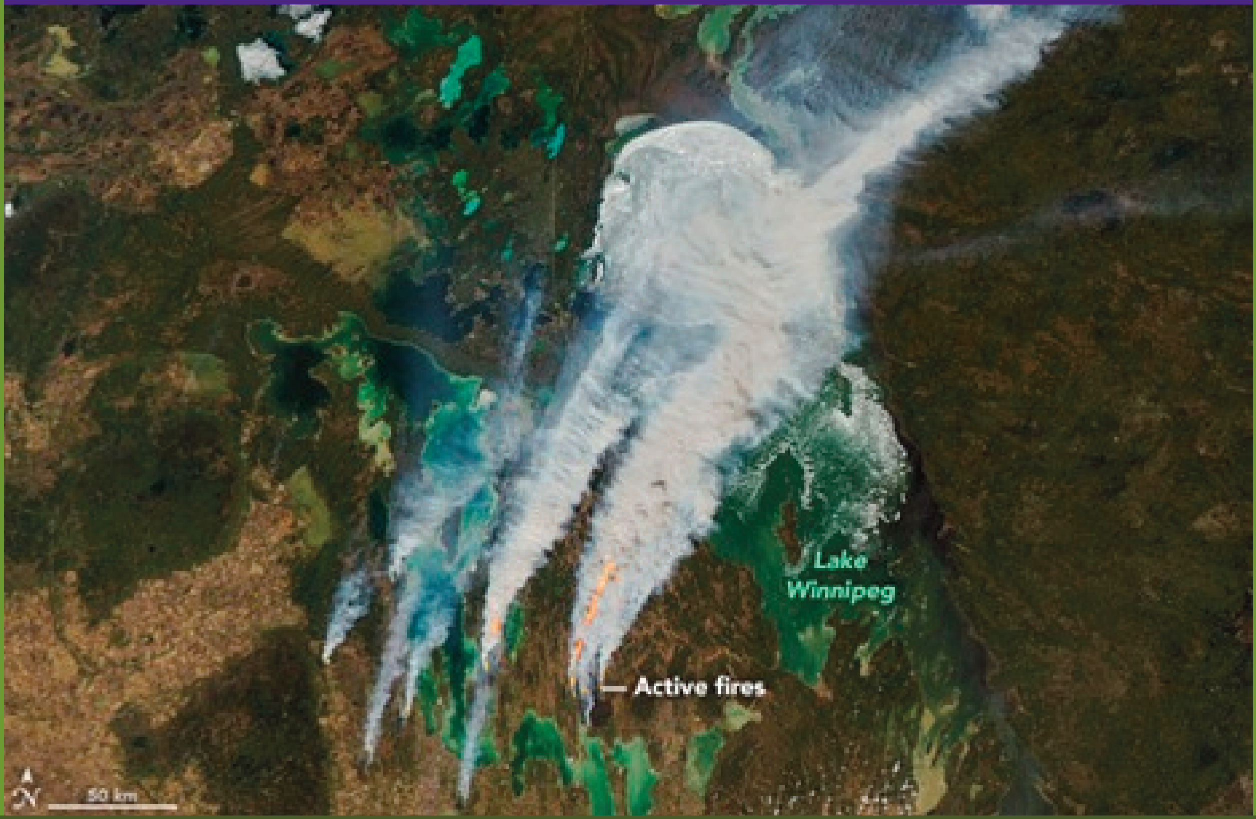

Smoke replaces ice at Lake Winnipeg.

True color image Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite, from the NASA Earth Observatory, May 2021 over Winnipeg, Canada. *Source:* https://Earthobservatory.nasa.gov/images/148340/smoke-replaces-ice-at-lake-winnipeg.

The Four Things to Know about Satellite Data for Air Quality Management

by Tracey Holloway and Jennifer Bratburd

From gray plumes of forest fire smoke to rainbow-colored maps showing pollution trends, satellite data products are becoming part of the air quality management toolbox. This overview introduces four key ideas to support air quality managers' use of satellite data products.

For decades, satellite technology has been evolving to detect a wide range of gases and particles in the atmosphere. Sometimes, the most compelling satellite images are akin to observations by a human eye or traditional camera, like the smoke plume shown in the image on the previous page. The satellite community refers to these camera-type visuals as "true color" images. True-color images can be useful for public outreach and analysis of major pollution events.

