

Delivering Revolutionary Satellite Data with NASA's Tropospheric Emissions:

Monitoring of Pollution (TEMPO) Mission

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This article introduces the revolutionary TEMPO—Tropospheric Emissions: Monitoring of Pollution—instrument, including the latest mission updates, data products, early results, and air quality management applications.

Satellite imaging spectrometers designed for measuring gaseous air pollutants, including ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and formaldehyde (HCHO), have been in Low Earth Orbit (LEO) for several decades (e.g., the Ozone Monitoring Instrument on NASA's Aura satellite). However, these LEO satellite instruments are usually limited to once per day observations of pollutants over a given location, either in the mid-morning or early afternoon local time. A new era of satellite data is upon us with the recent launch of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument into Geostationary Earth Orbit (GEO) on April 7, 2023.

The GEO position of TEMPO enables the instrument to gather neighborhood-scale observations of air pollutants each hour of the daytime (morning to evening) across the TEMPO field of regard (FoR) covering

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greater North America, which encompasses New York City, Los Angeles, the Canadian Tar Sands, Mexico City, Cuba, and Puerto Rico.[1] This view provides a new perspective of visualizing "chemical weather" as pollutants are emitted, transformed, and transported hour-by-hour. A brief background on satellite imaging spectrometers and the geostationary air quality constellation consisting of TEMPO, Geostationary Environment Monitoring Spectrometer (GEMS), and Sentinel-4 can be found in Naeger et al. (2021).[2]

TEMPO Instrument, Mission Status, and Data Products

TEMPO is an imaging spectrometer equipped with two detectors that measure the intensity of solar backscattered radiances from 293–494 nm (ultraviolet) and 538–741 nm (visible). The ultraviolet-visible capabilities of TEMPO enable the instrument to be sensitive to some trace gases, including policy-relevant air pollutants such as NO_2, SO_2, and O_3. TEMPO employs operational trace gas retrievals involving complex, multi-step procedures to derive level 2 data products containing vertical column densities (VCDs) for a target trace gas (e.g., NO_2) from the level 1 solar backscattered radiances. VCDs represent the total amount of a specific trace gas in the vertical column directly above the TEMPO footprint (e.g., ground pixel) with a spatial extent of 2 x 4.75 km^2 at the center of the FoR at 33.7°N, 91.7°W. While these columnar amounts are not surface concentrations, these values have already been shown to be useful in evaluating emissions inventories, validating models used in State Implementation Planning, and exceptional event demonstrations from LEO.[3-5]

