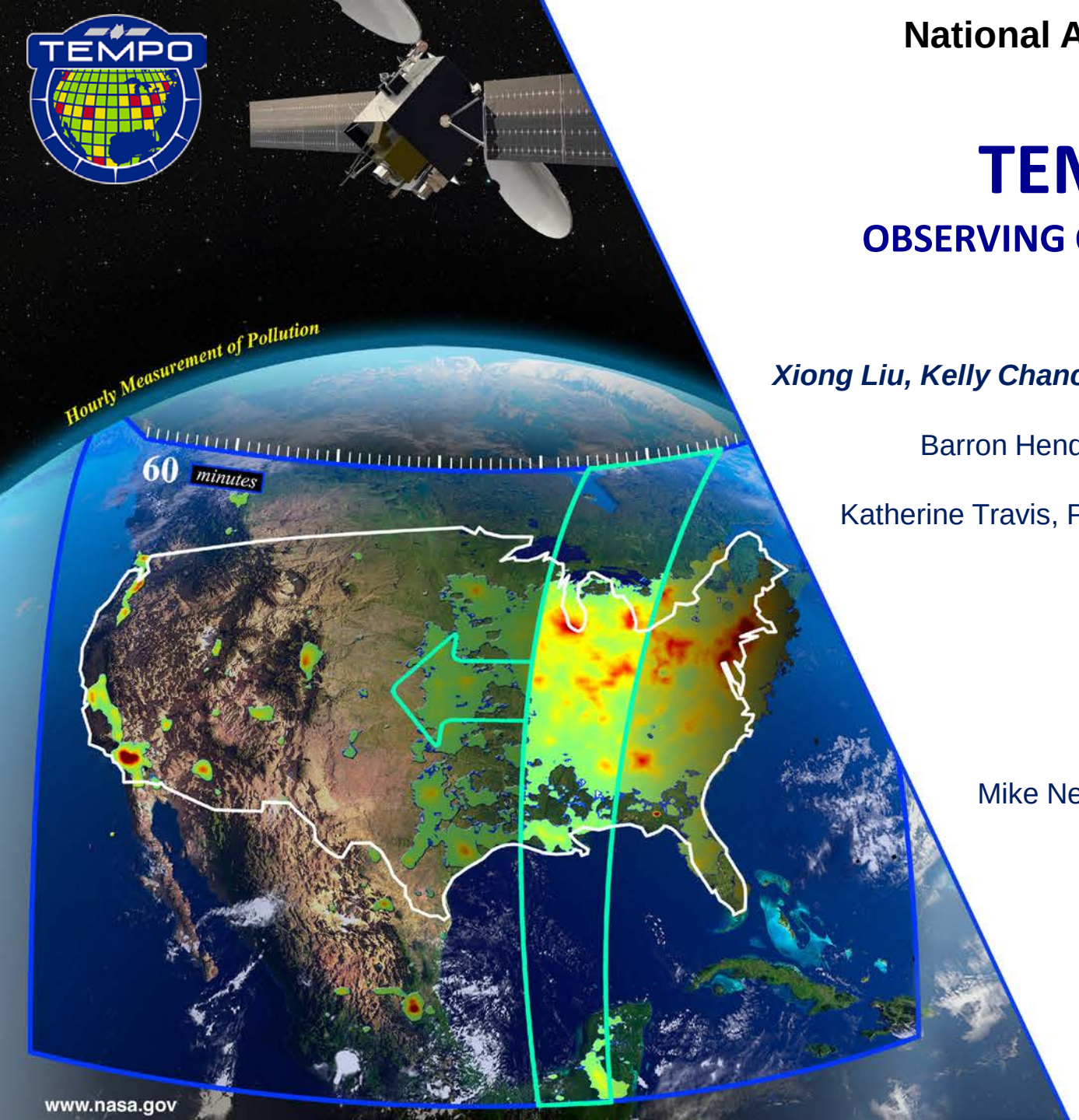


National Ambient Air Monitoring Conference
12-15 August 2024

TEMPO Status Update

OBSERVING OUR NATIONS AIR QUALITY FROM SPACE

James Szykman, US EPA
Xiong Liu, Kelly Chance, Gonzalo Gonzalez Abad, Caroline Nowlan, Huiqun Wang, and entire SAO TEAM.
Barron Henderson, Luke Valin, Eric Baumann, and David Williams
US EPA
Katherine Travis, Prajjwal Rawat, Jim Crawford, Laura Judd, and David Flittner
NASA LaRC
Brad Pierce
SSEC Univ of Wisc.
Shobha Kondragunta
NOAA/NESDIS
Barry Lefer
NASA HQs
Mike Newchurch-UAH & Ronald Cohen-UCB, plus others!

TEMPO Overview

Principal Investigator: Xiong Liu (present); Kelly Chance 2012-2024, Smithsonian Astrophysical Observatory

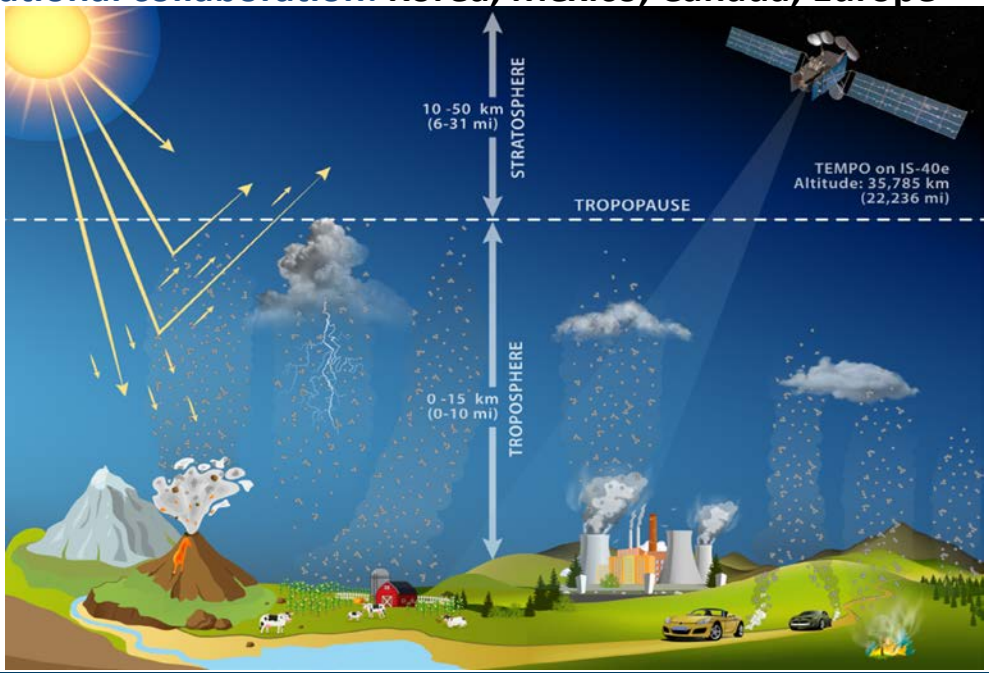
Project Management: NASA's Langley Research Center

Instrument Development: Ball Corporation

Satellite Hosts: Maxar, Intelsat

Science Team Institutions: EPA, NASA LaRC, NASA GSFC, NOAA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Iowa

International collaboration: Korea, Mexico, Canada, Europe



- Research instrument on a commercial communications satellite circling the Earth in a ***geosynchronous orbit providing constant view of North American***.
- Spectrometer which uses solar backscatter light (ultraviolet/visible) to provide daylight measurements on an ***hourly time basis of key ozone precursors*** (nitrogen dioxide and formaldehyde), ozone, sulfur dioxide, and aerosols across North America.
- ***High spatial scale resolution*** (multi-kilometer) data products focused on improving our understanding of temporal and spatial variation of emission sources, transport, and air quality at scales ranging from urban to continental, and diurnal to seasonal.
- **Pathfinder instrument to NOAA's** future GeoXO Satellite Mission **Atmospheric Composition (ACX) instrument launching in 2030's.**

TEMPO Timeline

The TEMPO satellite launched April 7, 2023. Credit: Walter Scriptunas/Center for Astrophysics | Harvard & Smithsonian

Date	Details
December 2012	NASA selects TEMPO as 1st Earth Venture Instrument
7 December 2018	TEMPO delivered to NASA
7 April 2023	Launch
2 August 2023	**First light (First data collected)**
19 October 2023	Nominal Operations
May 2024	NASA/NOAA award GeoXO ACX
18 June 2025	End of TEMPO Baseline Mission
Extended Operations	NASA Senior Review

Public Release	Details
V01	Limited 3 weeks released in February 2024
V02	Level 1 (radiances) released in February 2024
V03	**Level 1 updated, Level 2/3 NO_2, HCHO, total O_3 released May 2024; 13 May 2024 onwards; reprocessing for August forward on-going, currently up to Jan 2024. CPU limited.**

Baseline TEMPO Data Products

Level	Product	Validation Status
L1	Irradiance NRT	Beta
	Radiance NRT	Beta
	Radiance (twilight – city lights)	Beta
L2	Clouds NRT	Beta
	NO_2 NRT	**Beta**
	HCHO NRT	**Beta**
	O_3 (total)	Beta
	O_3 (profile)	Production/Release on hold
L3	L2 gridded to 0.02° × 0.02°	

*_**Beta**_: "minimally validated", publication "not recommended and highly discouraged"
→ Hope to go to ***provisional*** status after validation team approval