Multiple Satellite Data Products Relate to Air Quality Management

In addition to true-color images, multiple instruments in space also provide regular observations of gases, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde (HCHO), carbon monoxide (CO), and ammonia (NH_3). Existing satellite observations of ozone (O_3) reflect stratospheric and/or upper-tropospheric abundance rather than ground-level air quality. Satellite data for NO_2 have become one of the most widely used air quality metrics, especially as an indicator of nitrogen oxides ($NOx = NO + NO_2$).[1] Images of changing NO_2 in early 2020, as shown in Figure 1, highlight both the economic and environmental impact of lockdown policies in response to the COVID-19 pandemic.

Particulate matter (PM) is not directly observed by satellites, but may be inferred from other metrics, especially "aerosol optical depth" (AOD). AOD is a unitless measure of light absorption and scattering by particles in the atmosphere. AOD depends on the properties of the particles, including their mass, size, chemical characteristics, vertical distribution, and other factors.[2]

Satellites See the Column of Air

Most air quality managers are familiar with ground-based monitoring data, which provide "nose level" concentrations appropriate for estimating human exposure. Satellite data

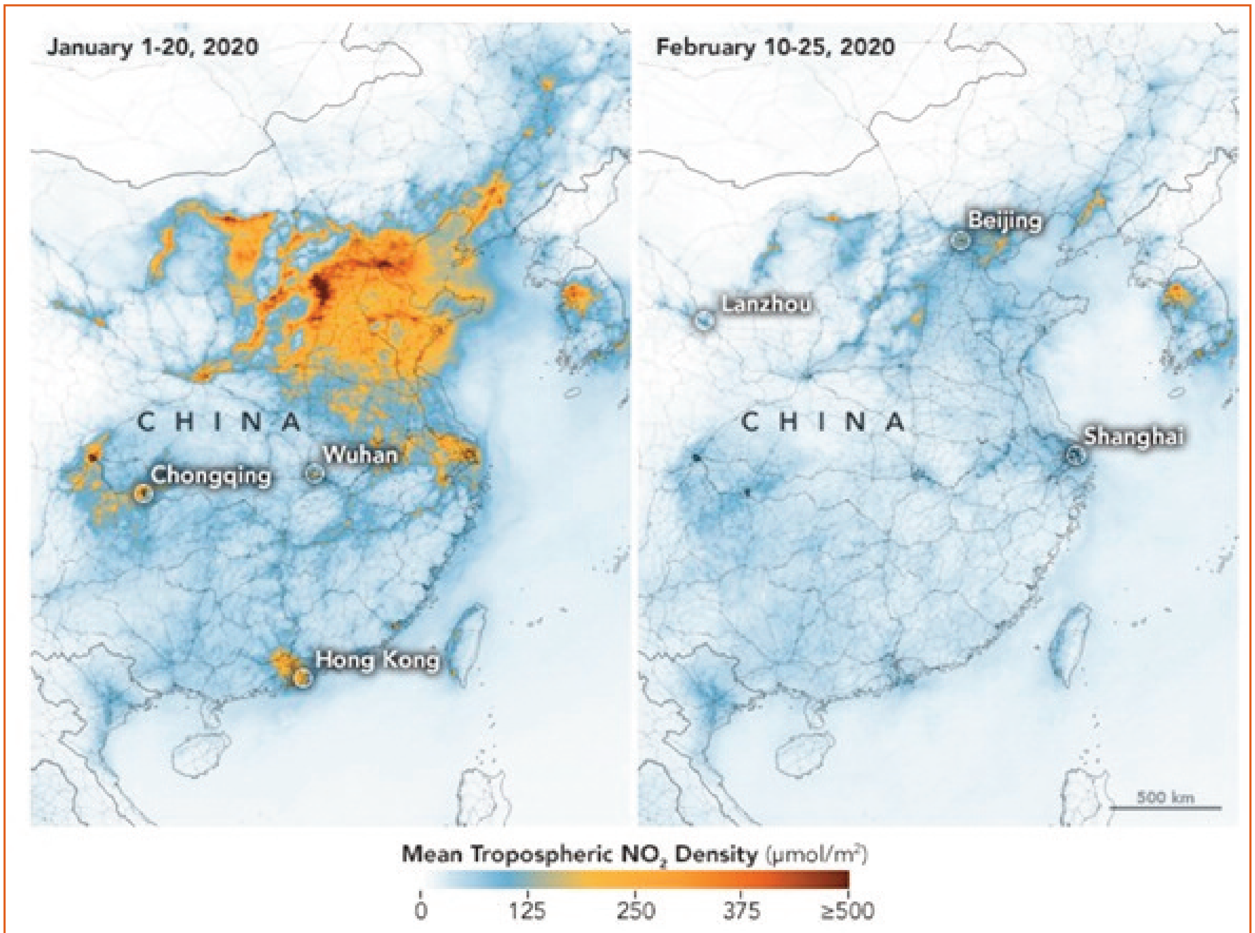

Figure 1. Tropospheric NO_2 column density over China as measured by the Tropospheric Monitoring Instrument (TROPOMI) instrument onboard the European Space Agency's Sentinel-5 satellite. Left panel shows values averaged over the period 1/1/20–1/20/20, prior to restrictions in response to COVID-19. The right panel shows the same data averaged over the period 2/10/20–2/25/20, during early stages of the quarantine restrictions.