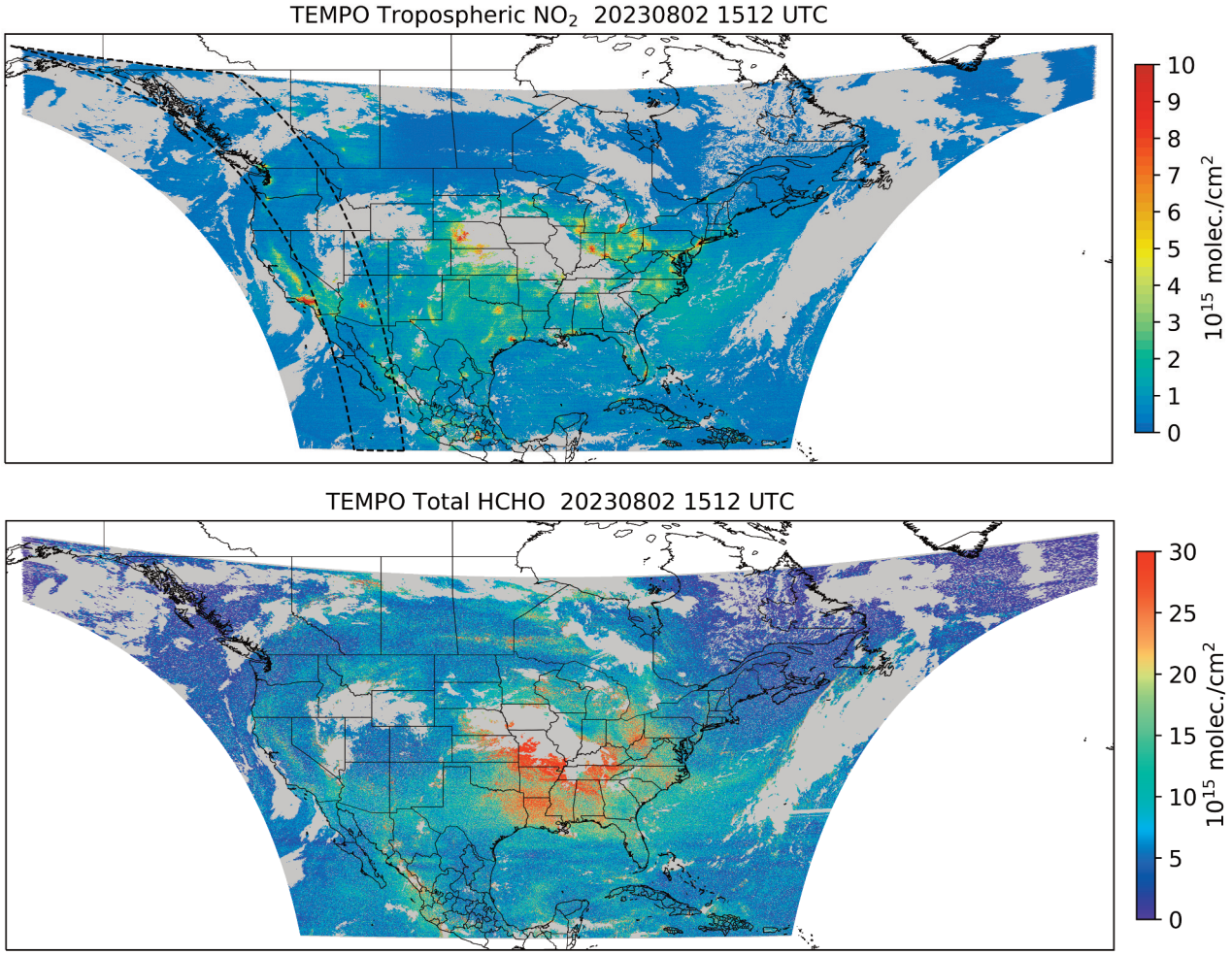


Figure 1. First nominal hourly East-to-West scan of the TEMPO mission across the FoR during First Light on August 2, 2023, starting at 1512 UTC and ending approximately 1 hour later. (top) Tropospheric NO_2 VCDs and (bottom) total HCHO VCDs observed during the hourly scan are shown. Areas of missing data in gray are due to cloud cover or poor data quality. An example L2 data granule is shown by the dashed black lines in the tropospheric NO_2 VCD map.

After being powered on June 7, 2023 at its GEO position (91°W) about 22,000 miles above the equator, TEMPO started its commissioning phase, which involved the successful testing of the instrument including first Earth imaging scans **(https://www.nasa.gov/news-release/nasa-shares-first-images-from-us-pollution-monitoring-instrument/)** on August 2. Nominal operations began on October 19, denoting the start of the baseline mission. TEMPO will continue to make measurements through at least the baseline mission period ending in June 2025 and will be extended through NASA's senior review process upon the evaluation of TEMPO's instrument performance.

The most novel perspective TEMPO provides is its unprecedented temporal resolution. TEMPO performs East–West scans across the TEMPO FoR covering greater North America with routine operations consisting of nominal (hourly; see Figure 1) and optimized (sub-hourly) scans during the daytime. Optimized scans are performed over the daylight portion (solar zenith angle >85°) of the FoR in the early morning and late afternoon (e.g., ~30 minute scans across the Eastern United States in the early morning). A portion of TEMPO's observing time (up to 25%) can be committed to special scans at even higher frequency (e.g., ≤10 minutes) over slices of the FoR for air quality hazard events (e.g., wildfires, dust storms, volcanoes), chemistry studies (e.g., lightning), and field campaigns. Altogether, the high spatiotemporal resolution of TEMPO enables the instrument to monitor the daytime diurnal evolution of air pollutants at neighborhood scale.