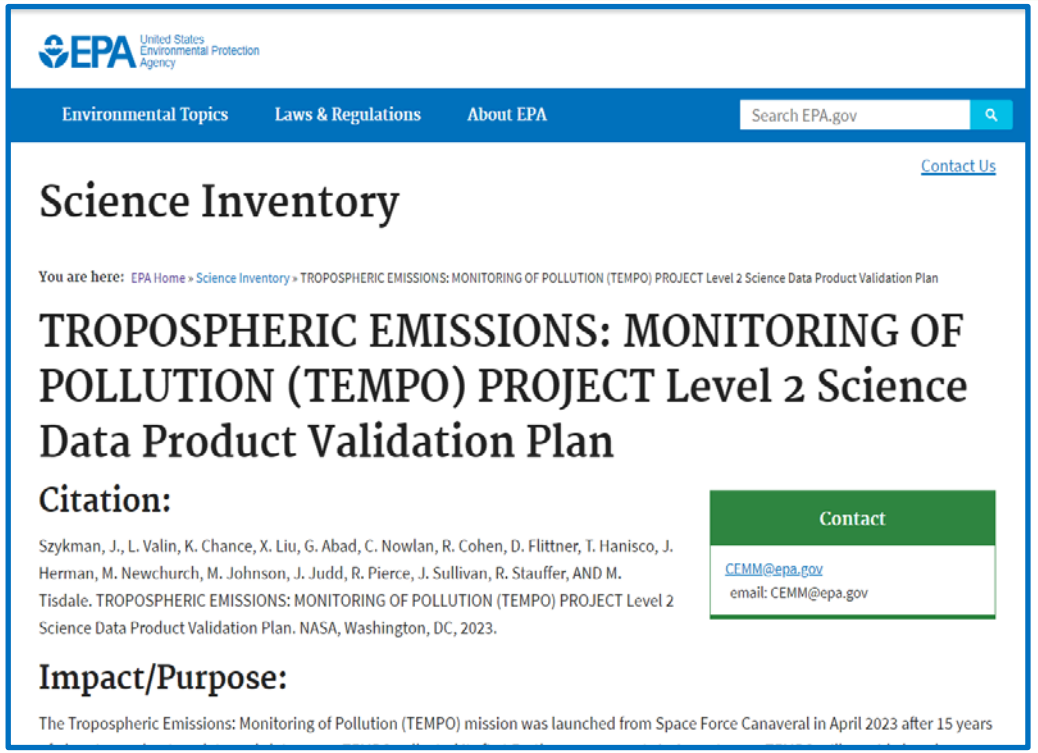
Satellite Needs Working Group has funded TEMPO Near-Real-Time (**NRT**) products (expected in 2025)

NOAA GeoXO ACX Team to product NRT aerosols (more later in presentation)

Enhanced research products: Aerosols, SO_2, ocean color, city lights

Future TEMPO products: H_2O vapor, glyoxal, BrO, HNO_2

TEMPO Level 2 Validation Plan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TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO) PROJECT Level 2 Science Data Product Validation Plan

Citation:

Szykman, J., L. Valin, K. Chance, X. Liu, G. Abad, C. Nowlan, R. Cohen, D. Flittner, T. Hanisco, J. Herman, M. Newchurch, M. Johnson, J. Judd, R. Pierce, J. Sullivan, R. Stauffer, AND M. Tisdale. TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO) PROJECT Level 2 Science Data Product Validation Plan. NASA, Washington, DC, 2023.

Contact

CEMM@epa.gov
email: CEMM@epa.gov

Impact/Purpose:

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission was launched from Space Force Canaveral in April 2023 after 15 years

(https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=362165&Lab=CEMM)

EPA ORD and Air, Climate and Energy Research Program filled a critical gap for the TEMPO mission by leading validation efforts and expanding the Pandonia Global Network of pandora spectrometers across the U.S.

- Facilitated and led by EPA in collaboration with TEMPO Validation and Science Team, NASA, and NOAA.
- Current plan **only addresses validation of the TEMPO baseline L2 data products: ozone, nitrogen dioxide, and formaldehyde.**
- Developed to provide (1) feedback to TEMPO algorithm team on the potential source errors in algorithms and (2) **guidance on data quality and fit for purpose use to science and application community** through routine and systematic (on-going) assessment of bias/precision/uncertainty.
- **Pandora spectrometers integrated within the existing air quality network are a critical component of the validation and potential applications (**collocation helps gain an improved understanding of satellites ability to measure near surface air quality (preliminary example later in talk)).
- **Analysis leverages** a comprehensive set of existing measurements (ground-based, airborne, and satellite) and analysis from **many organizations, (NASA, NOAA, ESA, EPA, ECCC, NCAR, State and Local agencies, and Universities).**

TEMPO L2 Total and Tropospheric NO_2

Product Maturity Levels & Product Specific Performance Indicators

Product Validation Level	Product-Specific Performance Indicators (PSPIs)
Beta Validation: the product is minimally validated but may still contain significant errors; based on product quick looks using the initial calibration parameters. Publication of research based on Beta maturity products is not recommended and highly discouraged.	**NO2-01**: Distinguish high NO2 urban areas from nearby rural areas for three select urban-rural scene combinations.
	NO2-02: 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.
	NO2-03: 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 Validation: 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 by operational users and may be suitable for scientific publication.	NO2-04: Assess performance metrics (bias/precision/uncertainty) of the tropospheric NO_2 product across the CONUS for 1 month period in two seasons, preferably summer and winter, that includes a range of column densities.
	NO2-05: Conduct deep-dive analyses for an episode with relatively poor product performance, identify the root cause and recommend algorithm improvements.
Full Validation: 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 systematic use and covering the full range of scientific and application use and publication.	NO2-06: Assess bias, precision, and uncertainty of the tropospheric NO_2 product across the CONUS for a wide range of representative conditions over a period of at least one year.
	NO2-07: Assess bias, precision, and uncertainty of the tropospheric NO_2 product over areas of interest using data gathered during targeted field campaigns.

Validation PSPI Analysis/Metric(s) contributed voluntarily by many PIs/Research Organizations

TEMPO L2 Total and Tropospheric NO_2

Product Maturity Levels & Product Specific Performance Indicators

The PSPI's are like the EPA Data Quality Objectives (DQO) Process used to establish performance and acceptance criteria, which serve as the basis for designing a plan for collecting data of sufficient quality and quantity to support the use of the data.

NO2-01: Distinguish high NO2 urban areas from nearby rural areas for three select urban-rural scene combinations.

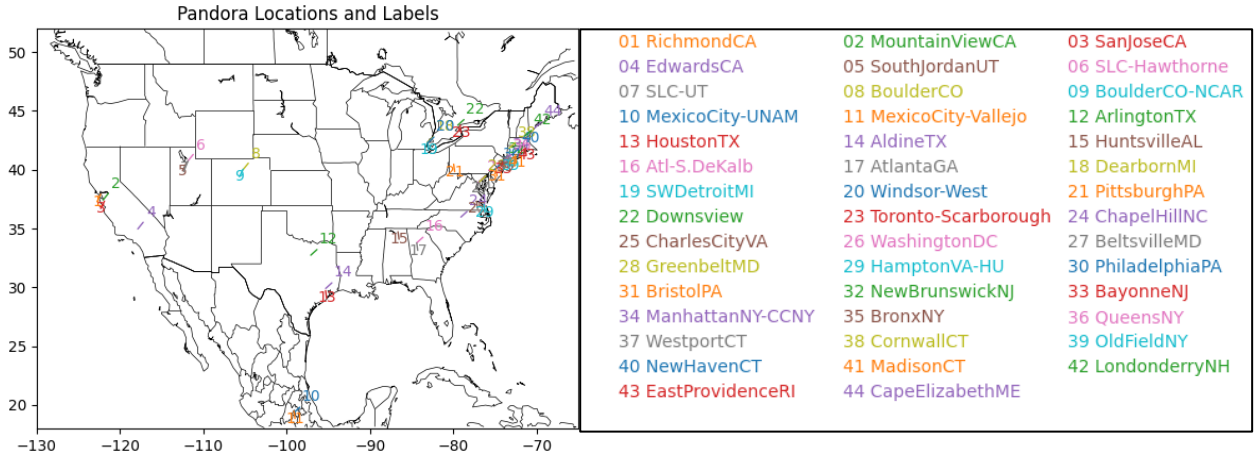
PSPI included use of ground-based and airborne spectrometers which can capture such gradients and provide independent similar geophysical measurements.

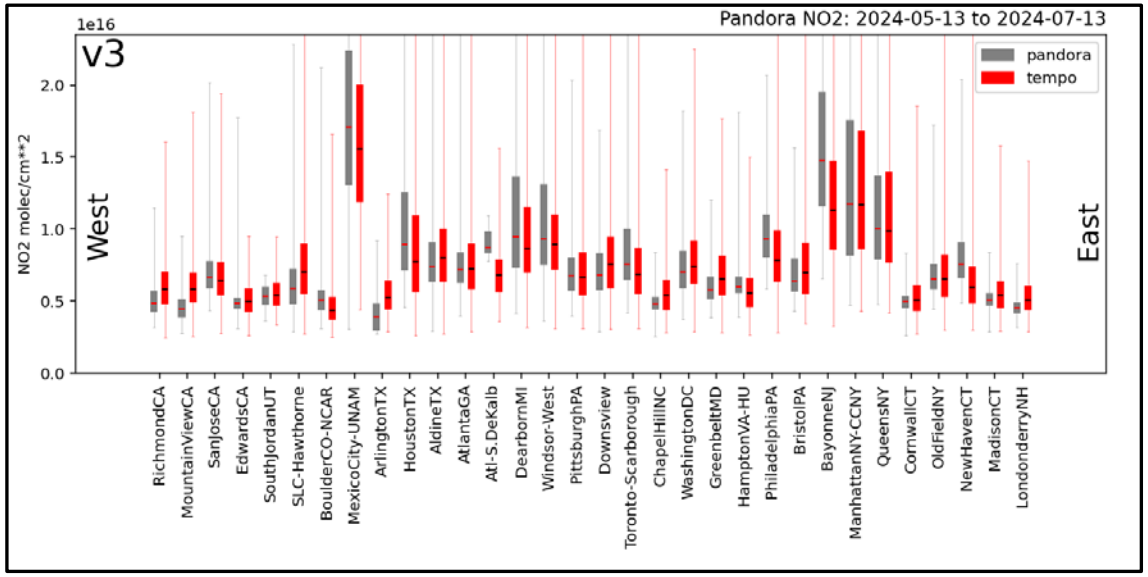
Product Validation	
Beta Validation: the … contain significant e… initial calibration pa… maturity products i…	…hree select urban- … comparison to …tion to the user …serve diurnal …heric NO2 …urface (e.g., snow, desert) under different solar zenith angles and compute point-to-point variability (1-σ) as an empirical estimate for fitting uncertainty. Compare and communicate empirical estimates
Provisional Validati… demonstrated thro… limited number of i… sufficient for limited qualitative determinations of product fitness-for-purpose, and the product is potentially ready for testing by operational users a…	…e tropospheric NO2 …y summer and NO2-05: Conduct deep-dive analyses for an episode with relatively poor product …vements.
Full Validation: pro… large and wide rang… comprehensive doc… known anomalies a… ready for systematic use and covering the full range of scientific and application use and publication.	…2 product across the …t least one year. …2 product over areas of interest using data gathered during targeted field campaigns.

