



The European Union's Copernicus Sentinel 5 Precursor (S5p) satellite in orbit.

TROPOMI: A Revolutionary New Satellite Instrument Measuring NO₂ Air Pollution

by Daniel L. Goldberg, Susan C. Anenberg, Gaige Hunter Kerr, Zifeng Lu,
and David G. Streets

An overview of the Tropospheric Monitoring Instrument (TROPOMI) satellite, which demonstrates enhanced technical capabilities in the observation of nitrogen dioxide (NO₂) air pollution from space.

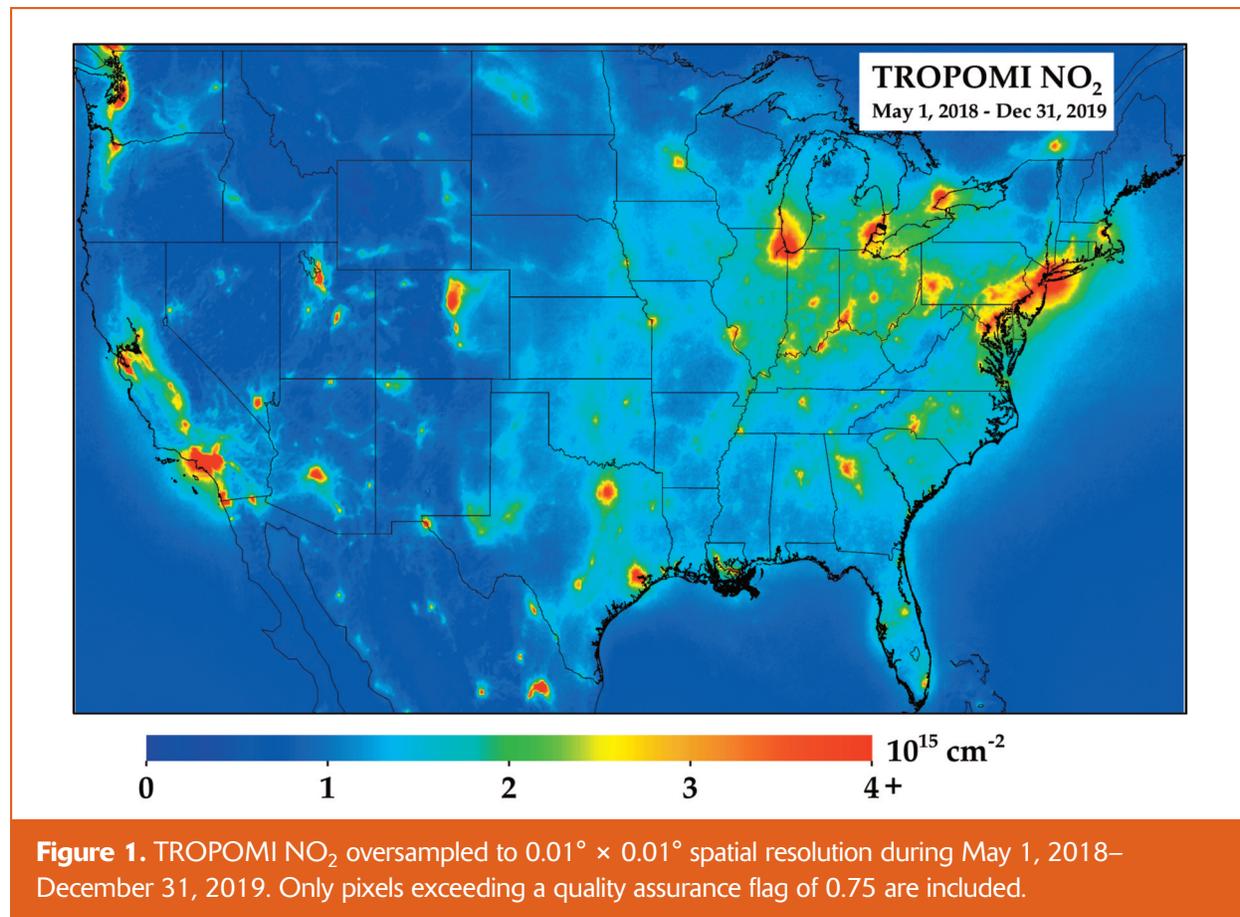
Nitrogen oxides (NO_x = NO + NO₂) are a critical participant in the formation of ozone (O₃) and particulate matter (PM) in urban areas. NO_x is also noted for its own damaging effects, including its contribution to acid rain,¹ premature aging of lungs,^{2,3} and premature mortality.⁴ Observing the spatial extent of NO₂ air pollution is an important first step in quantifying NO_x emission rates and human exposures. Satellite data can add value to the existing ground-based monitoring network by providing pollution estimates in the areas between monitors. This article documents the capabilities of a new satellite instrument, the Tropospheric Monitoring Instrument (TROPOMI), which demonstrates enhanced technical capabilities as compared to predecessor instruments.