Source: https://Earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china.

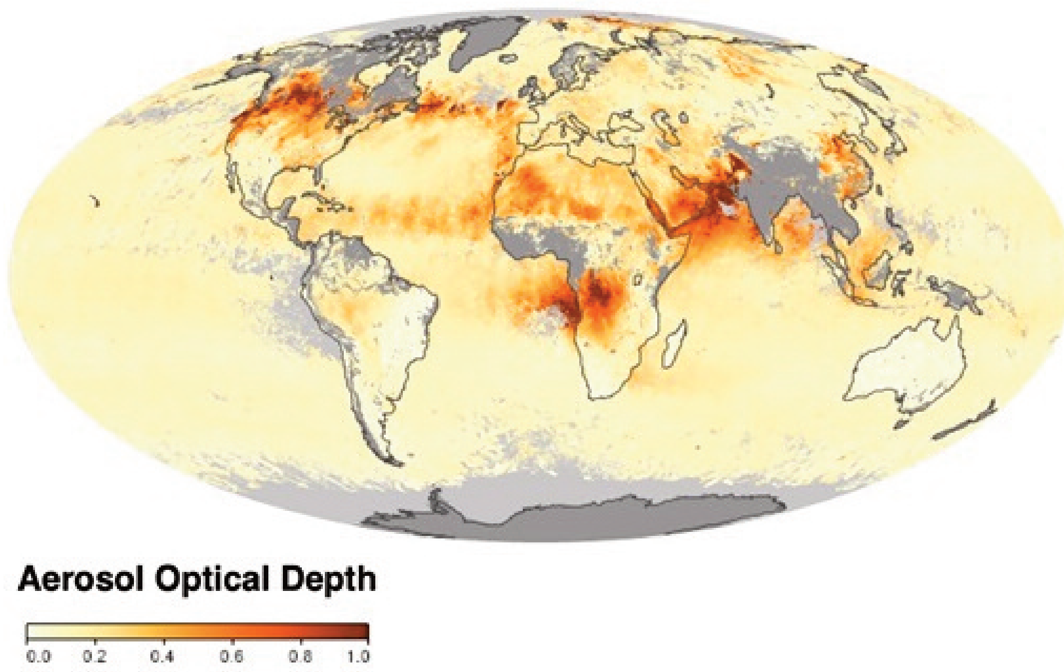

Figure 2. Aerosol Optical Depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite over the globe in August 2018 from NASA Earth Observatory.

Source: https://Earthobservatory.nasa.gov/global-maps/MODAL2_M_AER_OD.

are fundamentally different, representing the column of air stretching from the Earth's surface up to space. In some cases, a satellite's viewing of the total air column is a strength. For example, data on the full air column have been useful for tracking smoke and volcanic plumes and for evaluating three-dimensional air quality models. In some cases, satellite data may be indicative of air quality and emissions. For example, studies have found that satellite data for NO_2 show many of the same spatial and temporal patterns as ground-based NO_2 monitors and for NOx emissions.[3]

Different units are used for these different metrics. For example, where monitoring data of a gas may have mixing ratio units of parts per billion (ppb), satellite data for gas species are often provided in moles/m^2 or molecules/cm^2. These units, called the vertical column density (VCD) can be imagined as the sum of molecules above a square centimeter on Earth. VCD, especially for stratospheric O_3, may be reported as "thickness" called Dobson Units (DU). One DU is equivalent to 0.01 mm layer of the gas over a given area at standard temperature and pressure. Where ground-based monitors report PM in mass concentration units of micrograms/m^3, AOD is unitless, usually ranging between 0 (completely clear) and 1 (obscured), as shown in Figure 2. Calculating percent change over time or space offers one way to quantitatively compare satellite data with other data sources, despite the different units.