Validation PSPI Analysis/Metric(s) contributed voluntarily by many PIs/Research Organizations

Example Routine Validation Analysis

TEMPO L2 NO_2 vs Pandora Total NO_2





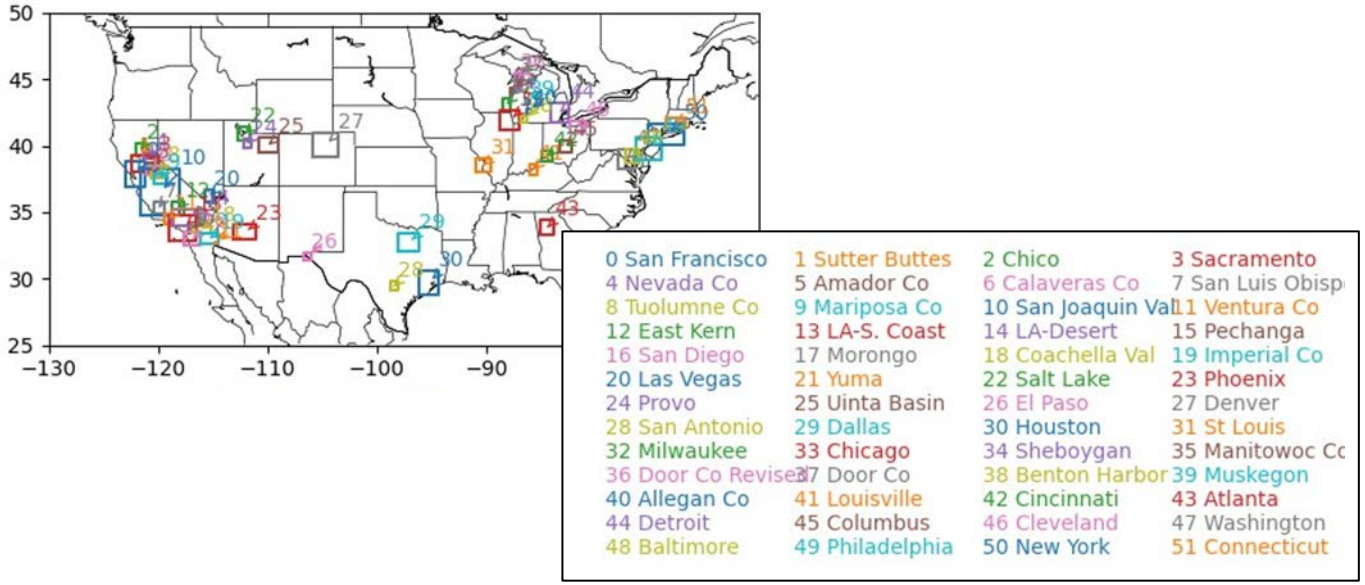
Pandora Spectrometers provide:

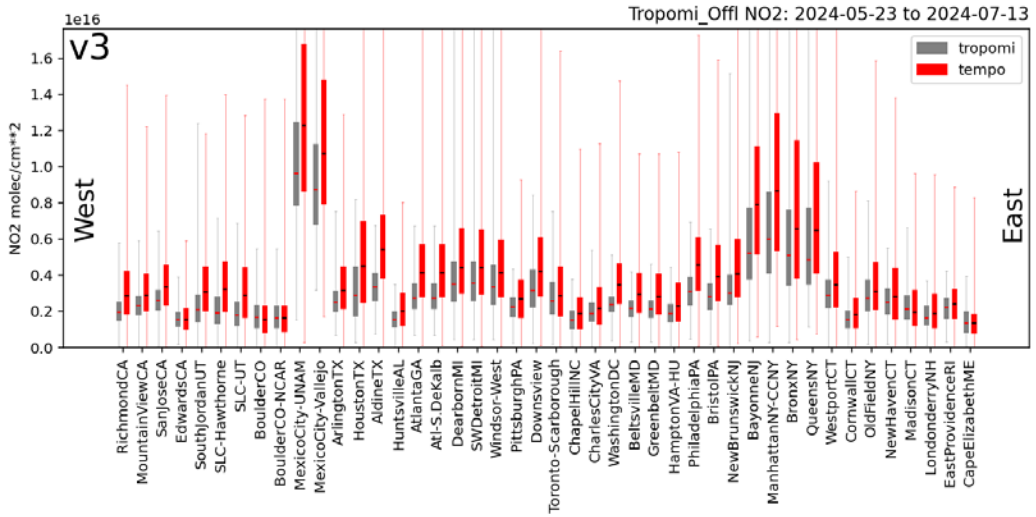
- A continues assessment of bias and precision over different regions and time scales (diurnal to seasonal) and solar zenith angle dependence.
- Assessment spatial representativeness of TEMPO pixel, such as differences in urban vs rural regions.
- Currently developing a validation dashboard that will include these and similar validation analysis.
- Anticipate initial validation report focused on version 3 Level 2 data in September 2024.

Figures: Barron Henderson, EPA

Example Routine Validation Analysis

TEMPO L2 vs TROPOMI L2 Tropospheric NO_2

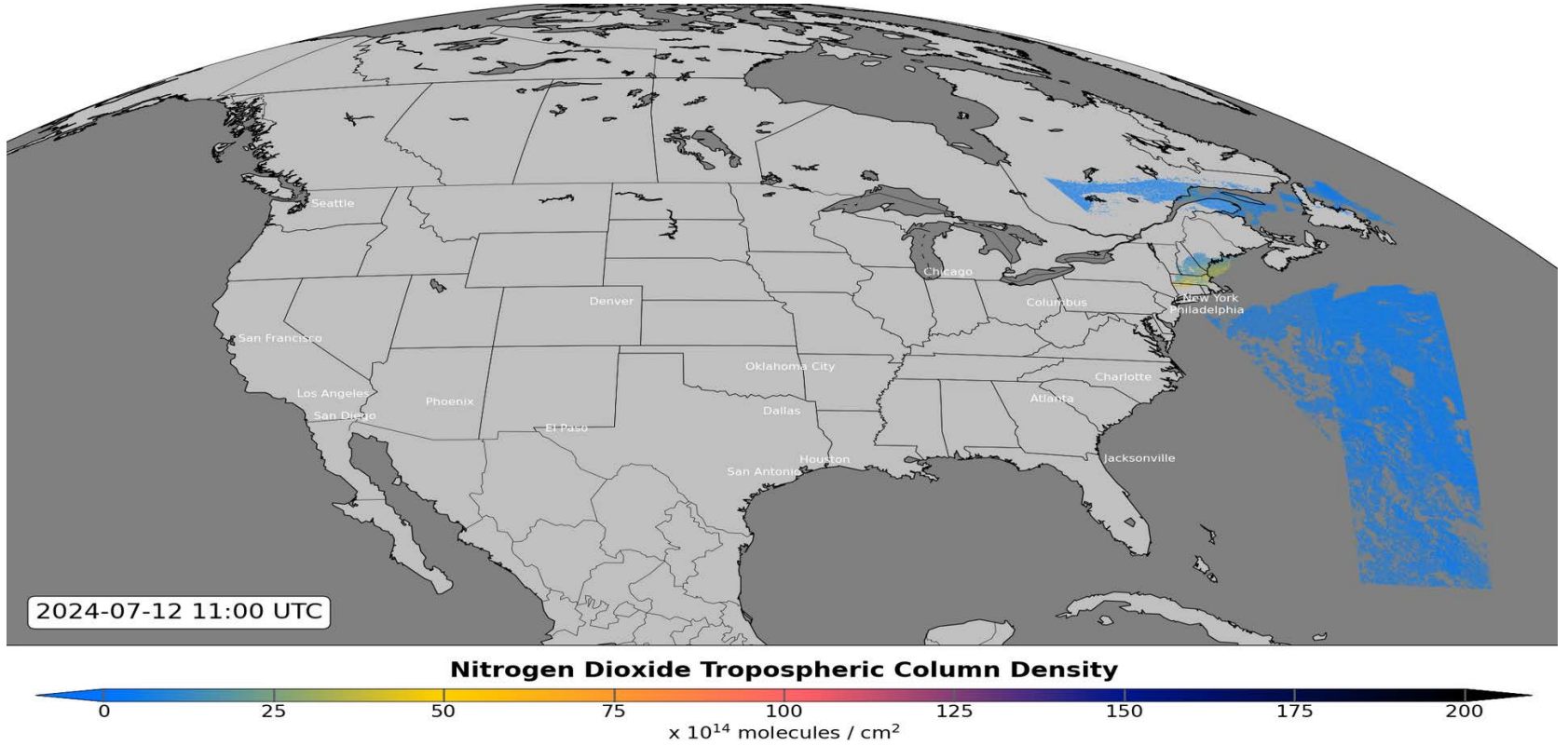




- Analysis is focused on assessment of bias and precision over ozone non-attainment areas (NAA). NAA regions are defined by a rectangular envelope that encompasses the nonrectangular region.
- Similar plots to Pandora/TEMPO analysis and AirNow/TEMPO analysis.
- Focus is on providing analysis relevant State, Local and EPA air quality management needs.

