# Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission and Level 2 Data Product Validation Plans

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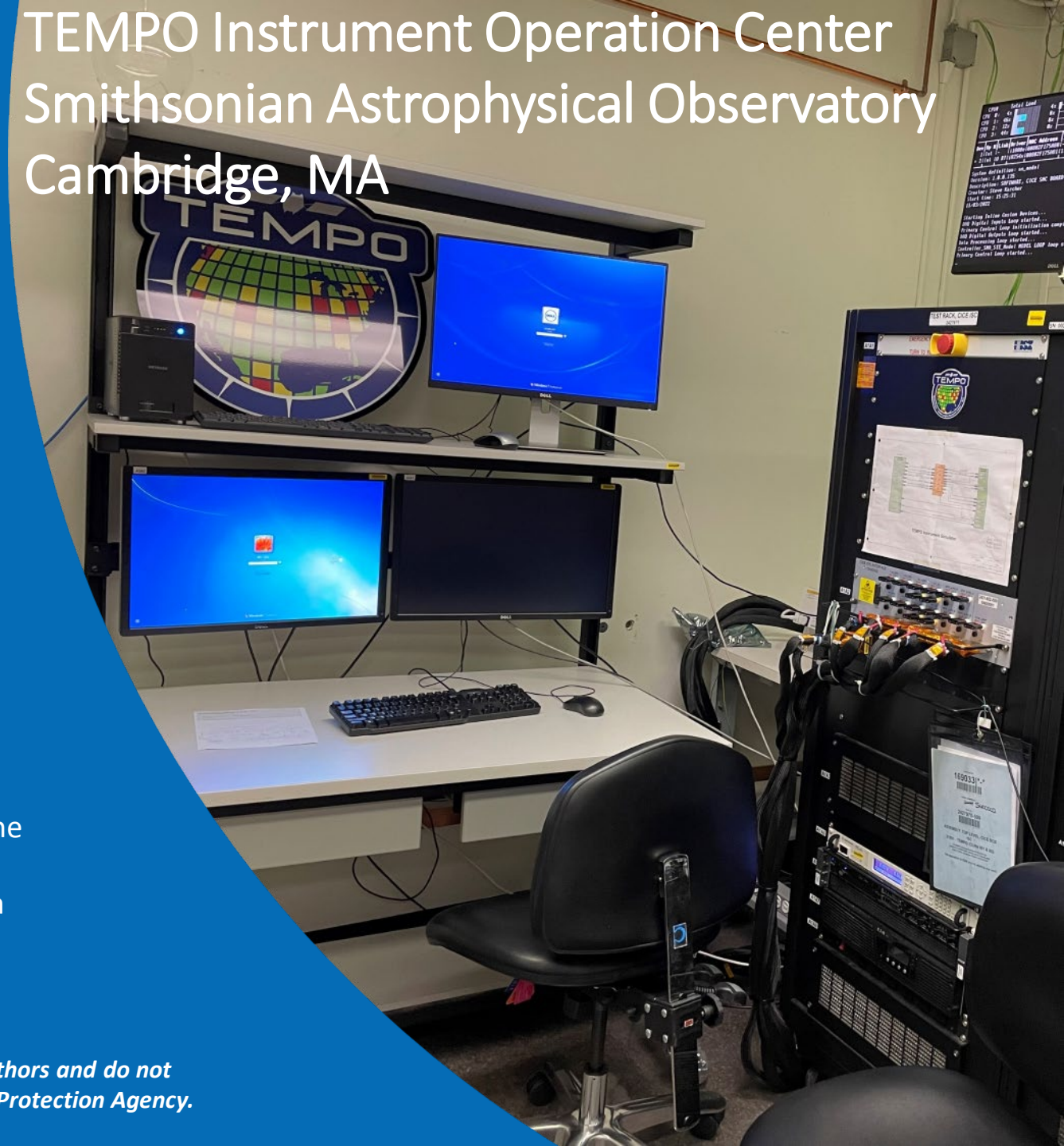


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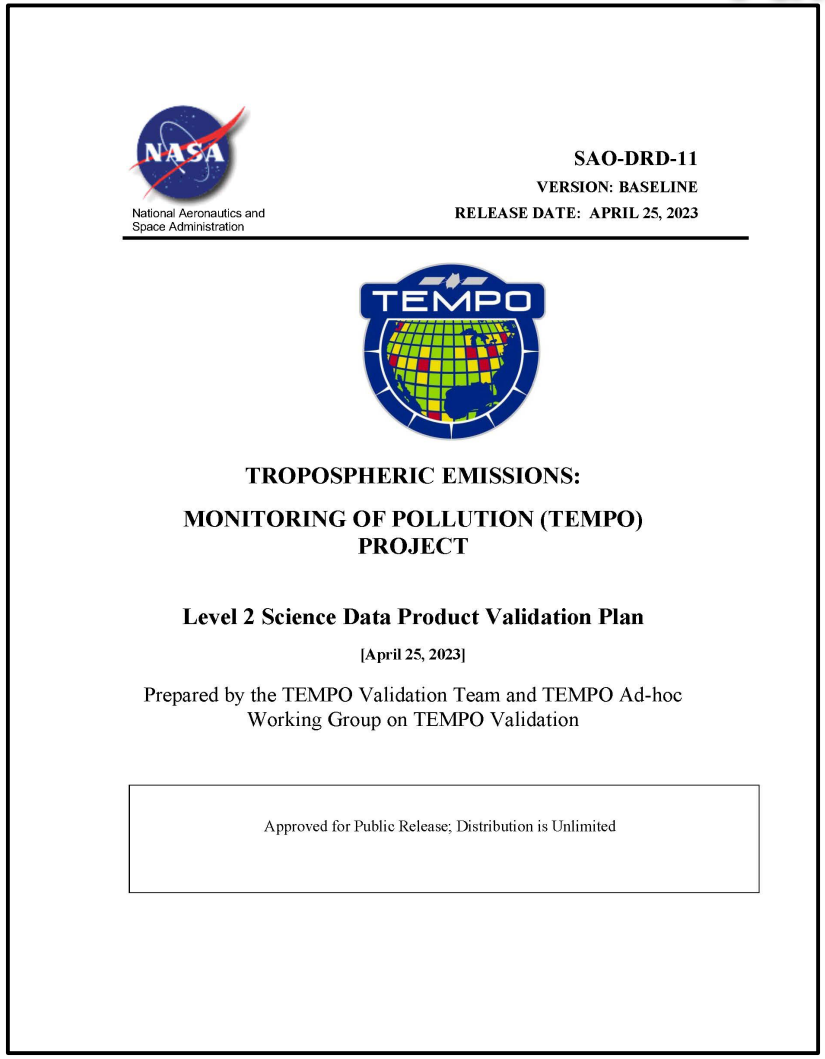
# TEMPO (Tropospheric Emissions: Monitoring Pollution) Validation Plan