Increasingly, satellite data are used to calculate surface concentrations. There are many different ways in which satellite data, model data, and/or in situ measurements may be combined to estimate surface concentrations.[4] "Data fusion" is the general term for methods combining multiple data sources. Data fusion is a rapidly growing field, especially methods for data assimilation—integrating satellite and/or in situ observations as a constraint on a model—and machine learning—a general term for adaptive statistical approaches. Because data fusion relies on both the fusion methods and the input data, a single satellite data product may be used to calculate different surface concentrations. There is no single "recipe" yet accepted to convert satellite data to surface concentrations.

Even without data fusion, calculations are required to produce a satellite data product from the 0s and 1s reported by an instrument in space. The AOD, NO_2, or other satellite data product is called the "retrieval." Different research groups use different calculation methods to create a retrieval, so the same data from the same satellite instrument may yield multiple retrievals due to different approaches in processing the data. These different retrievals may be thought of as different translations of the same original text. Sometimes different retrievals work better for different applications. For example, one retrieval may be more accurate over water, and another may be more accurate over land.

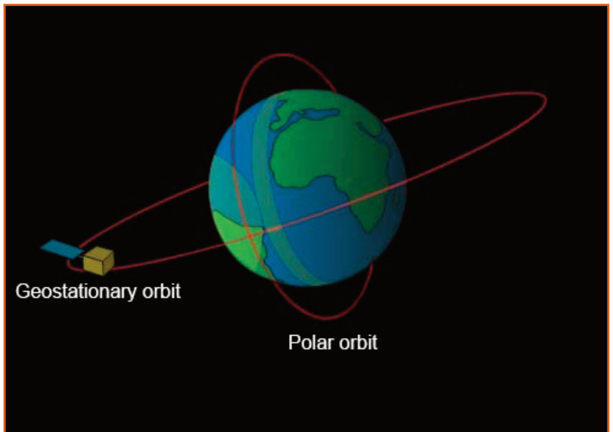

Figure 3. Comparison of high-altitude geostationary orbit (~36,000 km above the Earth's surface) with a low Earth polar orbit (180–2,000 km altitudes).

Source: Adapted from NOAA.

Most Satellites Provide Snapshots Once a Day for Every Location on Earth

There are three types of satellites relevant to air quality observations: polar-orbiting, geostationary, and targeted.

Most satellites detecting gases and aerosols are polar-orbiting, which means they pass over the poles of the Earth. These satellites provide one or two snapshots a day of most of the globe. Unfortunately, these snapshots may not provide useful data if there are clouds, bright surfaces, and/or mountains, and cannot measure air pollution at night. Although there are probably satellite data relevant to your air quality management needs, the daily availability will depend on your local climate and land cover. A few important NASA satellites pass overhead in the early afternoon, known as the A-train (A for afternoon), so retrievals from these satellites capture early afternoon conditions, with exact time varying by latitude.

A major advancement in satellite data for air quality relates to the growing number of geostationary satellites. Because polar-orbiting satellites only make one or two snapshots a day over each region, they do not capture rapidly changing air pollution events such as dust storms and wildland fires. A major advantage of the geostationary platform is its ability to observe a given region repeatedly during daytime. Geostationary satellites orbit with the Earth's rotation, so they can provide data over a particular geographic region at hourly or better frequencies during daylight hours. These two orbits are shown schematically in Figure 3.

Targeted satellites may be dispatched to specific locations for high-resolution, short-term observations. These have not yet been used for air quality management, but the potential is clear from studies showing methane release from oil and gas operations, or high-resolution smoke plumes. A number of these satellites are being developed and managed by commercial satellite companies, with potential to complement the wider coverage of polar-orbiting and geostationary instruments.

Much like a digital camera, newer instruments usually have higher resolution than older models. Today, there are four instruments in space that detect NO_2. Three are polar-orbiting, passing over the whole Earth once a day (resolutions of 40 km x 80 km, 13 km x 24 km and 7 km x 3.5 km). One is geostationary over East Asia, launched by South Korea with resolution for NO_2 up to 7 km x 8 km. In 2022, a geostationary instrument called TEMPO is set to launch over North America, and Sentinal-4 will provide similar coverage over Europe (with resolutions of 2.1×4.5 km and 8 km x 8 km respectively).[5,6]

Getting Started Is Easy

NASA has been working to make satellite data useful to the air quality and health communities, and there are a wide range of resources and communities (all free!) to support you and your work.