Figures: Barron Henderson, EPA

TEMPO Level 2 Tropospheric NO_2 (Version 3)

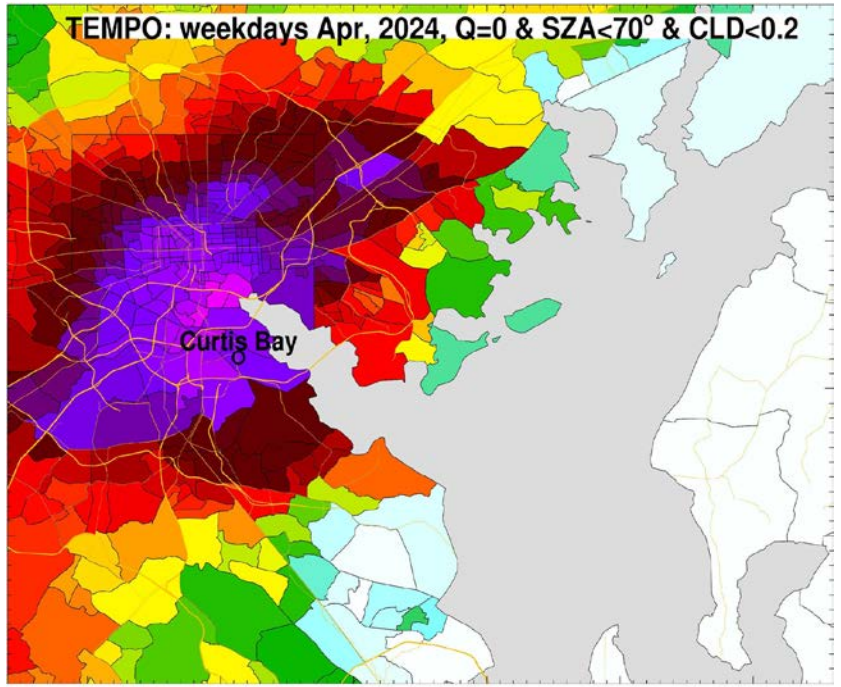


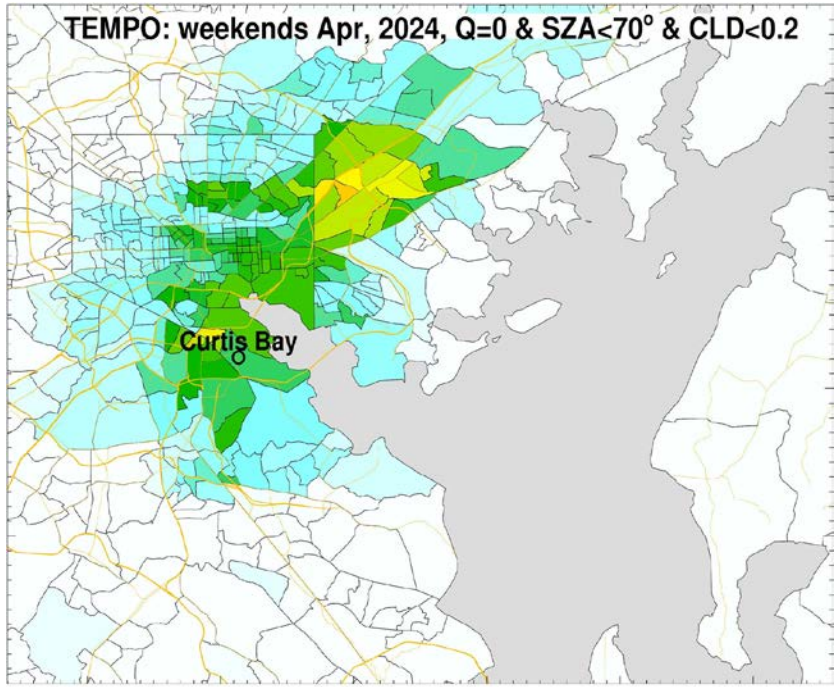
Validation shows TEMPO Level 2 NO_2 (& HCHO) meets precision requirement for >90% of cloud-free scenes at native pixel resolution versus project requirement of 4 pixel coadded for NO_2 (and 12 for HCHO).

ORD research is working to increase user access to TEMPO data through the Remote Sensing Information Gateway and adding daily visualizations of TEMPO L2 data (left image) with overlays of synergistic variables, such as AirNow, Pandora, and HRRR winds, release expected late August.

A New View of NO_2 over Urban Areas

TEMPO NO_2 data mapped to census tracts (weekdays vs. weekends in April 2024)



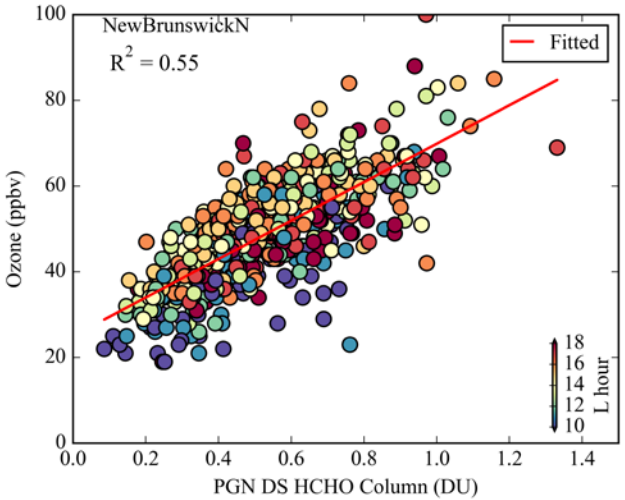


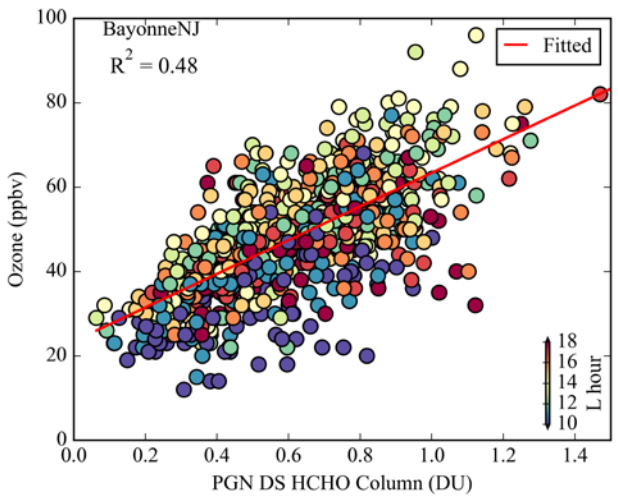
TEMPO Tropospheric Column NO_2 appears to capture changes in emissions between weekdays and weekends. Observing these changes on hourly, daily, and seasonal scale can be used to air assessment of NO_X emissions and air quality model performance – direct relevance to NAAQS

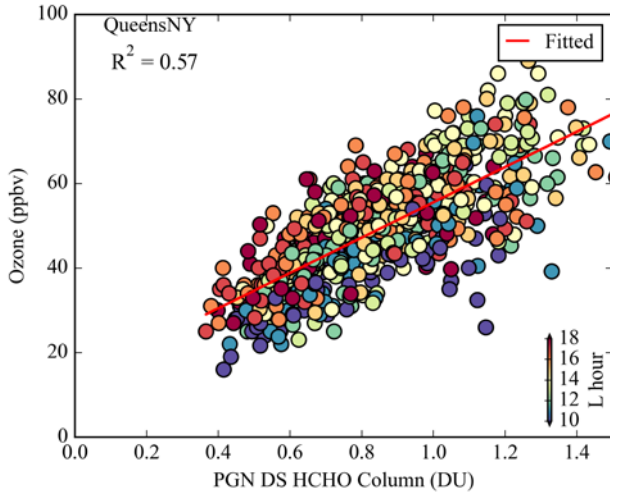
Source: NOAA/NESDIS

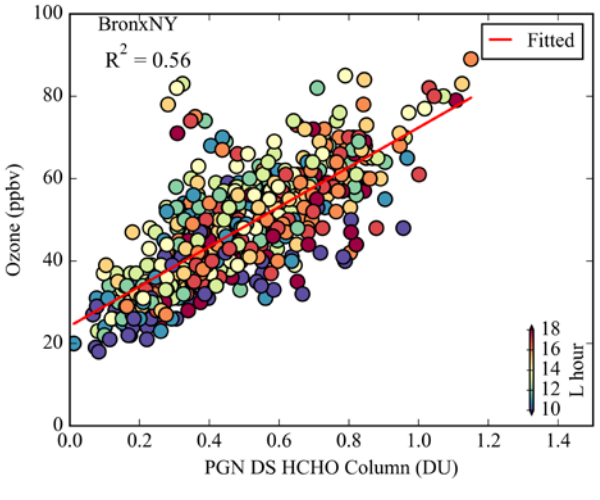
Can Column HCHO provide Insights into Infer Surface Ozone: TEMPO replicates performance of Pandora

Using remotely sensed HCHO column from Pandora ground-based spectrometers (July to Sep 2023)

