orbits, providing high-resolution, hourly information over a selected region throughout the day. Together, the

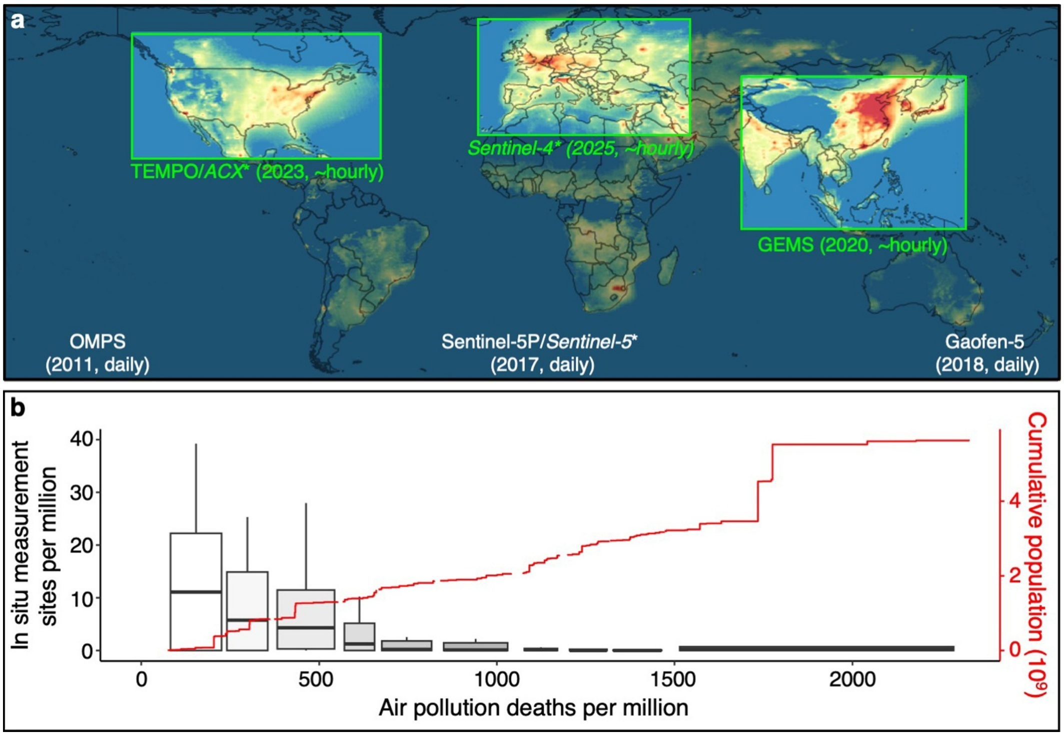

Figure 1. (a) Current and planned geostationary satellite-based observations of air quality in the ultraviolet/visible omit the tropics and Southern Hemisphere. Geostationary (green) and low-Earth orbit (white) spectrometers are shown; prospective future instruments are indicated with an asterisk. Background map shows NO_2 column observations from OMI (2005–2021 mean; Krotkov et al., 2019). Figure concept from NASA LaRC and KNMI/ESA. (b) The global ground-based air quality network is likewise biased to less-polluted, relatively wealthy parts of the world; countries with the most per-capita air pollution deaths tend to have far fewer monitoring sites per person (Global Burden of Disease Collaborative Network, 2020; World Health Organization, 2023).

GEMS (launched 2020), TEMPO (2023) and Sentinel-4 (planned for 2025) missions will form an air quality constellation around the northern midlatitudes. However, these measurements will be restricted to East Asia, North America, and Europe, neglecting large parts of the world—including Africa and South America, where air pollution challenges are severe (Gómez Peláez et al., 2020; Health Effects Institute, 2022) and in-situ measurements are scarce. The UV/Vis atmospheric chemistry missions, as currently configured, will thus perpetuate the same global inequities that afflict the ground-based observations (Figures 1a and 1b).