TEMPO is also capable of adjusting its FoR to collect measurements outside the standard FoR coverage. For instance, TEMPO could perform more southward scans in the winter to cover some of Central America when there is limited daylight across the northern extent of the standard FoR. More northward scans covering much of the Canadian North could be desired in the summer, particularly during the wildfire season. The maximum FoR coverage for TEMPO scans is shown in Figure 2.

TEMPO will begin releasing products publicly in April 2024, including O_3 profiles, total O_3, NO_2, and HCHO. Most of the level 2 granules (example granule in Figure 1) will be provided at the

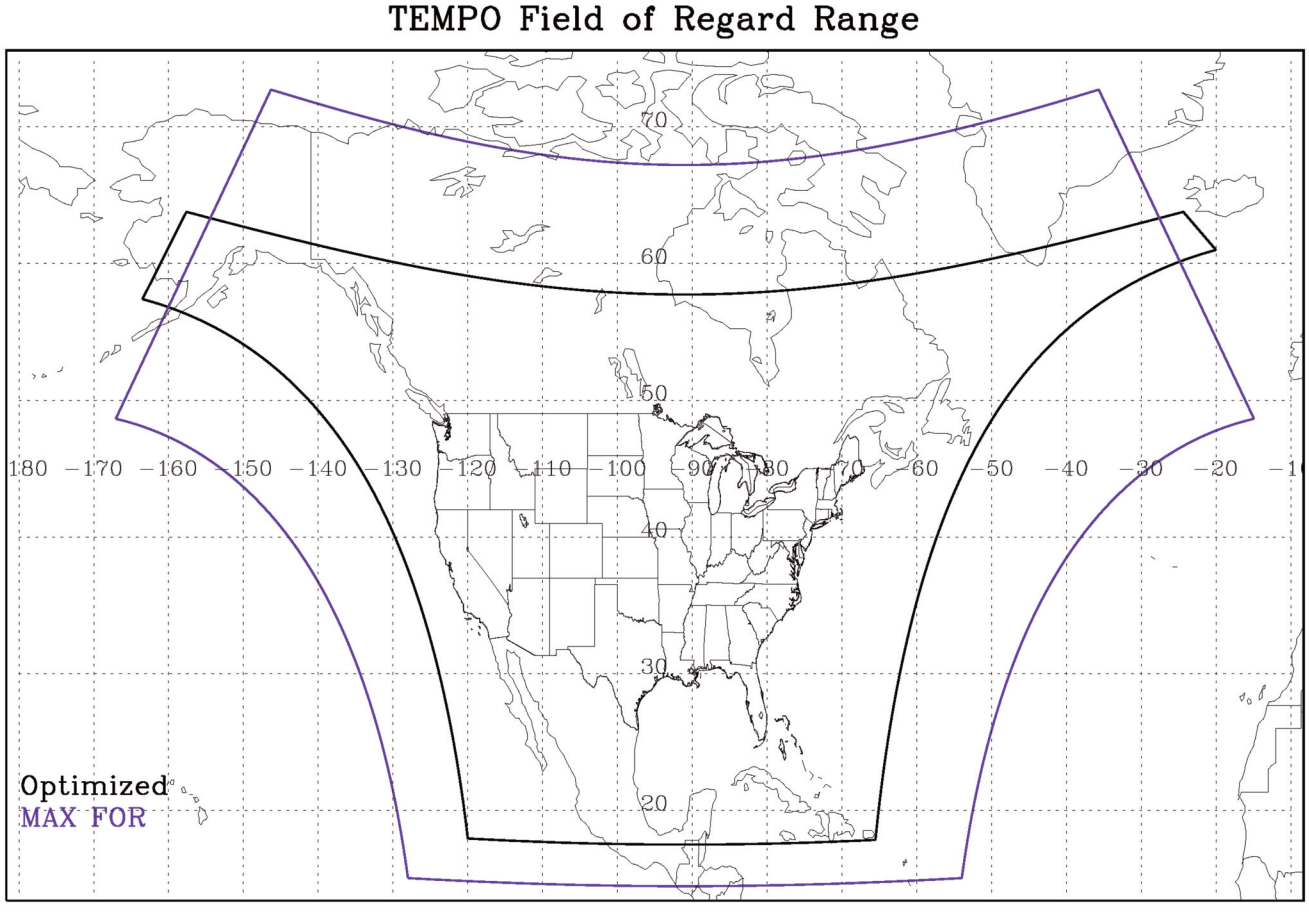


Figure 2. Standard or optimized FoR coverage is shown in black. Maximum FoR coverage is shown in purple.