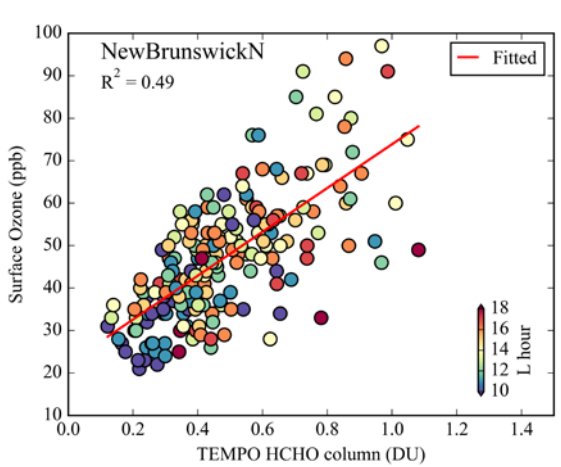


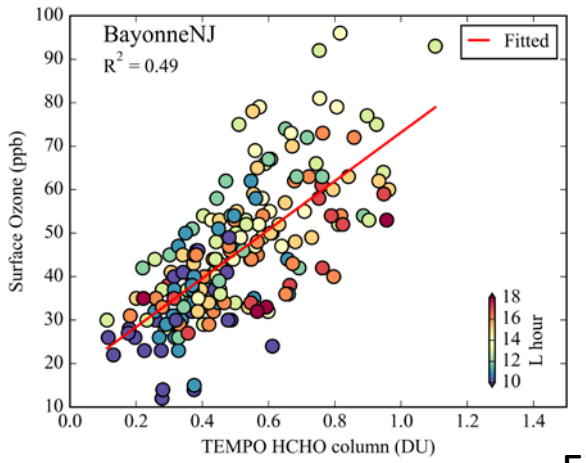


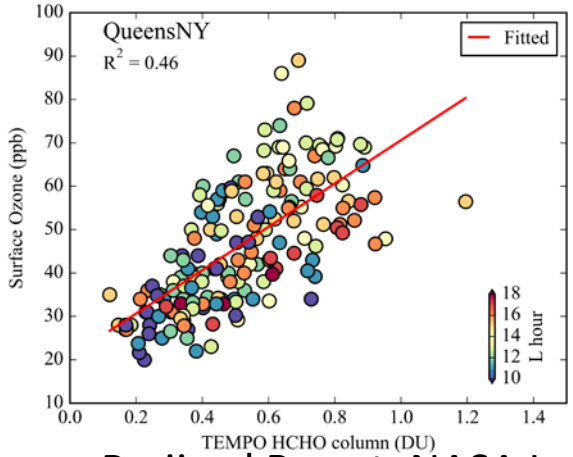


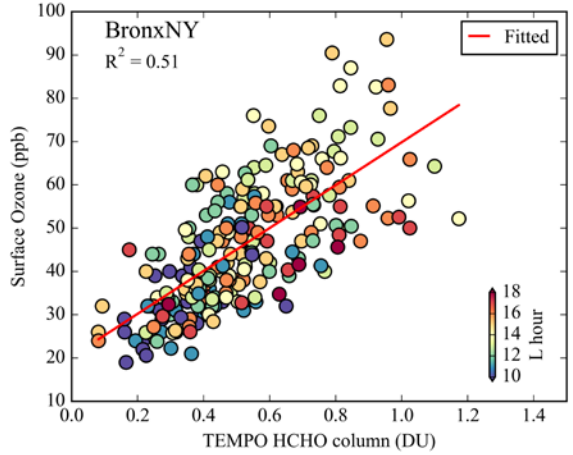


Using remotely sensed HCHO column from the TEMPO spaceborne spectrometer









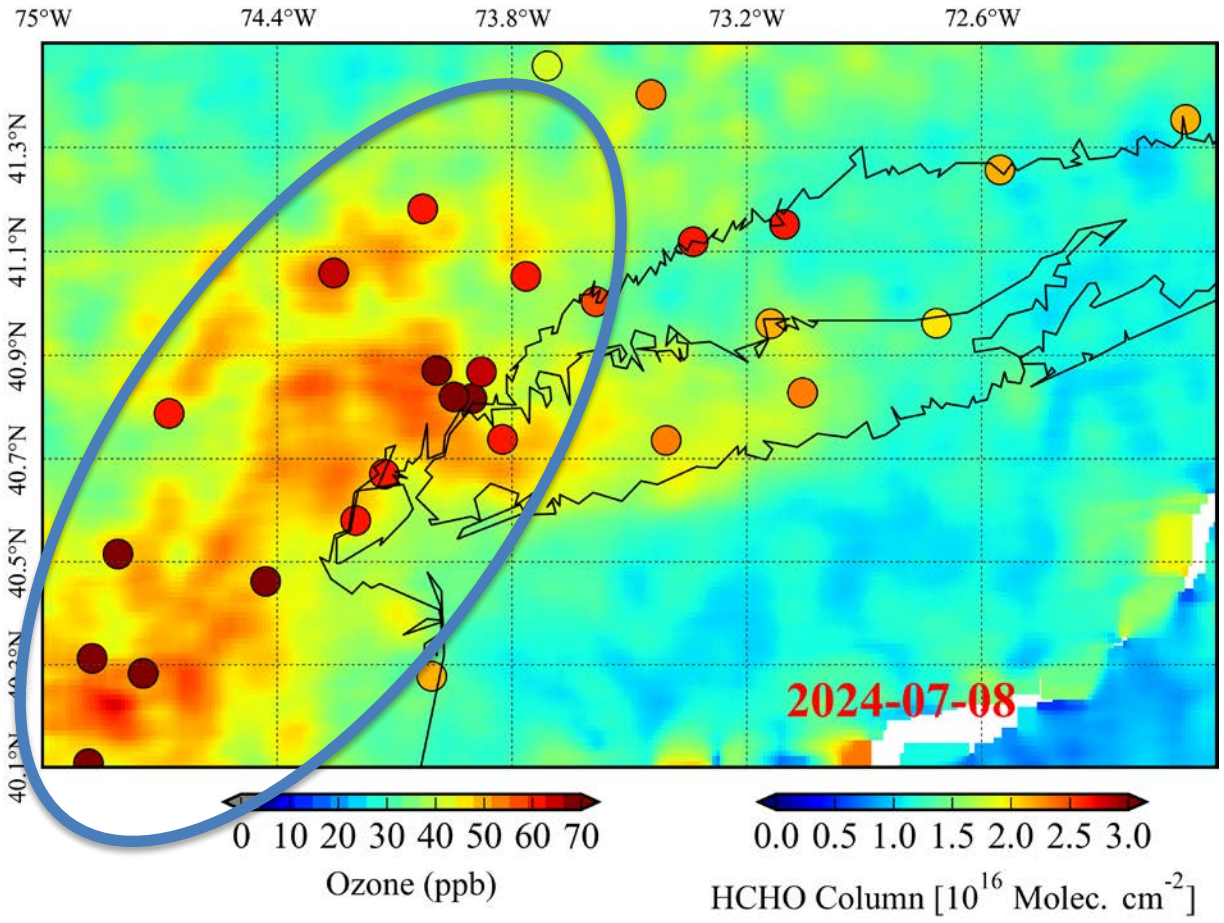
Figures: Prajjwal Rawat, NASA LaRC

Can TEMPO column HCHO provide new insights Surface Ozone production

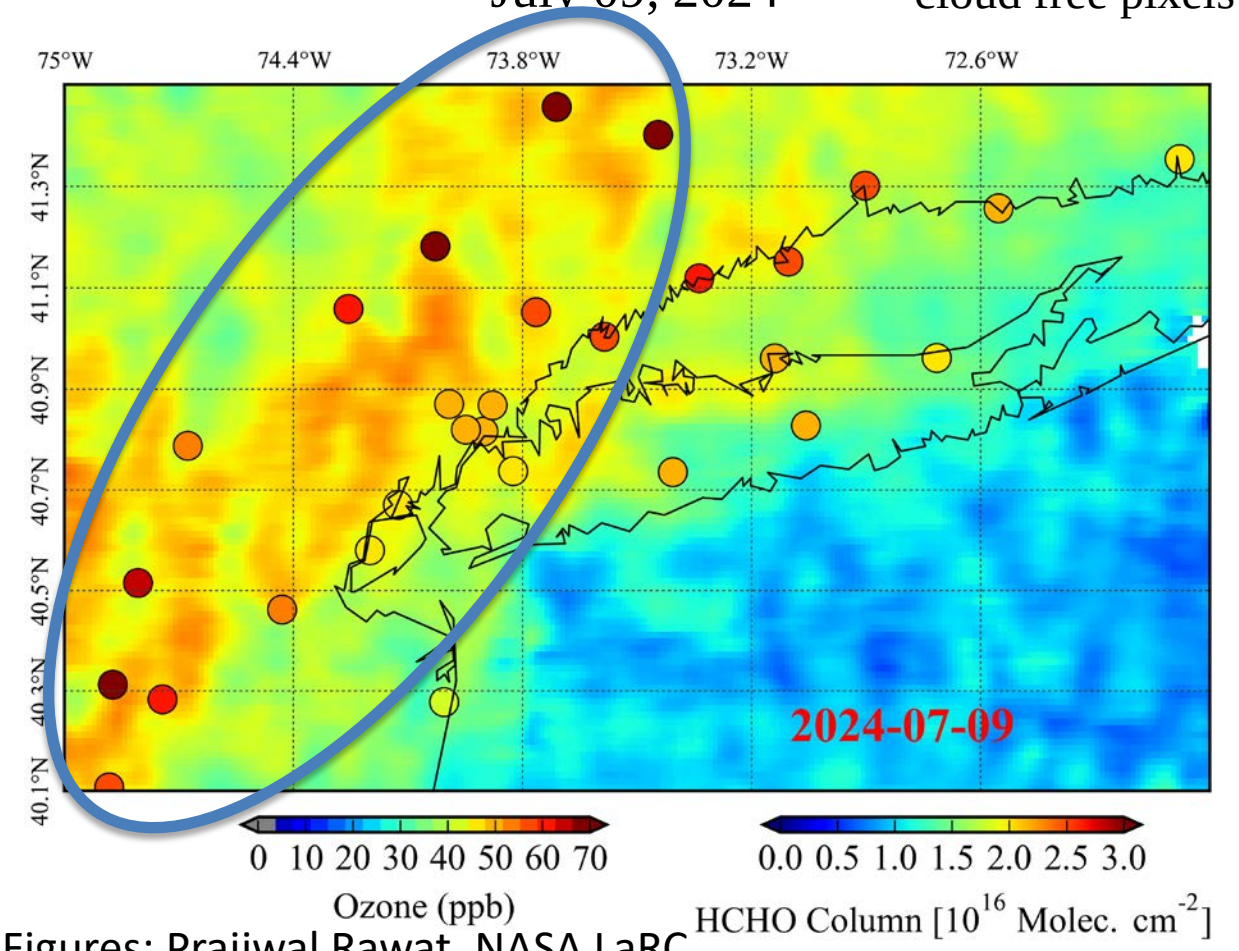
New York region with daily oversampled TEMPO HCHO column