If you are new to satellite data, a great starting point is the NASA Earth Observatory (https://Earthobservatory.nasa.gov). Like a museum of satellite data, the Earth Observatory is a curated gallery of over 11,000 satellite data images and archives of easy-to-use global maps. Whether you start with the Image of the Day or jump right into the data with global maps (see Figure 4), visiting the Earth Observatory (https://Earthobservatory.nasa.gov/global-maps) will probably feel more like fun than work.

The maps from the Earth Observatory provide monthly average maps for the whole globe. To zoom in on your community, on specific days, NASA Worldview (https://worldview.Earthdata.nasa.gov) is a great next step. Worldview provides the capability to interact with global, full-resolution satellite imagery and then download the underlying data (see Figure 4). Most of the 400+ available products are updated within three hours of observation, essentially showing the entire Earth as it looks "right now." Many of the data products go back ten years or more, so you can use Worldview for current or historic evaluations.

Where Worldview shows day-by-day data snapshots, NASA Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/) allows you to plot averages, calculate ratios, and make line plots over time (see Figure 5). Giovanni allows users to analyze gridded data online with its web application.

The NASA Health and Air Quality Applied Sciences Team (HAQAST; https://haqast.org), now in its third generation, has been working for over 10 years to bridge the capabilities

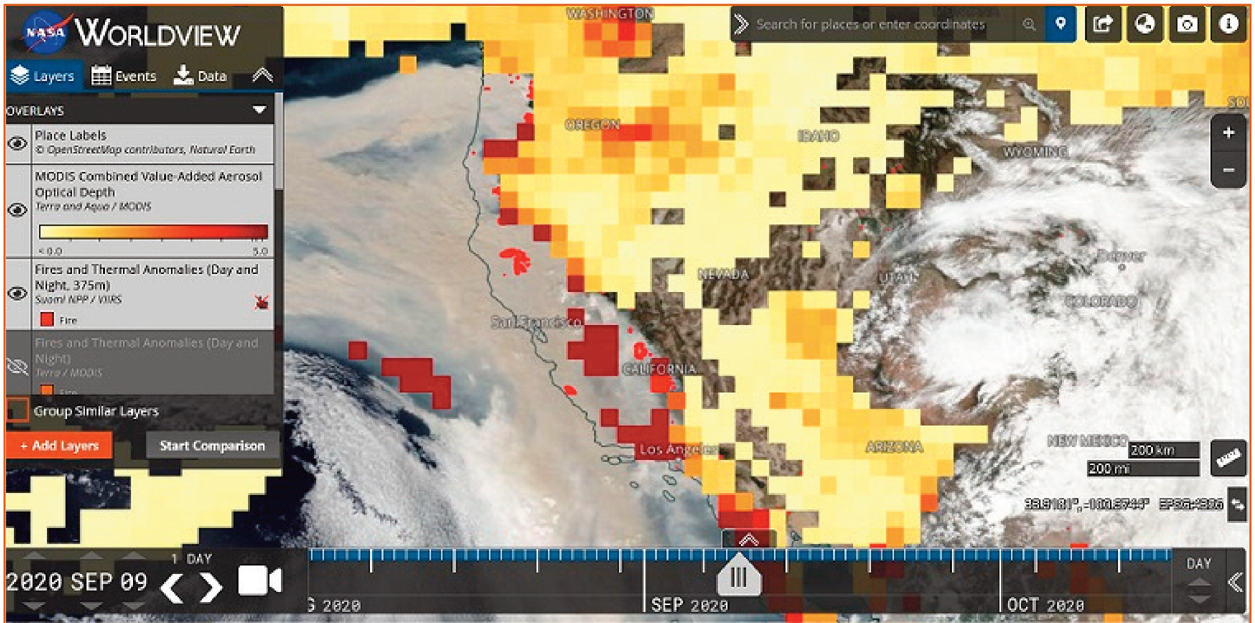

Figure 4. Screenshot of NASA Worldview over the western United States on September 9, 2020, with an overlay of AOD and fires.