TROPOMI is a passive spectrometer orbiting approximately 825 km (~500 miles) above the Earth's surface as part of the European Union's Copernicus Sentinel 5 Precursor (S5p) satellite mission.^{5,6} It was launched on October 13, 2017, and its dimensions are 1.4 m × 0.65 m × 0.75 m, approximately the size of large bookcase, and weighs 900 kg. TROPOMI passively observes sunlight radiation reflected back to space by the Earth's surface and atmosphere in order to calculate the amount of NO₂ in the atmospheric column. The algorithm is able to calculate NO₂ by taking a difference between a theoretical reflectance with no NO₂ pollution and the actual reflectance; the difference is

equivalent to the radiation absorbed by NO₂ in the atmosphere. TROPOMI pixel sizes are 3.5 × 5.6 km², and the instrument observes the atmosphere globally once daily at approximately 13:30 local time. Overlapping pixel measurements over many days can be aggregated together and averaged to finer spatial resolution, such as 1 × 1 km²; this process is called oversampling.⁷ The TROPOMI S5p satellite mission follows in the successful footsteps of the NASA Aura Ozone Monitoring Instrument (OMI)⁸ and Global Ozone Monitoring Experiment (GOME)⁹ satellite missions. Most notably, TROPOMI has ~16x higher spatial resolution than OMI (launched 2004) and ~650x higher spatial resolution than GOME (launched 1995).

The Unprecedented Sensitivity of TROPOMI

TROPOMI, when averaged over multiple days, can differentiate the fine-scale spatial heterogeneities in urban areas,¹⁰ such as emissions related to airport/shipping operations and high traffic, and the small spatial extent of emission sources in rural areas, such as power plants, mining operations, and wildfires. When visually inspecting the continental U.S. TROPOMI NO₂ average during the initial 20 months of the TROPOMI record (May 1, 2018–Dec 31, 2019), we see the clear spatial heterogeneity of NO₂ pollution across the United States (see Figure 1). The largest U.S. cities can be seen, and their concentration magnitudes can be compared to each other.