Oversampled at 10 x 10 km^2 for cloud free pixels

July 08, 2024



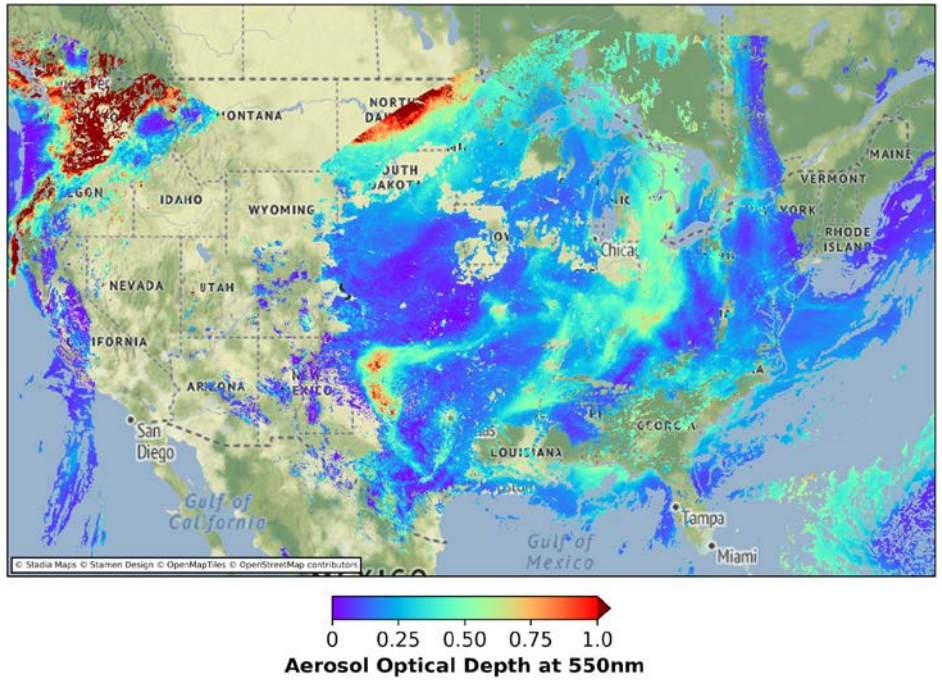
July 09, 2024



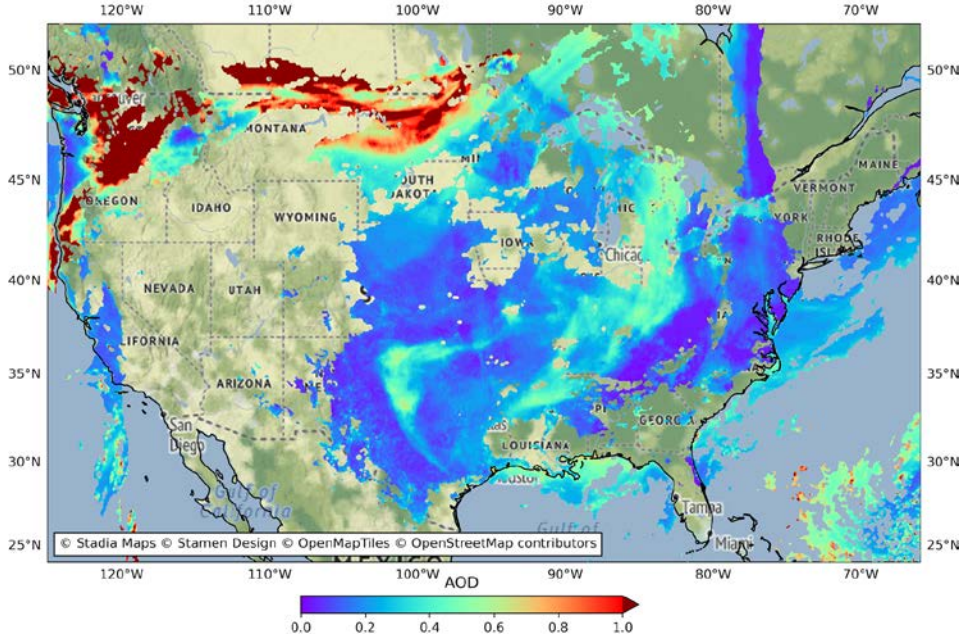
Figures: Prajjwal Rawat, NASA LaRC

Improving Information on Aerosol distributions

***GOES-16:** Atmospheric Aerosol Concentrations Measured as Column Optical Depth*



***TEMPO:** Atmospheric Aerosol Concentrations Measured as Column Optical Depth*



TEMPO provides additional information on how much and where in the atmosphere the bulk of fine particles are versus current GOES 16 Imager. Important for:

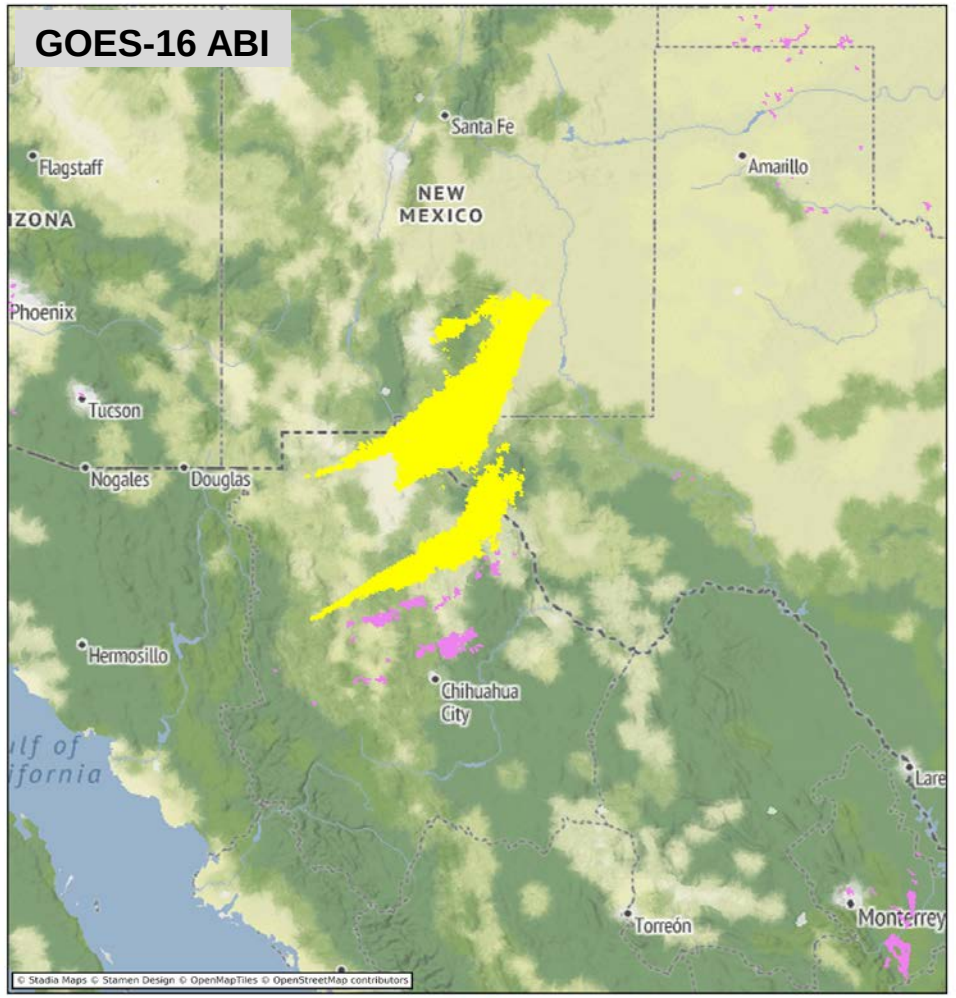
- **Algorithms that estimate surface fine particle pollution;**
- **Assessing air quality models performance;**
- **Understanding smoke plume injection and transport.**