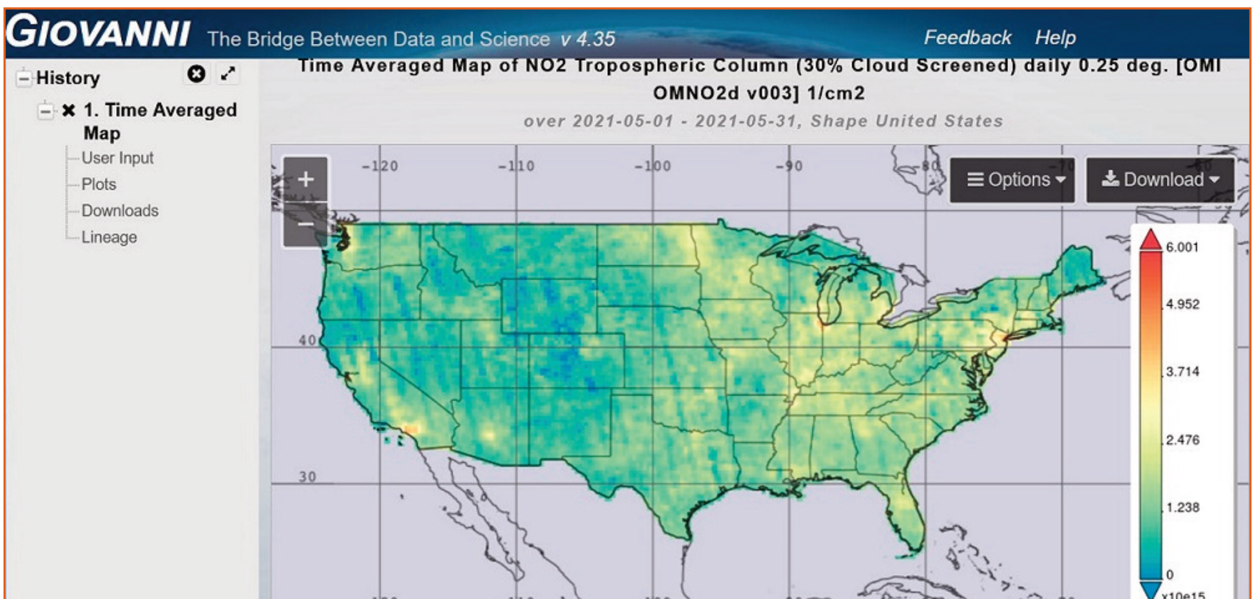

Figure 5. Screenshot of NASA Giovanni showing the NO_2 tropospheric column averaged over the month of May 2021 over the continental United States.

of remote sensing data with the needs of air quality managers and health professionals.[4] The HAQAST website links to the Earth Observatory, Worldview, Giovanni, and many more portals, with tutorials and overview information. Recognizing that there is often a trade-off between ease-of-use and flexibility, HAQAST has labeled each tool from basic to advanced.

The NASA Applied Remote Sensing Training Program (ARSET; https://appliedsciences.nasa.gov/arset) offers free online and in-person training opportunities on how to use tools like Worldview and Giovanni, and more advanced methods for satellite data analysis with Python and other scripting languages.

Examples of satellite data applications to air quality management are growing. HAQAST has been active in advancing and documenting these successes (see https://haqast.org and https://airquality.gsfc.nasa.gov). For example, HAQAST researchers and stakeholder partners have worked together to develop technical guidance documents to highlight ways satellite data can be useful for State Implementation Plans.

Whatever your level of technical know-how or application area, you are invited to join the HAQAST community. With regular meetings online and in-person, social media and newsletter updates, as well as collaborative applied research opportunities, HAQAST has the mission of bridging air quality and health organization needs with NASA capabilities. Our third-generation team just launched, and this NASA-funded effort will continue through 2025. We welcome you as part of this growing community. **em**

Dr. Tracey Holloway leads the NASA Health and Air Quality Applied Sciences Team (HAQAST), now in its third generation. In addition to leading the current (2021–2025) HAQAST, Holloway led the second generation of the team (2016–2020), and she served as Deputy Leader of the first-generation team (2011–2016), known at the time as AQAST. Holloway is the Gaylord Nelson Distinguished Professor at the University of Wisconsin–Madison, with appointments in the Nelson Institute for Environmental Studies and the Department of Atmospheric and Oceanic Sciences. **Dr. Jennifer Bratburd** is the Outreach Manager for HAQAST, following her Ph.D. in Microbiology and post-doctoral work as a Missouri Science & Technology Policy Fellow. Holloway and Bratburd work together at the University of Wisconsin–Madison, in the Nelson Institute's Center for Sustainability and the Global Environment (SAGE). E-mail: **taholloway@wisc.edu**.

Acknowledgment: Funding for this study was provided by the NASA Applied Sciences Program, through a grant for the NASA Health and Air Quality Applied Sciences Team. The authors would also like to acknowledge Bryan Duncan, Arlene Fiore, Barron Henderson, Ana Prados, and additional partners for comments and review of this article, as well as the investigators and stakeholders engaged since 2011 in the work of NASA AQAST and HAQAST.

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