National Aeronautics and Space Administration

SAO-DRD-11
VERSION: BASELINE
RELEASE DATE: APRIL 25, 2023

TROPOSPHERIC EMISSIONS:

MONITORING OF POLLUTION (TEMPO) PROJECT

Level 2 Science Data Product Validation Plan

[April 25, 2023]

Prepared by the TEMPO Validation Team and TEMPO Ad-hoc Working Group on TEMPO Validation

Approved for Public Release; Distribution is Unlimited

- Available at SAO TEMPO website: https://tempo.si.edu/documents.html
- Outlines a best-efforts validation approach for the TEMPO for **ozone, nitrogen dioxide, and formaldehyde** data products.
- Seeks to leverage a comprehensive set of existing measurements (ground-based and satellite) for routine validation enhanced by episodic field mission and modeling efforts.
- Describes a structure for the geophysical data product maturity progression and discusses specific metrics to be generated to provide a ‘fit for purpose’ applications framework.

# TEMPO Validation - Geophysical Data Products

Product Validation Maturity level were adopted from the NOAA GOES-R program Level 2 aerosol products:

- Beta: the product is minimally validated and may still contain significant errors; based on product quick looks using the initial calibration parameters.

- Provisional: product performance has been demonstrated through a large, but still (seasonally or otherwise) limited, number of independent measurements. The analysis is sufficient for limited qualitative determinations of product fitness-for-purpose, and the product is potentially ready for testing operational use.

- Full: product performance has been demonstrated over a large and wide range of representative conditions, with comprehensive documentation of product performance, including known anomalies and their remediation strategies. Products are ready for operational use.

# Nitrogen Dioxide Product Validation Overview

Beta product maturity:

- $NO_2$-01: Distinguish high $NO_2$ urban areas from nearby rural areas for three select urban-rural scene combinations.
- $NO_2$-02: Assess bias and precision for at least one month of retrievals in comparison to independent correlative measurements to convey an initial characterization to the user community. The assessment should evaluate TEMPO's capability to observe diurnal variations.
- $NO_2$-03: Identify two radiatively homogenous, cloud-clear, low tropospheric $NO_2$ background scenes over a dark surface (e.g., water) and over a bright surface (e.g., snow, desert) under different solar zenith angles and compute point-to-point variability (1-σ) as an empirical estimate for fitting uncertainty. Compare and communicate empirical estimates with those derived from the spectral fitting process.

Provisional product maturity:

- $NO_2$-04: Assess performance metrics (bias/precision/uncertainty) of TropNO2 product across the CONUS for 1 month period in two season that includes a range of column densities.
- $NO_2$-05: Conduct deep-dive analyses for a pollution event with relatively poor performance and identify the root cause and recommend algorithm improvements.

Full product maturity:

- $NO_2$-06: assess accuracy, precision, and uncertainty of the Trop$NO_2$ product across the CONUS for a wide range of representative conditions over a period of at least one year.
- $NO_2$-07: assess accuracy, precision, and uncertainty of the Trop$NO_2$ product over areas of interest using data gathered during targeted field campaigns.