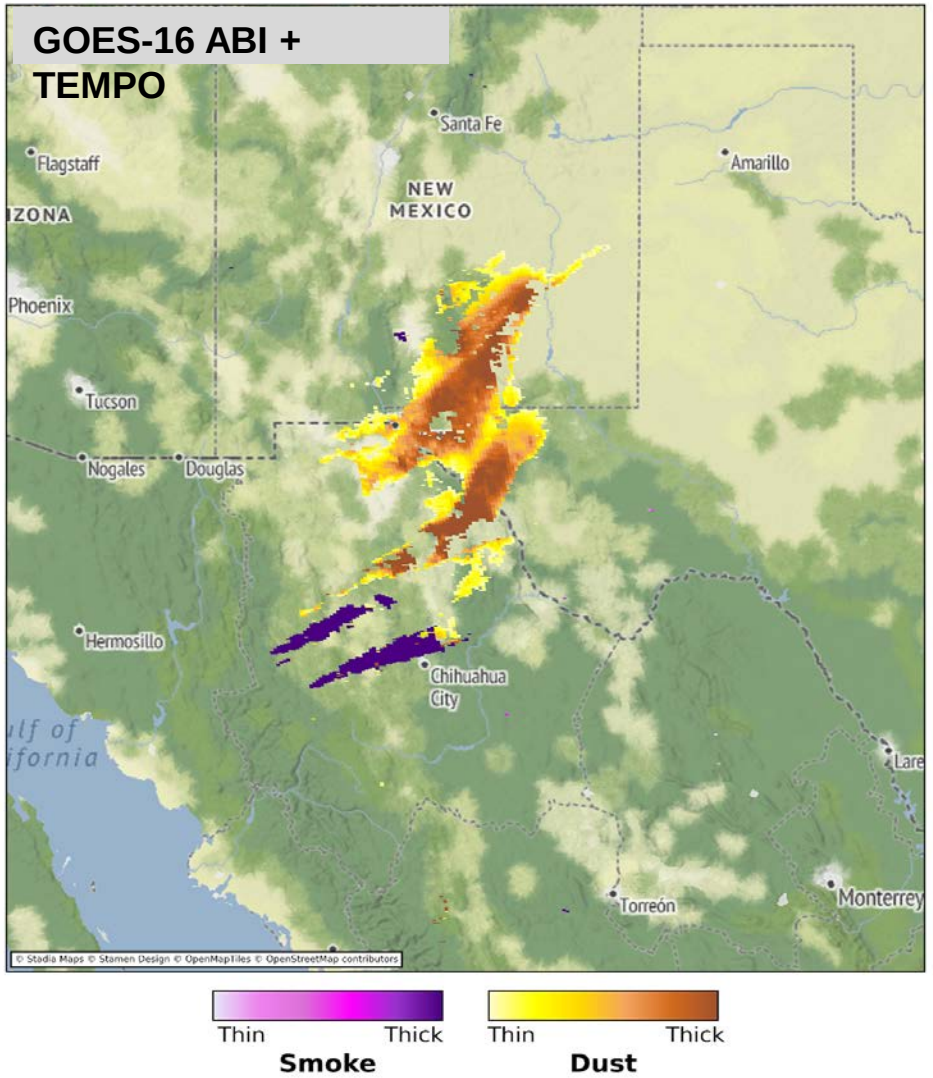
Source: NOAA/NESDIS

Improving Information on Aerosol distributions

TEMPO combined with GOES-16 ABI will provide improved information ofn aerosol type and measure density for smoke and dust events.

NOAA/NESDIS is lead for these products and plans to provide products in < 3 hrs.





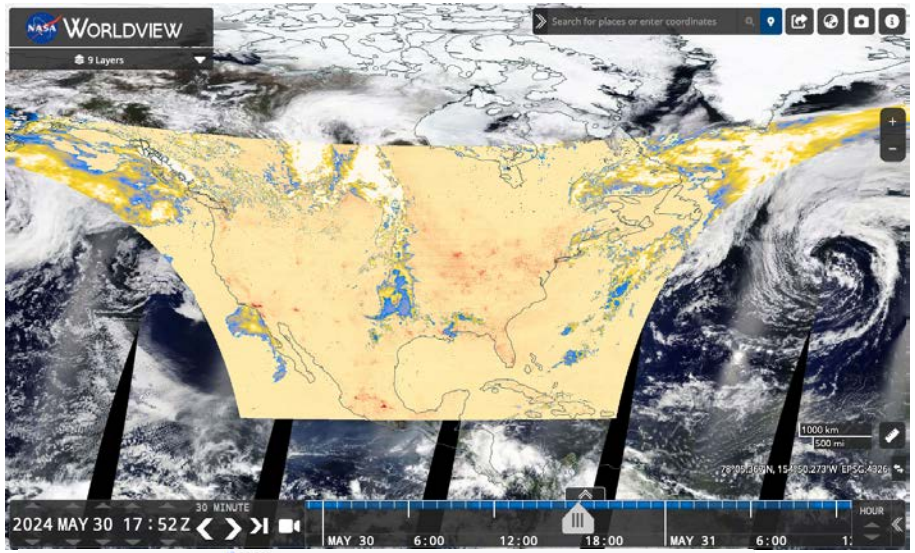
Source: NOAA/NESDIS

Getting TEMPO Data

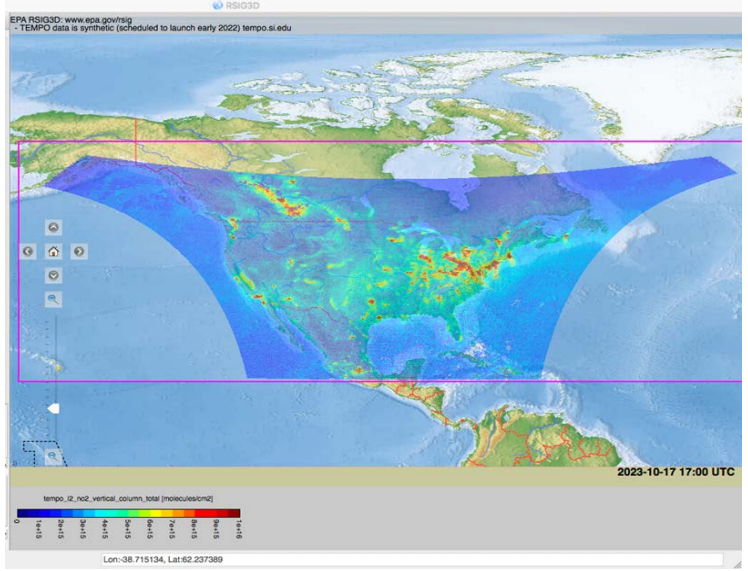
- TEMPO data now publicly available through NASA Atmospheric Science Data Center
  - 13 May 2024 onward, August-December 2023
  - Reprocessing from Dec 2023 to May 2024

- Multiple tools:
  - Earthdata Search, OPeNDAP
  - NASA Worldview
  - ArcGIS services: currently NO_2
  - RSIG, including pyrisg (EPA)
  - TEMPO-Lite (CfA): currently NO2
  - RETIGO: NO_2 (EPA – updated version coming in 2025)

- For more information check out:
  - **User Guide**
  - Daily log
  - Validation plan
  - Validation reports (coming soon)
  - Algorithm Theoretical Basis Documents (drafts available upon request, not yet reviewed)

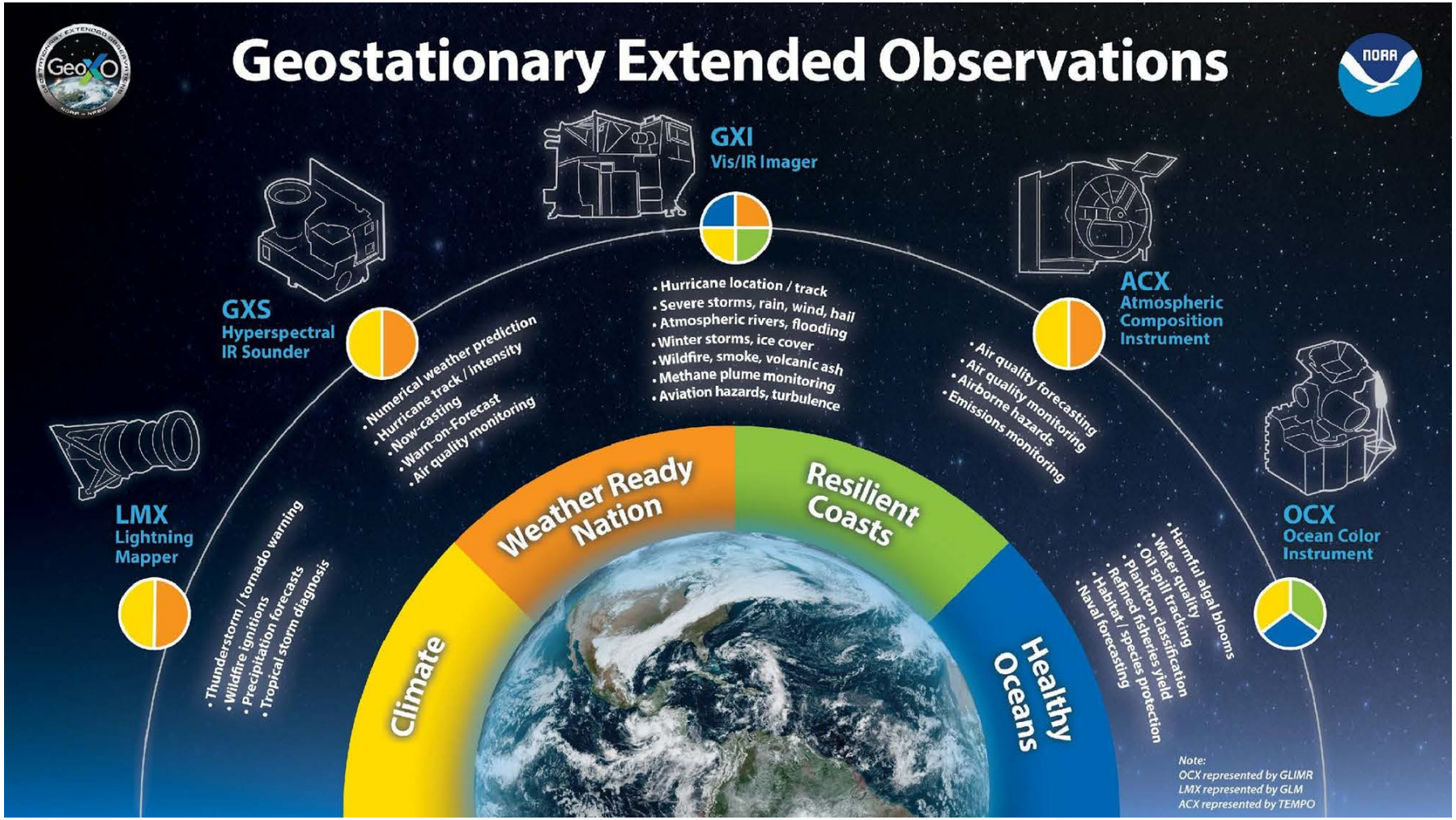


NASA Worldview



EPA RSIG

TEMPO (2020s research) →ACX (2030's operations)



On May 1st, NOAA/NASA awarded a contract to develop the GeoXO ACX instrument.