Our second challenge is to harness the full suite of available information from UV/Vis through infrared (IR) wavelengths. The emerging air quality constellation has so far prioritized measurements in the UV/Vis, where several relevant air quality gases can be observed (Figure 2a). But a wide range of atmospheric pollutants are only observable at IR wavelengths by virtue of their molecular structure. Prominent examples in the thermal IR include: ammonia—linked to agriculture and a source of atmospheric particulate matter (PM); isoprene—emitted by forests and a central driver of tropospheric chemistry; and peroxyacetyl nitrate (PAN)—a reservoir species enabling long-range transport of environmental nitrogen. Satellite observations at thermal IR wavelengths are also crucial for measuring other volatile organic compounds (which are precursors of ozone and PM), while observations in the shortwave IR can map the distributions of carbon monoxide, carbon dioxide, and methane with sensitivity through the tropospheric column. Carbon dioxide and methane are the most important anthropogenic greenhouse gases, while carbon monoxide and methane together control the global abundance of ozone, itself a greenhouse gas and the source of the hydroxyl radicals that dictate the atmosphere's oxidizing capacity.

Accessing the air quality and climate information afforded in the IR requires instruments that combine high spectral resolution with the noise performance needed to detect and quantify weakly-absorbing atmospheric species. The IR observing portfolio also needs to accommodate both global coverage and fine space-time sampling to advance process understanding. Global thermal IR sampling is obtainable from current (and upcoming)

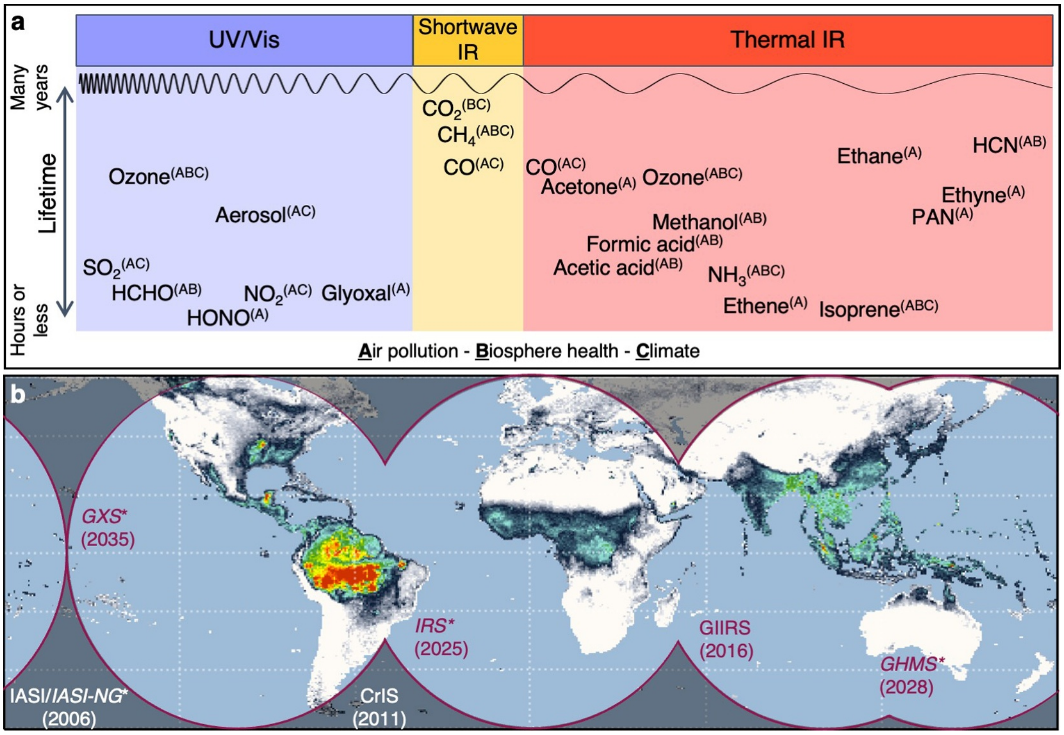

Figure 2. (a) Measurements spanning ultraviolet (UV) through infrared (IR) wavelengths are needed for a comprehensive view of the tropospheric chemicals relevant to air pollution, the biosphere, and climate change. (b) Concept for an advanced geostationary ring of thermal IR sounders (Li et al., 2022). A future constellation of this type would provide high-frequency, fine-scale coverage for important atmospheric species that are not detectable in the UV/visible. Geostationary (maroon) and low-Earth orbit (white) sounders are shown; prospective future instruments are indicated with an asterisk. The instruments in low-Earth orbit cover any given region twice daily; the geostationary sensors will provide hourly or sub-hourly observations. Background map shows isoprene column observations from CrIS (2012–2020 August mean; Wells et al., 2022).