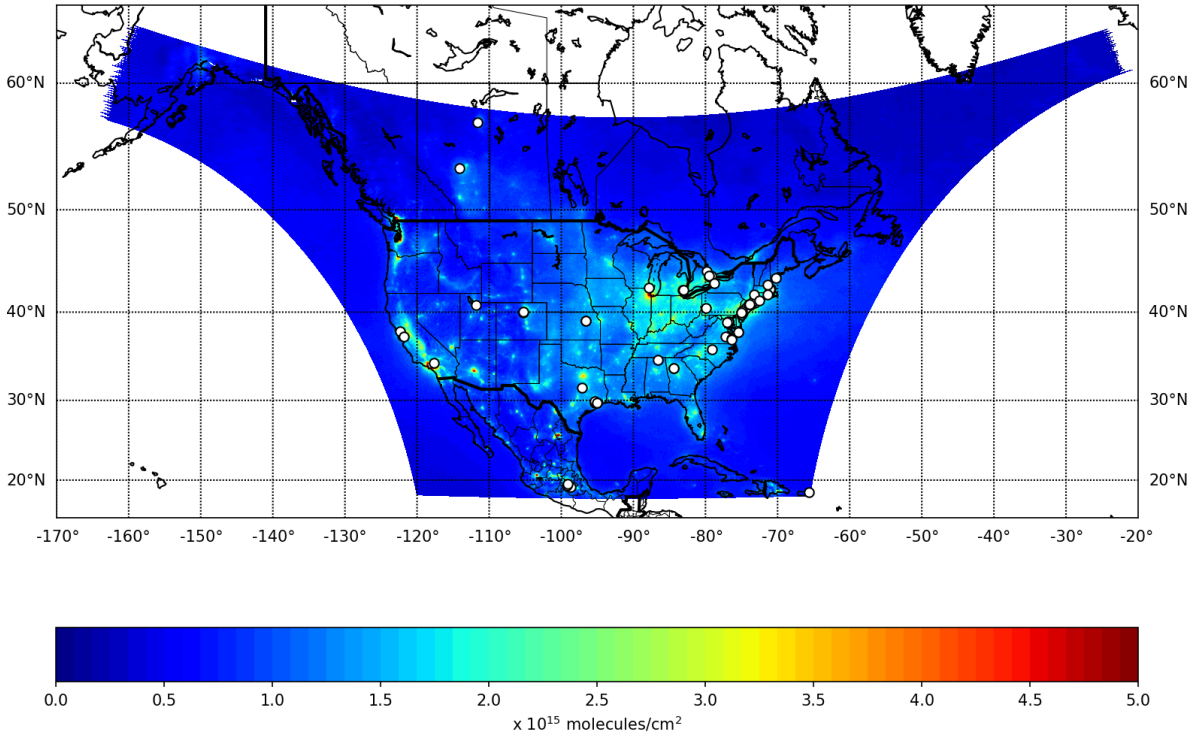
# Primary correlative measurement systems for validation of TEMPO Measurements and Baseline Products:

| Baseline Product Name | Product Horizontal Resolution N/S x E/W @ center of FOR[1] | Product Precision | Air Quality relevant (All in surface- 1 km) Product Precision | Frequency[2] | Ground-based data sources | Satellite data sources |
|---|---|---|---|---|---|---|
| Total Column $O_3$ | 2.0 x 4.75 $km^2$ | 3% | | 1 hour | Brewer, Dobson, PGN (pandora) | TROPOMI, OMI, OMPS |
| Tropospheric Column $O_3$ | 8.0 x 4.75 $km^2$ (4 N/S across-track pixels coadded) | 10 ppbv | 10 ppb | 1 hour | Ozonesonde, TOLNET | TROPOMI, OMI, OMPS |
| 0-2 km $O_3$ selected scenes | 8.0 x 4.75 $km^2$ (4 N/S across-track pixels coadded) | 10 ppbv | 10 ppb | 2 hours | Ozonesonde, TOLNET | |
| Total Column $NO_2$ | 2.0 x 4.75 $km^2$ | 1.0 × $10^{15}$ molecules $cm^{-2}$ | 0.4 ppb | 1 hour | PGN (pandora) Direct Sun | TROPOMI, OMI, OMPS |
| Tropospheric Column $NO_2$ | 2.0 x 4.75 $km^2$ | 1.0 × $10^{15}$ molecules $cm^{-2}$ | 0.4 ppb | 1 hour | PGN (pandora) Direct Sun and MAX-DOAS | TROPOMI, OMI, OMPS |
| Tropospheric column HCHO | 2.0 x 4.75 $km^2$ | 1.0 × $10^{16}$ molecules $cm^{-2}$ | 4.0 ppb | 3 hours | PGN (pandora) Direct Sun and MAX-DOAS, FTIR MAX-DAOS | TROPOMI, OMI, OMPS |

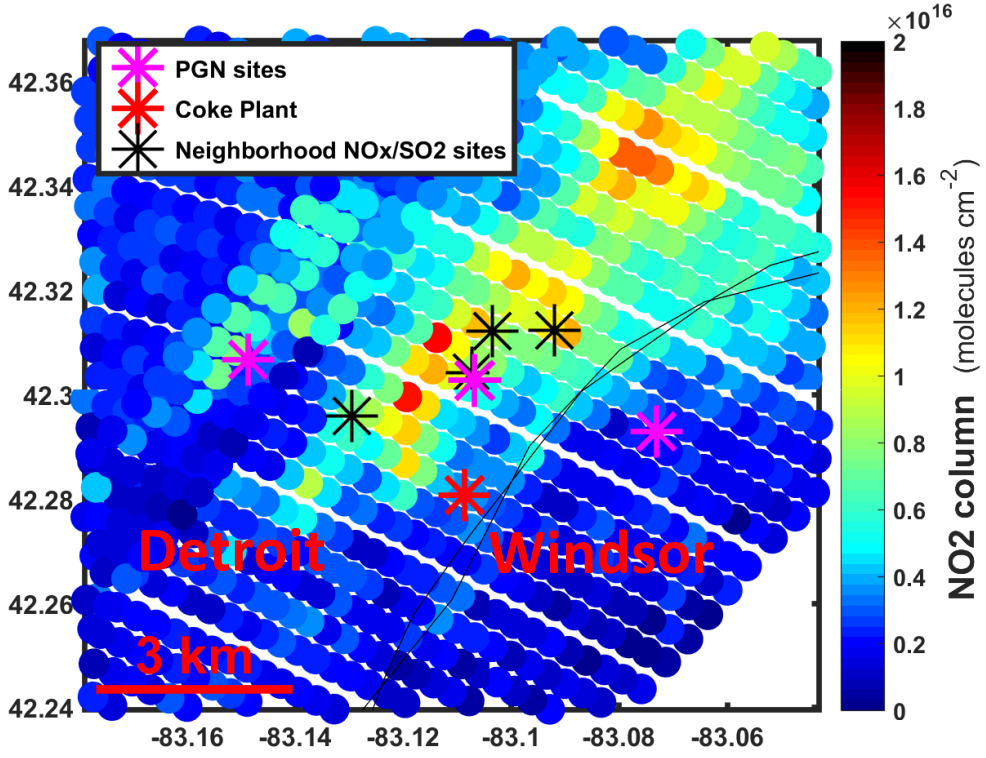
- **The integration of key (chemical and meteorological) measurements within the existing air quality networks will contribute to an improved assessment of TEMPO product precision plus an improved assessment of biases, and possibility allow an assessment of product accuracy.**