nominal TEMPO footprint (e.g., pixel size) of 2 x 4.75 km^2 at the center of the FoR, except for the O_3 profile with an expected spatial resolution of 8 x 4.75 km^2 or coarser by spatially co-adding at least four TEMPO pixels due to limited computational resources to produce the very computationally intensive product. Gridded level 3 products at a 0.02° resolution across each TEMPO scan are created from the level 2 granules (9 different granules makeup a complete hourly FoR scan). The standard operational products of TEMPO will have low latency (time between when TEMPO collects measurements and when data are made available to the public) of 3–6 hours, except for O_3 profile with an expected latency of about 24 hours. Near real-time NO_2, HCHO, and aerosol products with latency less than 3 hours are targeted for public release in January 2025. A summary of the suite of products is shown in Table 1. Future standard TEMPO products could also include aerosols, SO_2, BrO, CHOCHO, H_2O, and UV-B radiation.

TEMPO data products will be disseminated by the NASA Atmospheric Science Data Center (ASDC) with access points including the NASA Earthdata Search interface and visualizations of TEMPO data in NASA Worldview. The Remote Sensing Information Gateway (RSIG) maintained by the U.S. Environmental Protection Agency (EPA) will also provide tools for disseminating, visualizing, and analyzing TEMPO data.

TEMPO Early Adopters Program

The TEMPO Early Adopters (EA) Program **(https://weather.ndc.nasa.gov/tempo/)**, formally established in 2019, has focused on the following key objectives:

1. Engaging a broad spectrum of stakeholders and end users to expand knowledge of the TEMPO mission and characterize needs within the community;
2. Using simulated proxy data for early demonstration of TEMPO data;[6] and
3. Aligning the TEMPO observing time, products, and data interfaces to user needs and applications.

The overarching goal of the EA program is to enhance and accelerate applications of TEMPO data and maximize the value of the data for societal benefit. Meetings and workshops are regularly hosted by the program to engage the EA community. The program has grown into a large network of approximately 580 members (as of January 2024) from a myriad of organizations across the TEMPO FoR (and beyond), including more than 100 members from U.S. federal, state, local, and tribal air agencies, with a particular focus on air quality management applications from TEMPO.[7]

Table 1. List of TEMPO level 2 (L2) and level 3 (L3) products set for public release in April 2024, except for the near real-time (NRT) aerosol product planned for public release in January 2025. NRT versions of the standard cloud, NO_2, and HCHO products are also planned for release in January 2025. Spatial resolution shown for L2 products is valid at the center of FoR (33.7°N, 91.7°W), with the majority of the products at the TEMPO footprint size (2 x 4.75 km^2). O_3 profile may be coarser than 8 x 4.75 km^2. Aerosol product may be produced at the TEMPO footprint size. L3 products will be produced for all L2 products.

Level	Product	Key Variables	Resolution (km2)	Frequency / Notes
L2	Cloud NRT	Cloud Fraction, Cloud Pressure	2.0 x 4.75	Per granule, produced every ~6 minutes and 40 seconds during each East–West scan. Granules are north–south slices across each TEMPO scan (example in Figure 1). Nine granules makeup the nominal hourly scan over the FoR. Granule 1 on easternmost and Granule 9 on westernmost sections of the hourly scan.
	O_3 profile	0–2 km O_3, Tropospheric O_3 column, Total O_3 column, Stratospheric O_3 column	>= 8.0 x 4.75	
	Total O_3	Total column O_3	2.0 x 4.75	
	NO_2 NRT	Tropospheric Vertical Column Density (VCD), Total VCD, Stratospheric VCD	2.0 x 4.75	
	HCHO NRT	Total VCD	2.0 x 4.75	
	Aerosol NRT	Aerosol Optical Depth, Aerosol Layer Height	8.0 x 4.75 (TBD)	
L3	Same as L2	Same as L2	0.02° x 0.02°	Per scan, hourly (nominal) or sub-hourly (optimized)