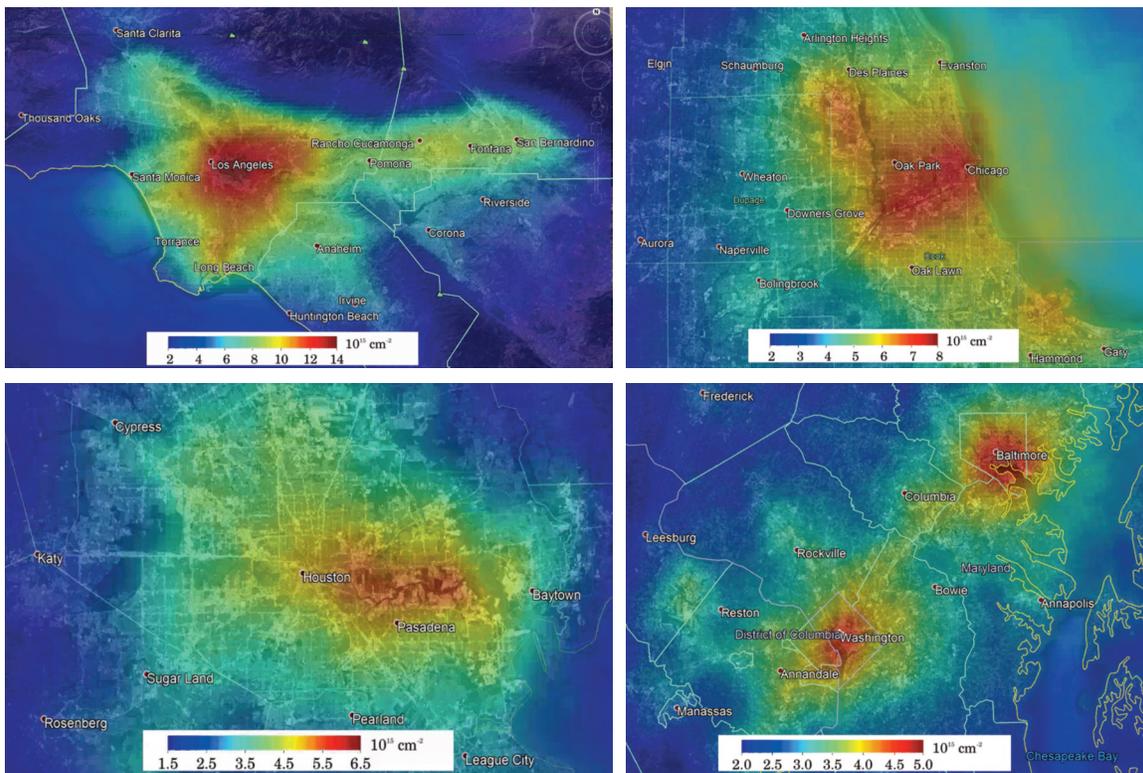


Figure 2. Same data shown in Figure 1, but now zoomed into four different U.S. cities (clockwise from top left: Los Angeles, Chicago, Washington DC/Baltimore corridor, and Houston). Color bar has been adjusted to better differentiate spatial heterogeneity on a local scale.

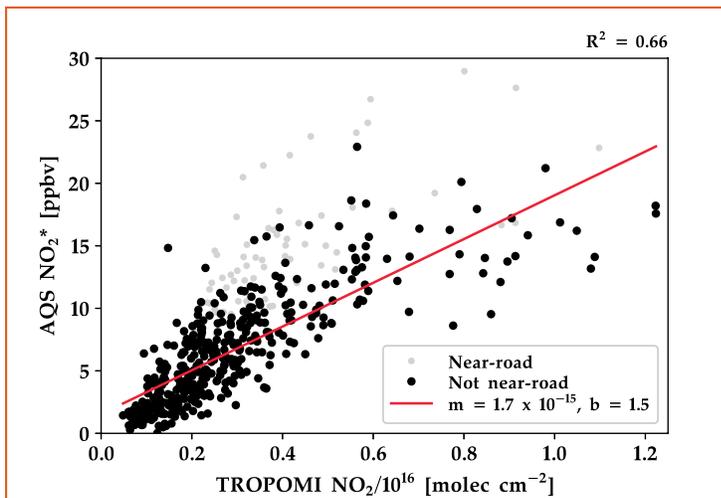


Figure 3. EPA AQS annual surface NO₂* observations for 2019 compared to the collocated oversampled 0.01° × 0.01° TROPOMI value during the same timeframe.