# Photochemical Assessment Monitoring Stations (PAMS) Enhanced Monitoring has allowed EPA ORD to collaborate with SLT Agencies to build out the Pandonia Global Network in conjunction with NASA and the European Space Agency across the U.S. for use in validating the TEMPO satellite mission

Pandonia Global Network Locations
in TEMPO Field of Regard




**NASA airborne GCAS NO2 column – MOOSE 2021**



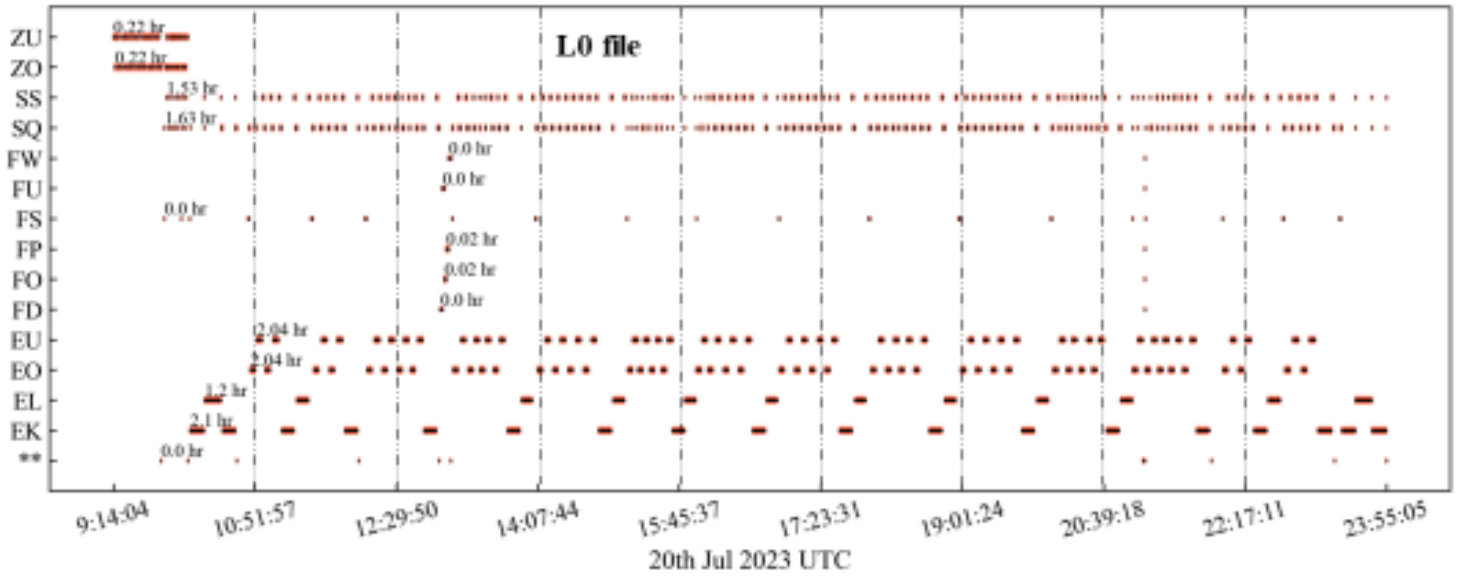

In addition to partnering on the larger TEMPO validation effort across North America, EPA and ECCC have contributed long-term total column NO2, O3, formaldehyde and SO2 measurements to Dearborn, Detroit and Windsor. One of several locations across the FOR to assess TEMPO sub-pixel variability for $NO_2$, HCHO, and $SO_2$ and improve our understanding of satellite/surface air quality inferences at neighborhood scales