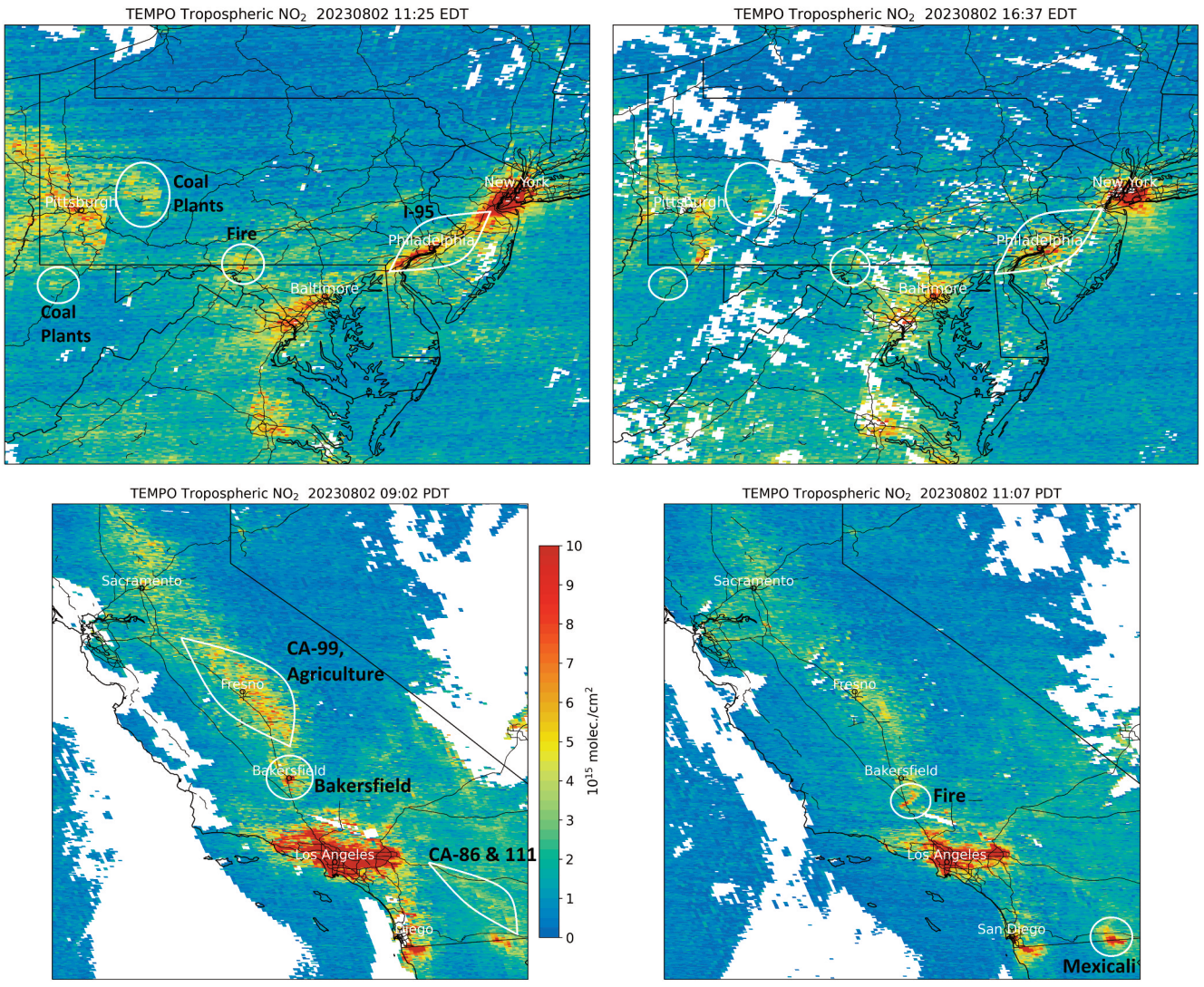


Figure 3. (Top) Zoom in to the Mid-Atlantic region showing tropospheric NO_2 VCDs observed by TEMPO during the midday (~11:30 EDT; left) and late afternoon (~16:37 EDT; right) on August 2, 2023. (Bottom) Zoom in to California showing tropospheric NO_2 VCDs observed by TEMPO during the early morning (~9:00 PDT; left) and late morning (~11:00 PDT; right) on August 2, 2023. Locations of interest involving notable NO_2 changes are denoted. NO_2 variations across the Central Valley are likely attributed to a combination of factors, including traffic and agricultural emissions.