sensors in low-Earth orbit, whereas high-frequency observations require geostationary sampling. A global ring of geostationary thermal IR sounders, currently under development (Figure 2b), is an essential part of a comprehensive observing system. However, these thermal IR sounders are motivated by meteorological needs, and it is crucial that instrument designs also accommodate requirements for trace gas observations. Furthermore, the operational sounder products are primarily weather-related (e.g., temperature and humidity); trace gases that can also be retrieved in the thermal IR are not seen as primary products, and are typically not operationally produced. This is an important gap and an opportunity for better integration.

Our third challenge is to create and maintain self-consistent satellite data records of atmospheric composition over the long-term. Atmospheric remote sensing is performed by a patchwork of countries, agencies, and public/private entities, and increased international coordination is needed to connect these resources into a sustained and globally integrated observing system. The CEOS AC-VC effort (Committee on Earth Observation Satellites, 2024) is one good example of this type of coordination, integrating efforts on existing satellites to ensure the overall measurement system has more value than the sum of its parts. However, each contributing mission is typically conceived on its own. Consequently, the current observing system has gaps in terms of both geographic coverage and measured quantities: in short, it is not optimized for science and policy applications. An optimized system could be delivered by the global community (including representatives from Africa, South America, and around the world) with a focus on coordinating the next generation of sensors to collectively deliver the best possible actionable information for stakeholders.

Partnership opportunities also arise from the fact that the weather, air quality, and climate communities have complementary instrumentation needs—for example, IR sounders measure temperature/humidity profiles to support weather forecasting but can also track air quality gases. So far, limited emphasis on sounder trace gas capabilities compared to their meteorological applications, differing data processing needs (e.g., prioritizing long-term continuity vs. short-term forecasting accuracy), and siloed research landscapes that can hinder external collaborations have prevented these connections from being fully leveraged.

3. Needs

Addressing the above challenges requires effort along several fronts:

1. *International coordination for comprehensive satellite-based measurements of climate and air quality*. Spaceborne measurements provide the means to address the problematic data gaps that are embedded in the ground-based network. Developing a truly global and long-term constellation of geostationary UV/Vis and IR sensors should be a top international priority.
2. *Exploit information from UV/Vis through IR wavelengths to deliver more actionable information about Earth's atmosphere*. UV/Vis and IR measurements are typically used in isolation and by distinct communities, but alone they give an incomplete view of atmospheric composition. The work that has been done to date linking UV/Vis and IR information demonstrates their complementarity for understanding atmospheric composition, improving forecasts, and developing next-generation models to inform science and policy.
3. *Leverage international and disciplinary synergies*. We need to develop infrastructure, expertise, and funding mechanisms that can link complementary remote sensing efforts to advance trace gas and meteorological capabilities from space, and in a way that efficiently supports both short-term forecasting and longer-term global change research objectives. Exploiting thermal IR satellite instrumentation (primarily used for meteorological applications) for operational trace gas retrievals, and developing geostationary satellite observations over the Southern Hemisphere are two key opportunities in this regard.
4. The above efforts need to work from a perspective of *inclusion and partnership* (Garland et al., 2024) with scientists and space agencies from Africa, South America, Oceania, and throughout the world.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

OMI NO_2 columns plotted in Figure 1 were visualized using the Giovanni online data system (developed and maintained by the NASA GES DISC) and are publicly available at https://doi.org/10.5067/Aura/OMI/DATA3007 (Krotkov et al., 2019). Air pollution mortality, population, and monitoring data shown in Figure 1 are publicly available from https://www.healthdata.org/research-analysis and https://www.who.int/publications/m/item/who-ambient-air-quality-database-(update-2023). CrIS isoprene columns mapped in Figure 2 are available via https://doi.org/10.13020/5n0j-wx73 (Wells & Millet, 2022).

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