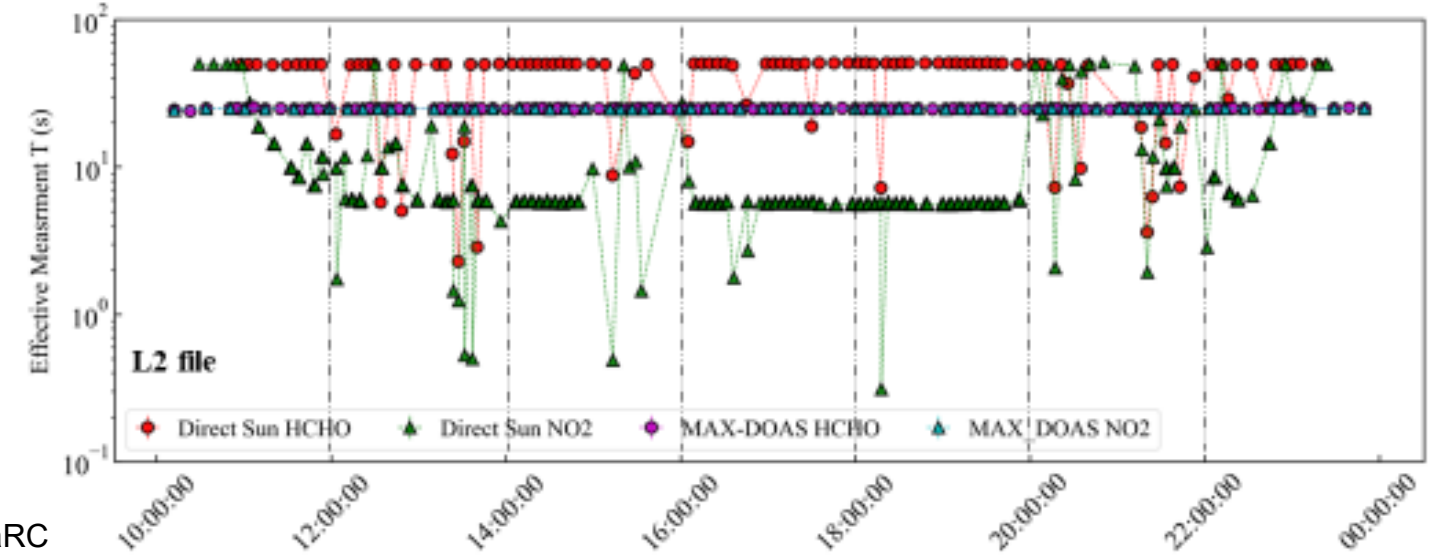
# Assessing need for a TEMPO Specific PGN Schedule

**Pandora NEW Brunswick schedule on 20th July 2023**

| Mode | Explanation |
|---|---|
| EK | Detailed sky scan at standard azimuth without filter; the standard azimuth is the one given in the BlickO Instrument Configuration |
| EL | Detailed sky scan at standard azimuth with U340 |
| EO | Quick sky scan (5 zenith angles) at standard azimuth without filter |
| EU | Quick sky scan (5 zenith angles) at standard azimuth with open U340 |
| FD | FD=FS, but with diffuser in the optical path) |
| FO | =FD, but scanning only around the center of the FOV with longer measurement duration. This is not used to "find" the sun. |
| FP | =FU, but scanning only around the center of the FOV with longer measurement duration. This is not used to "find" the sun. |
| FS | Find Sun; long sun search for all spectrometers, saves final figure and averaged data, but not spectral data |
| FU | FS, but with U340 plus diffuser combination in the optical path |
| FW | =FA, but showing the results in 4 wavelength regions (FA=FS, but also saving the spectral data) |
| SQ | Quick direct-Sun without filter |
| SS | Quick direct-Sun with U340 |
| ZU | Zenith-Sky with U340 |
| ZO | Zenith-Sky without filter |

Total measurement time is annotated (hr) in leftside for each mode on day 20th.



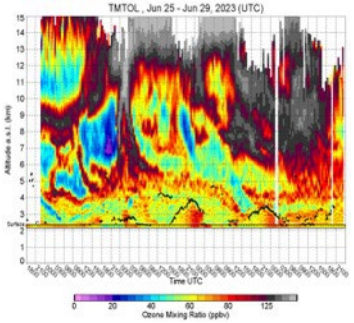




Credit: Prajjwal Rawat and Jim Crawford, NASA LaRC

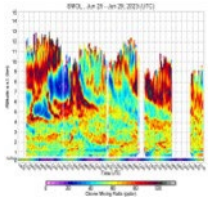
# AGES+ TOLNet Ground Support Network

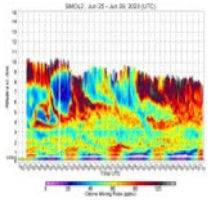
Tropospheric Ozone Lidar NETwork *https://tolnet.larc.nasa.gov/*


## San Bernardino, CA



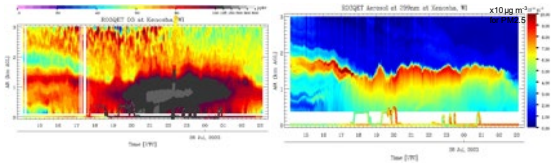

*SMOL – Compact Ozone Lidar characterizing the evolution of high ozone in Los Angeles during June 2023*



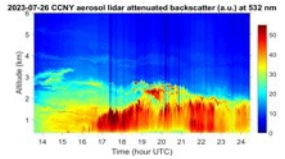


## Kenosha, WI ($RO_3QET$)

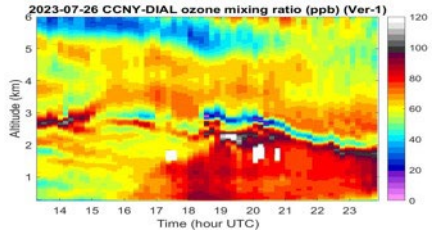

*$RO_3QET$ and SeaRey characterize high $O_3$ over Lake Michigan and at the Chiwaukee Prairie Site*



## Manhattan, NY (CCNY)

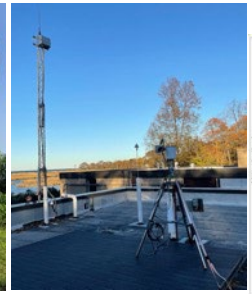


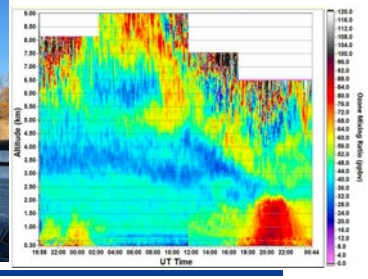

CCNY Ozone-DIAL observed ozone formation process in the PBL and aloft ozone in NYC