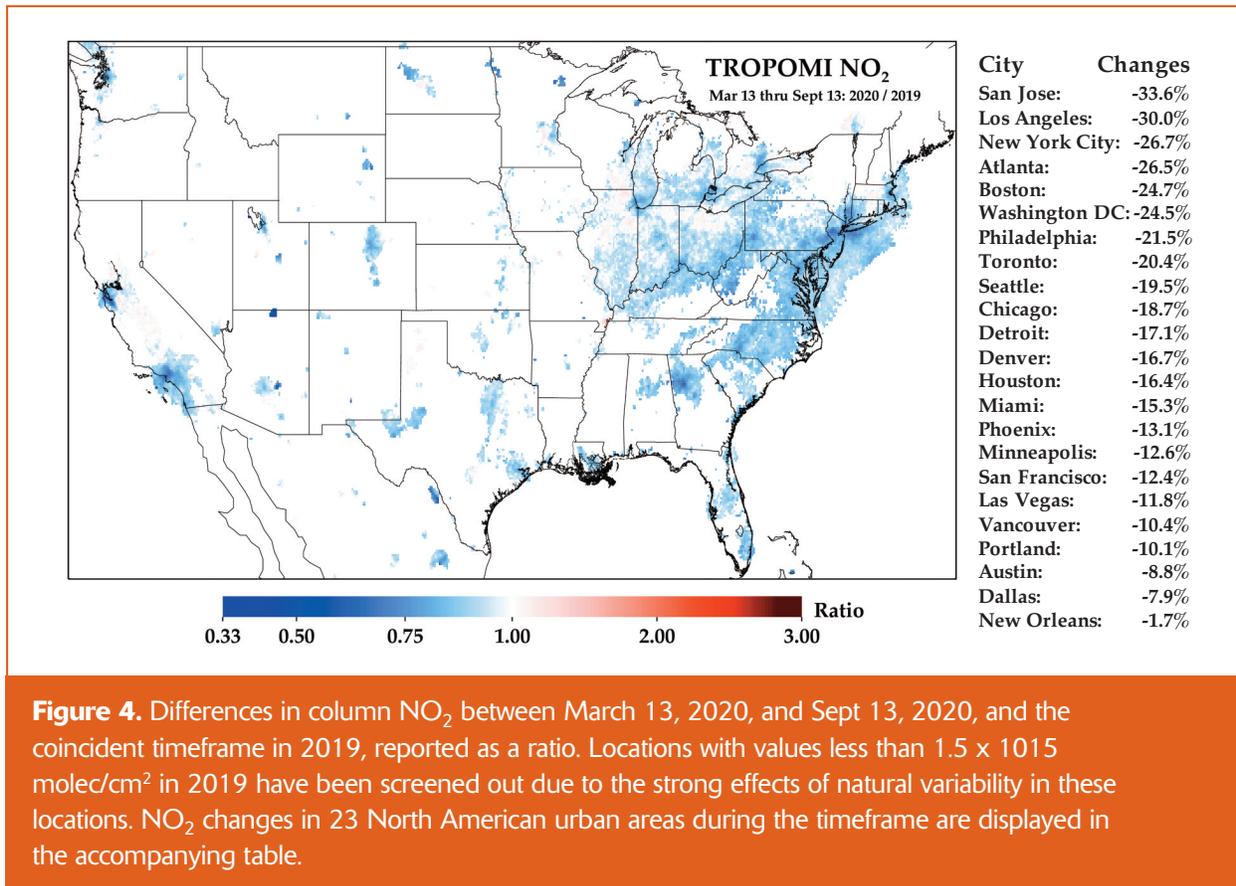
Equally important, relatively smaller sources of NO₂ pollution can now be observed, and they are not spatially smeared into the background NO₂ concentration. For example, the roadway network and related activity in the Idaho Snake River valley can be clearly observed. Individual spikes in NO₂ associated with NO_x emissions from large

power plants (e.g., Colstrip in Montana, Hunter/Huntington in Utah) can also be observed during this 2018–2019 period even though there have been large reductions (~85%) in the NO_x emissions from large power plants since the introduction of the federally mandated NO_x SIP Call in 2003. Other examples are the metal mining operations in Nevada and Arizona, the coal mining operations in the Powder River and Green River Basins in Wyoming, and oil and gas operations in the Permian (Texas) and Bakken (North Dakota) Basins.

TROPOMI data are especially powerful in analyzing local variations in NO₂ pollution as compared to predecessor instruments. Figure 2 zooms into four different U.S. metropolitan areas. In each instance, the oversampled TROPOMI NO₂ images exhibit features that match known NO_x emissions patterns. Larger

NO₂ values can be seen around the interstate network, population density, and industrial activity hubs (e.g., manufacturing facilities, airports, and shipping ports).