The EA program has been an important facet of the TEMPO mission. Early adopters stressed their critical need for near real-time TEMPO data since the formal establishment of the program, which helped promote the inclusion of the lower latency data into the pipeline of TEMPO products. Inputs from EAs were key in defining the core application focus areas of the TEMPO mission, consisting of air pollution emissions and monitoring, air quality modeling and forecasting, public health, vegetation and ocean monitoring, and weather analysis and forecasting. Early adopters have also expanded the breadth of application studies in the living TEMPO Green Paper,[8] which is the mechanism for documenting and organizing studies requesting the special operation scans from the mission.

Early look at TEMPO Preliminary Data

The TEMPO science and validation teams are analyzing and evaluating the TEMPO preliminary data in order to communicate the quality of the products for public release in April 2024. A few use cases from First Light, August 2, 2023, will be highlighted here, with the important note that these data are preliminary or "beta" level, meaning little is known on the data quality. Figure 3 shows tropospheric NO_2 VCDs observed by TEMPO over the Mid-Atlantic region of the United States during midday (~11:30 EDT) and late afternoon (~16:37 EDT) scans. Notable changes in NO_2 VCDs are shown along traffic corridors, across major cities, and in areas of coal power plants and fires. Changes in NO_2 VCDs in the location of several coal plants east of