## Flax Pond, NY (TROPOZ)

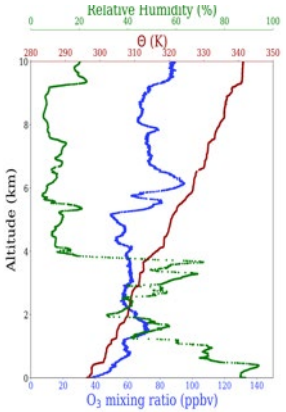
*NASA GSFC Ozone Lidar and Mobile Sampling Lab Lidars characterizing the evolution of high ozone along Long island*





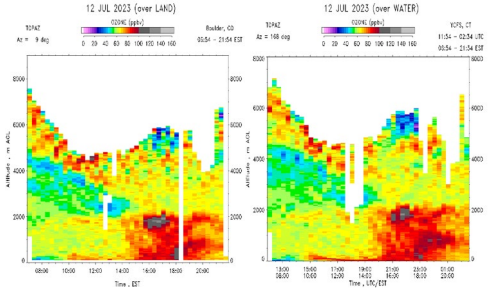

## Westport, CT (LMOL)

*NASA LaRC Lidar and Ozonesondes characterizing the evolution of high ozone along the CT shoreline in July*




## Yale Coastal, CT (TOPAZ)

*NOAA Ozone and Wind Lidars characterizing the evolution of high ozone along the CT Shoreline*




*Contact: John Sullivan – john.t.Sullivan@nasa.gov*

# Primary correlative measurements for episodic validation of TEMPO data products – field campaigns

**STAQS** Synergistic TEMPO Air Quality Science

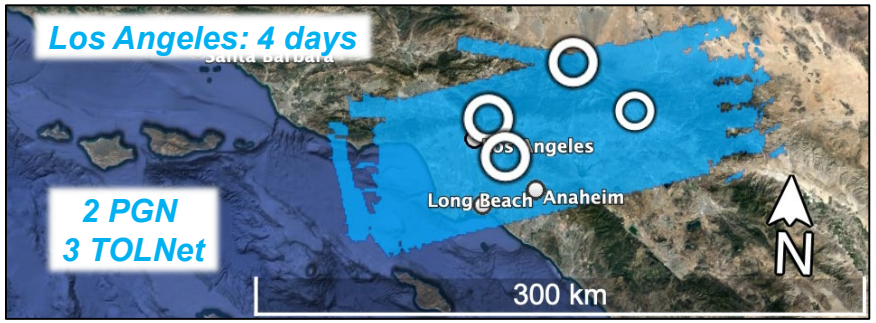
**Focus on aircraft measurements ($NO_2$, HCHO, ozone, aerosols, and GHGs) in major urban areas (shaded areas in maps) multiple times of day.**

**STAQS flights were coordinated with NOAA AEROMMA DC8 flights in each domain.**


Maps show areas flown during STAQS by the TEMPO airborne proxy.

*Table summarizing the observing system deployed for STAQS*

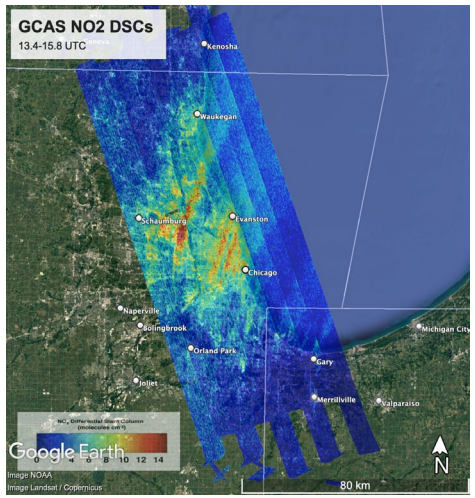
| Platform | Instrument | Data Products | Sampling Strategy |
|---|---|---|---|
| NASA JSC G-V | GCAS | $NO_2$ Column (250 x 560 m)<br>HCHO Column (750 x 1680 m) | Systematic sampling of a ~ 50 x 140 km area 3x per day (morning-midday-afternoon) |
| | HSRL2/DIAL | Ozone profiles, aerosol profiles, mixed layer height | |
| NASA LaRC G-III | AVIRIS-NG | $CH_4$ (> 10 kg/hr) and $CO_2$ (large point sources) emissions | Systematic sampling of a ~ 50 x 140 km area 2x per day (morning-afternoon) |
| | HALO | $CH_4$ columns, aerosol profiles, mixed layer height | |
| Ground-based | TOLNet | Lower tropospheric ozone profiles | Routine sampling with enhanced measurements during flight days within the domain |
| | Pandora | $NO_2$ and HCHO columns and profiles | |