For example, in Los Angeles, the spatial pattern matches the basin outline very well, with the largest values between



downtown Los Angeles and the Long Beach Shipping Port. The largest values in Chicago exist along the I-55 corridor, which has a high traffic volume and a high density of industrial facilities, with secondary maxima at the O'Hare International airport and the U.S. Steel Corp operations in East Chicago, Indiana. In the image of Maryland and Washington DC, the largest value is observed at the Baltimore Harbor, which has a confluence of several major highways, a large shipping port, the city incinerator, and many industrial facilities. In Houston, Texas the largest values are nearest to the petrochemical refining facilities east of town.

In all cases, TROPOMI captures the collocation of the largest sources of NO_x emissions and NO₂ concentrations. For this reason, TROPOMI observations can be a valuable way to evaluate the fine-scale structure of NO₂ concentrations in environmental justice communities.¹¹⁻¹³

Relationship with Surface Monitor NO₂ Concentrations

To understand how well TROPOMI, without any adjustment, captures surface-level NO₂ concentrations, we compare the 2019 annual TROPOMI NO₂ average to 24-hr annual average surface NO₂ concentrations from the U.S. Environmental Protection Agency (EPA) Air Quality System (AQS) monitor network. Figure 3 shows a scatterplot between 2019 annual averages of oversampled TROPOMI NO₂ and AQS surface-level NO₂* (surface-level concentrations from

the EPA AQS network are known to have a high instrument bias that varies spatiotemporally,^{14,15} and are thus referred here to as NO₂*).

Figure 3 demonstrates that there is a strong correlation ($R^2 = 0.66$) between TROPOMI NO₂ values and surface NO₂* observations at monitoring sites considered to be not within 20 m of a roadway (i.e., "not near-road"), which suggests that many (but not all) of the spatial heterogeneities observed by TROPOMI over long time intervals (e.g., year) are real and not an artifact of the processing algorithms. To better estimate surface-level concentrations, TROPOMI NO₂ data should be merged with a model simulation¹⁶ and/or land-use characteristics.¹⁷⁻²⁰

Case Study: Changes due to the COVID-19 Lockdowns

In Figure 4, we use TROPOMI NO₂ to quantify the NO₂ changes in the continental United States and southern Canada due to the COVID-19 pandemic lockdowns.

TROPOMI is an advantageous tool in this instance due to its global spatial coverage and the rapid availability of observations in a consistent data format transcending the borders of all countries. We compare the TROPOMI NO₂ mean of the first six months of the COVID lockdowns (March 13, 2020–September 13, 2020) to the coincident timeframe of 2019 in order to account for the effects of seasonality and meteorology on NO₂ concentrations.²¹ Because we compare over a

six-month period, it is reasonable to assume that the majority of the NO₂ changes are due to NO_x emissions changes.

The largest NO₂ decreases due to the lockdowns were seen in California (San Jose and Los Angeles) and the major cities of the eastern United States (New York City, Washington, DC, Atlanta, and Boston). Conversely, the cities in the central United States documented smaller NO₂ changes (Dallas, Austin, New Orleans, and Minneapolis). We also observe substantial NO₂ decreases near the retired Navajo power plant in northern Arizona. Areas with small NO₂ have been screened due to the high fraction of NO₂ attributed to biogenic sources and long-range transport.

Conclusion

This article describes the capabilities of TROPOMI in observing the spatial and temporal patterns of NO₂ pollution in the Continental United States. TROPOMI has unprecedented spatial resolution that allows it to quantify

the fine-scale patterns of NO_x emissions that had previously been reported at coarser resolution or in some cases had gone completely undetected from space-based instruments. Furthermore, due to the instrument's excellent stability, precision, and spatial resolution, it is no longer necessary to average over 6+ months of data to gain a clear depiction of regional NO₂ abundances; instead, monthly, weekly, or even daily aggregations could suffice for many purposes.

The examples presented here demonstrate how TROPOMI NO₂ satellite data can be advantageous for assessing, designing, and evaluating regulations and other factors influencing emission changes. Future health impact assessment studies can use the high-spatial resolution capabilities of TROPOMI NO₂ to investigate disparities in traffic-related air pollution exposure and associated health effects between neighborhoods and population sub-groups within cities. **em**

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