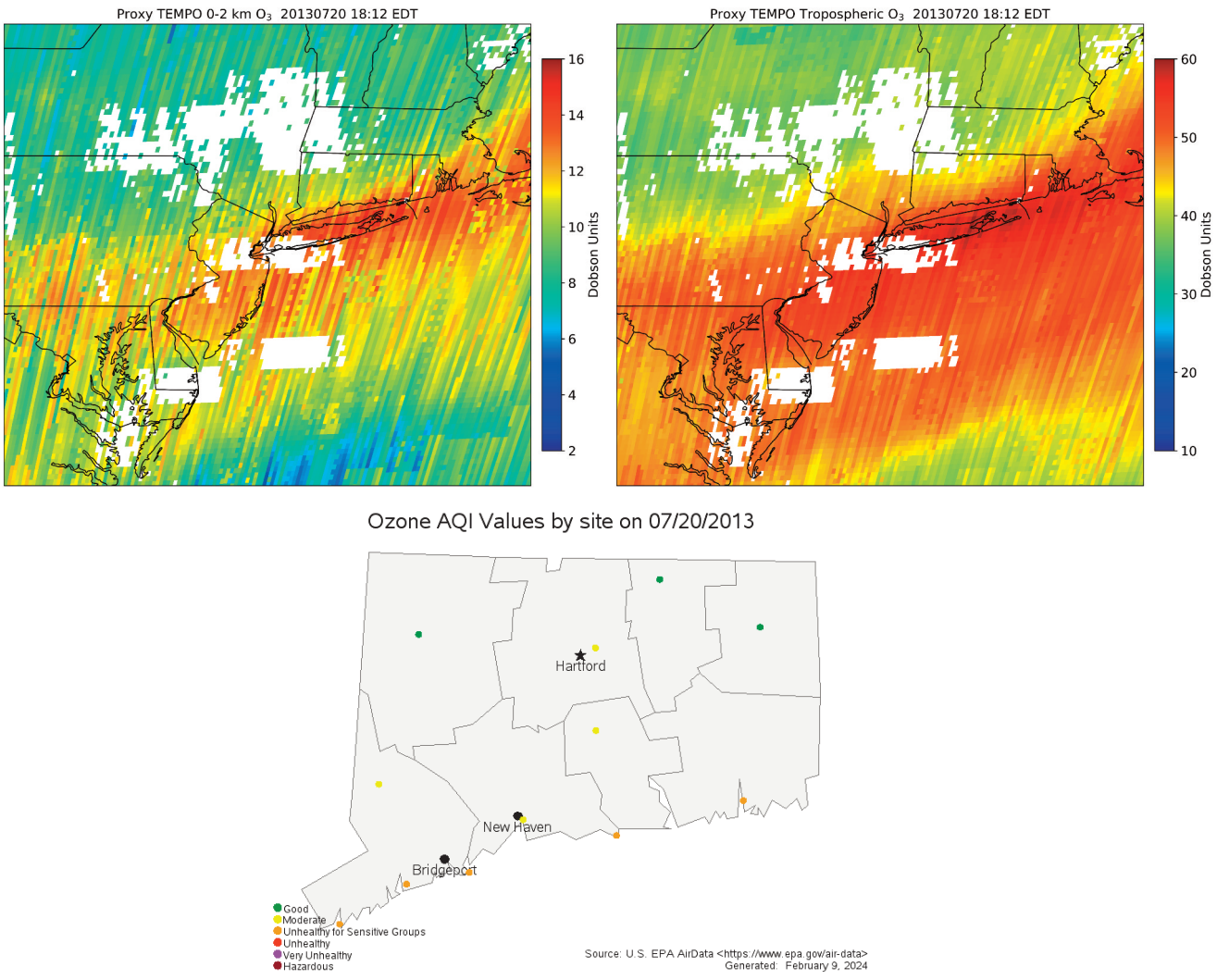


Figure 4. The TEMPO O_3 simulated proxy profile product on July 20, 2013, showing tropospheric O_3 columns (left) and 0–2 km O_3 columns (right). (Bottom) Daily O_3 AQI (Air Quality Index) values for AirNow surface monitors in Connecticut on the same day with unhealthy O_3 concentrations along the coastline (*Source:* U.S. EPA AirData).

Pittsburgh are apparent in the maps. NO2 plume transport is tracked by TEMPO, such as the plume from New York City extending over Long Island.

Similarly, in Figure 3, data over California shows tropospheric NO_2 VCDs during the early (~9:00 PDT) and late (~11:00 PDT) morning on August 2. High NO_2 VCDs along traffic corridors and cities during the morning rush hour period are particularly evident. A distinct NO_2 plume from a wildfire to the south of Bakersfield is also captured in the late morning scan. The increases in NO_2 from the mid to late morning scan over Mexicali, Mexico are likely associated with the major industrial activities across the city. Together, the multiple observations per day reveal a story of how emissions are transported and how they evolve on the order of hours.

In preparation for TEMPO data, proxy products were produced from robust chemical transport model simulations during the pre-launch era of the mission.[2] Figure 4 is an example of the proxy O_3 profile product during the evening (~18:10 EDT) of an O_3 day characterized as unhealthy for sensitive groups according to surface monitors along Long Island Sound and the Connecticut coast. Increases in the tropospheric and 0–2 km O_3 columns are shown across Long Island Sound and into Connecticut, which highlights the anticipated capability of TEMPO to monitor O_3 pollution in different layers of the troposphere extending down to the boundary layer where people live and breathe.

Conclusion

The TEMPO mission will deliver game-changing data products and imagery for enhancing air quality management applications,



including exceptional event analyses, analyzing long-term pollutant trends, emission inventory assessments, and air quality forecasting across the TEMPO FoR. The use cases discussed in this article provide a glimpse of TEMPO's ability to observe hourly variations of NO_2 from a myriad of emission sources and its transport. The NO_2 product along with HCHO observations represent satellite observable precursors to O_3 production, which have been used in combination with LEO data to better understand chemical regimes and pathways toward lowering concentrations.

Hourly observations will now open our ability to study the strength and movement of precursor plumes as air quality events unfold from morning to evening. Near real-time TEMPO data will be ingested into air quality forecasting models to improve their accuracy, quantitatively. Qualitatively, these products can even provide an additional tool to air quality forecasters to "nowcast" air quality events to keep the public informed as they go about their daily lives. Altogether, the TEMPO mission will provide game-changing data products and imagery for enhancing air quality management applications, including exceptional event analyses, analyzing long-term pollutant trends, emission inventory assessments, and air quality forecasting across the TEMPO FoR. **em**

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