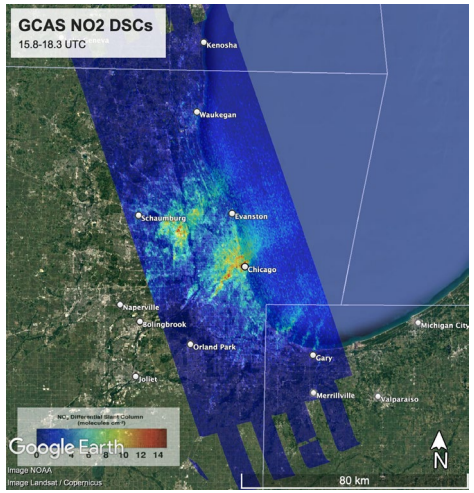


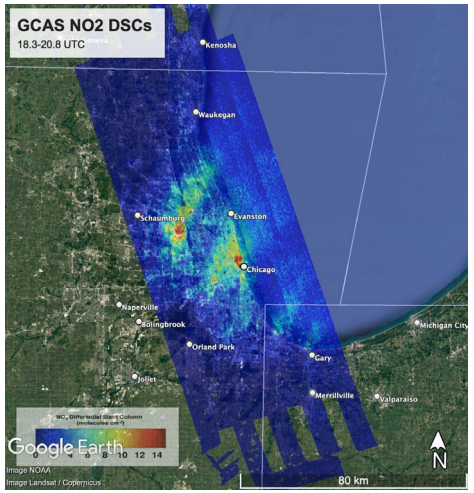
# Example Preliminary Measurements from STAQS

## Chicago August 2, 2023—TEMPO First light

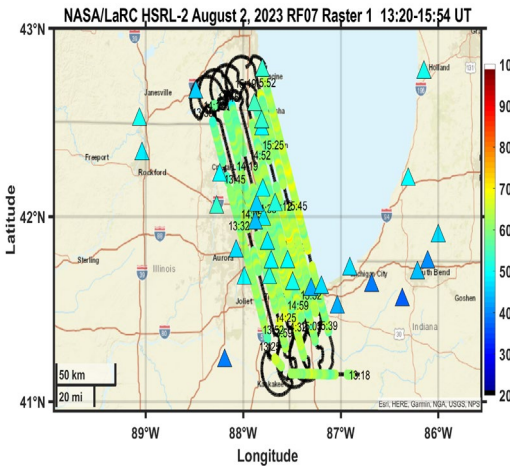
**PRELIMINARY** $NO_2$ Differential Slant Columns from GCAS

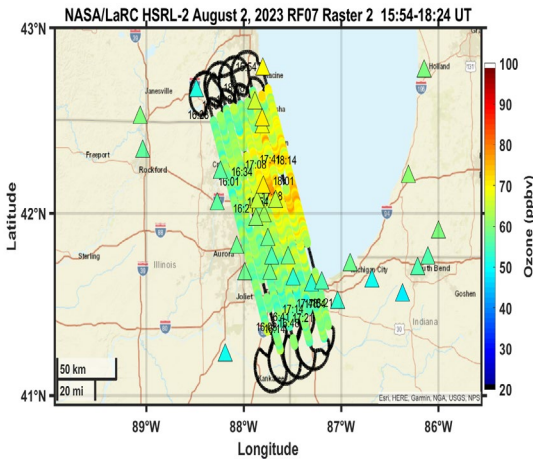


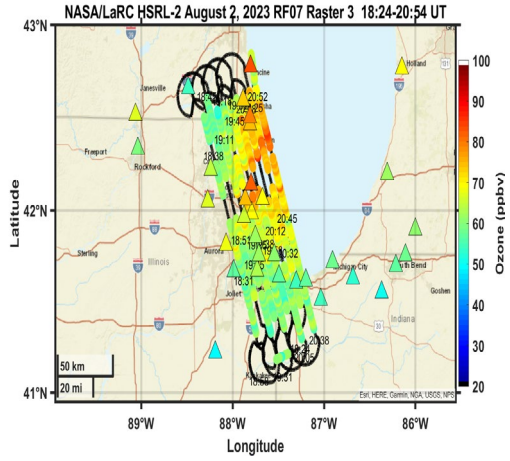




**PRELIMINARY** Near Surface Ozone Concentrations from HSRL2



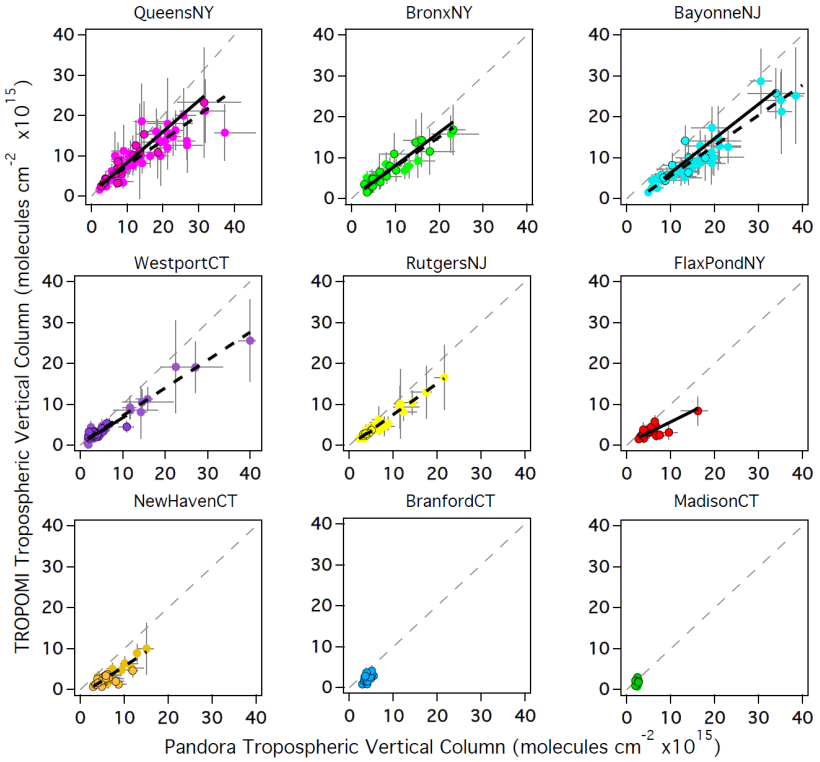



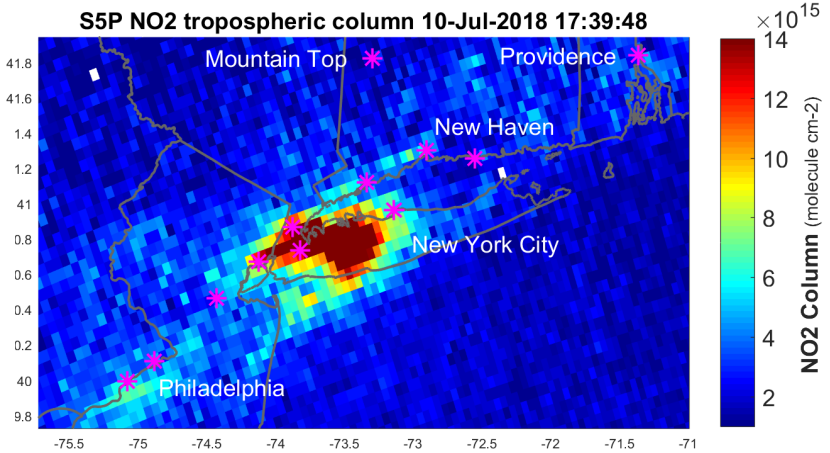

**Other helpful airborne parameters for TEMPO validation:**

- ⇢ GCAS HCHO Columns
- ⇢ AOD (355/532 nm) + other aerosol characteristics
- ⇢ Derived mixed layer heights
- ⇢ Vertical profiles from NOAA AEROMMA/NASA DC8

*STAQS data will be available no later than April 1*

# PGN Northeast U.S. sites are primarily located at U.S. air quality measurement sites and provide a dense network for comparison between TROPOMI and TEMPO

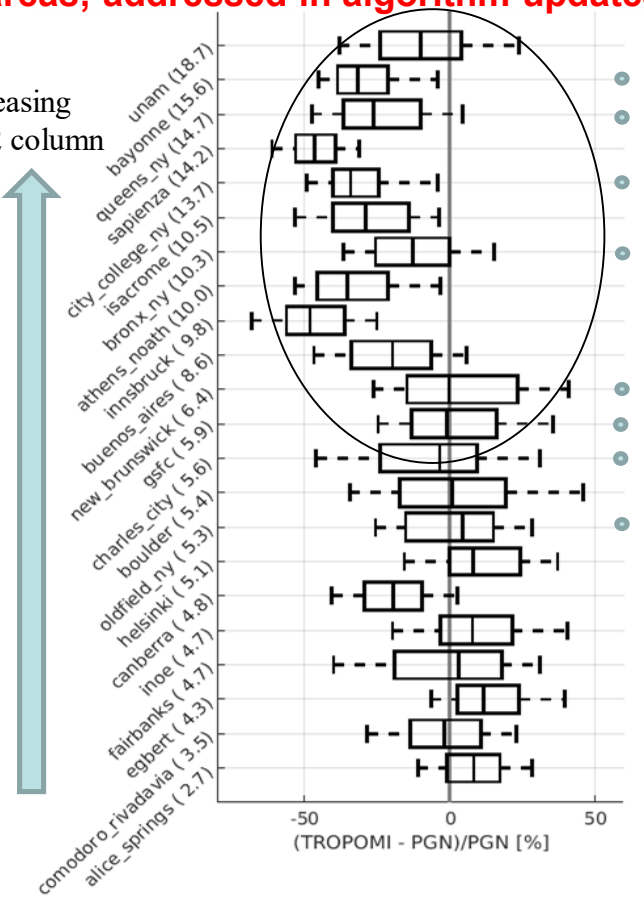



The PGN provides years-long data sets from around the world to compare with TROPOMI **(Pandoras in the OTR )**

These types of comparisons can be used to refine TEMPO retrievals

- **EPA pandoras hosted by state and local agencies help confirm low bias in polluted areas; addressed in algorithm updates**





**Judd et al**, Evaluating Sentinel-5P TROPOMI tropospheric NO2 column densities with airborne and Pandora spectrometers near New York City and Long Island Sound, *AMT,* 2020.

**Verhoelst et al**, : Ground-based validation of the Copernicus Sentinel-5p TROPOMI $NO_2$ measurements with the NDACC ZSL-DOAS, MAX-DOAS and Pandonia global networks, *AMT,* 2021.

# Summary

- TEMPO is funded as a research demonstration mission with minimal validation.
- To address this unmet need the validation team developed a best effort approach for validation of TEMPO data products which leverages NASA and non-NASA resources, including a large set of operational and research air quality surface observing systems.
- TEMPO validation efforts should evolve into routine and systematic (on-going) validation using correlative measurements from PGN, NDACC, and satellites along with more complex (episodic) validation via planned science campaigns with focus on satellite data and local air quality.
- For the first time, validation measurements for a satellite mission are being integrated within operational air quality networks on large-scale through collaboration with the PGN.
- The validation plan provides a framework for facilitating greater use of satellite data products. The emerging TEMPO validation paradigm is focused on providing information on the reliability and fit for purpose of L2 data products.
- A goal is to address what the satellites agencies expressed in the CEOS White Paper: Geostationary Satellite Constellation for Observing Global Air Quality: Geophysical Validation Needs – this will require additional resources.