ACX performance will be similar to TEMPO, with design updates made to improve lifetime, reliability, etc. for a 10-year operational mission.

Development of new science and applications from TEMPO are key to the success of ACX.

Summary

- TEMPO is currently providing new hourly daytime atmospheric pollution measurements at high spatial resolution over North America with data products relevant to both the NAAQS (NO_2, HCHO, O_3) and Air Toxics (HCHO) which will help provide new insights emissions, transport, and pollutant distributions to the air quality community.

- TEMPO Level 2 baseline data products availability starts in August 2024, with more routine operations starting on October 19, 2024 (increased data availability)

- Calibration and validation activities are on-going with a Level 2 validation report scheduled for release in September along with development of routine validation analysis that will continue through the mission

- Data products (L1b, cloud, NO_2, HCHO, total O_3) are classified as the Beta validation at this early stage with several likely to move to Provisional validation in the coming months; TEMPO instrument and science algorithms are working very well

- New data products (ozone profile, aerosols, and near-real-time) continue to be developed and should be ready for public release over the next year

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Thank You!

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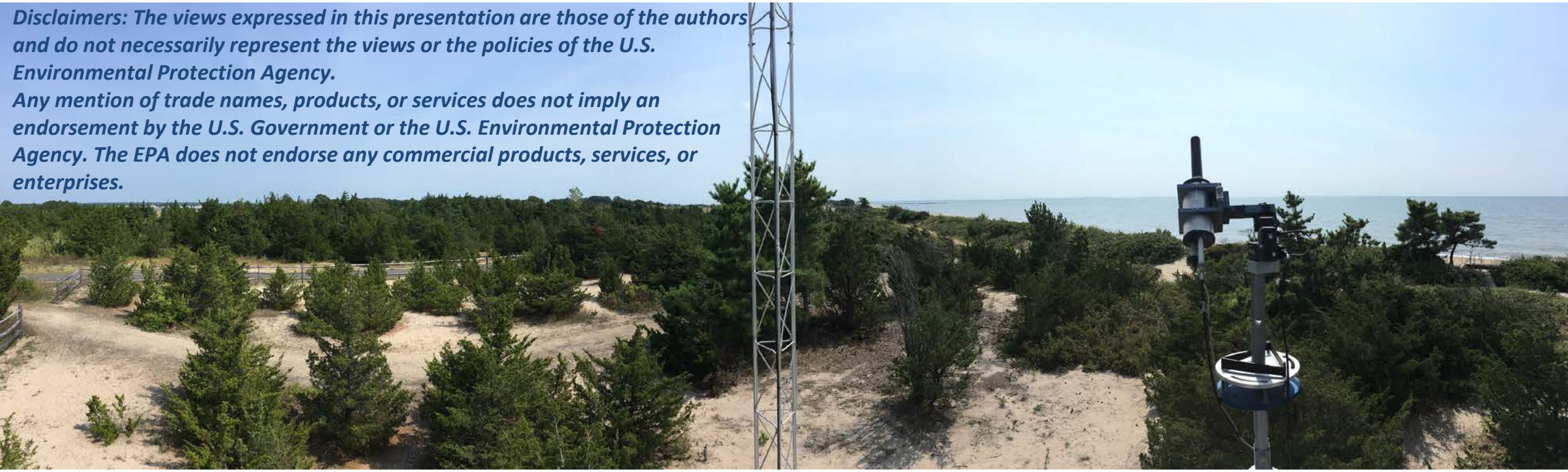


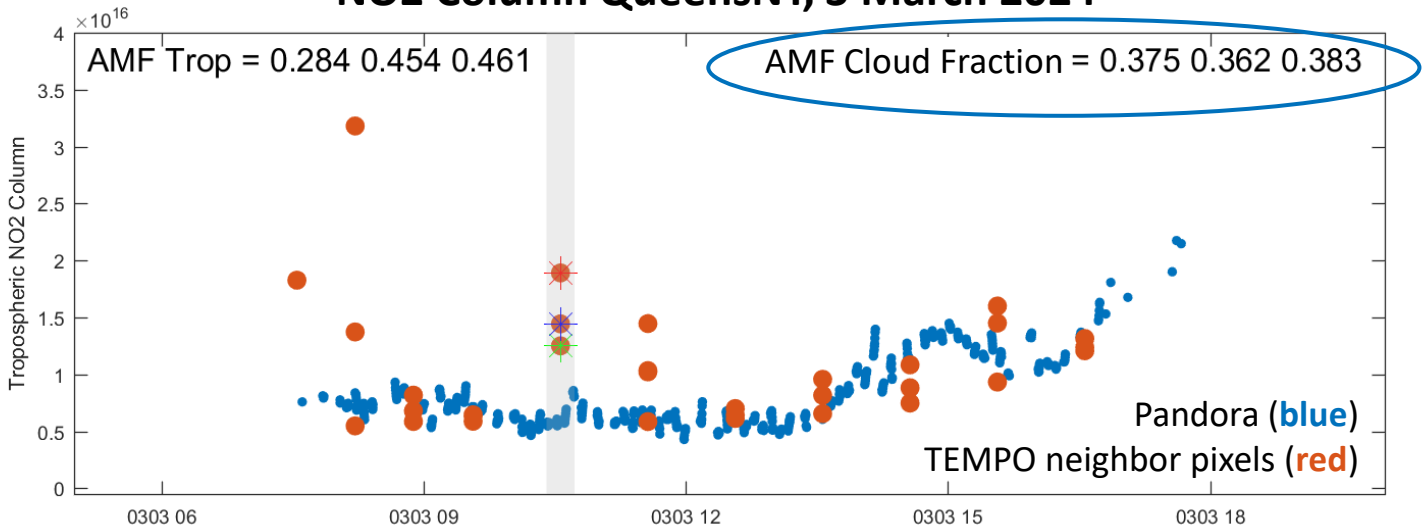
Backup Slides

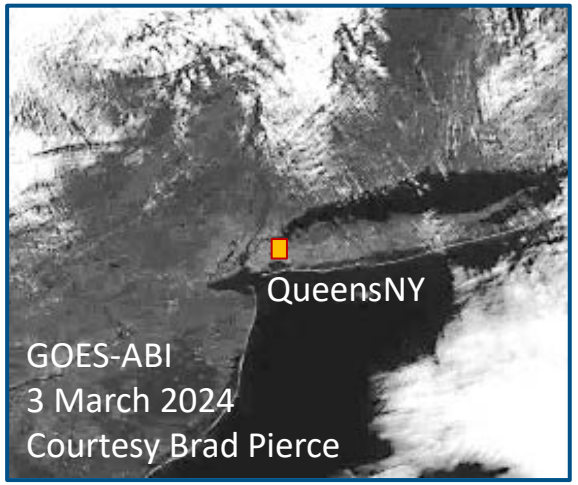
Attribution of TEMPO NO2 bias and uncertainty over Queens NY

Baseline cloud radiance fraction bias, ~0.4 for all pixels for clear sky

Likely due to albedo and/or L1 radiance calibration

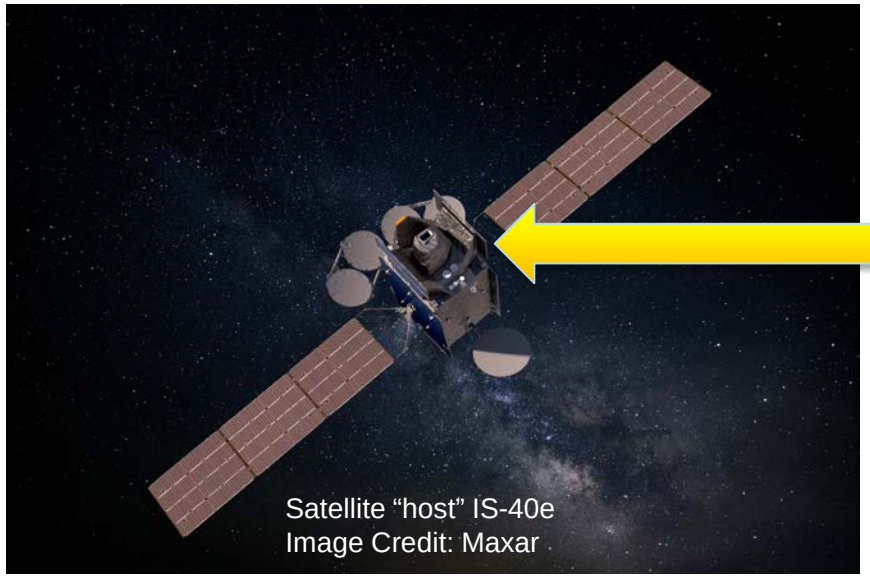
Translates to NO2 biases/uncertainty



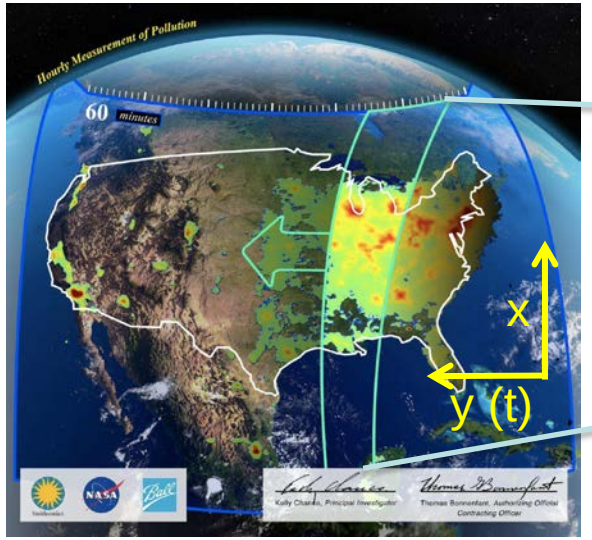


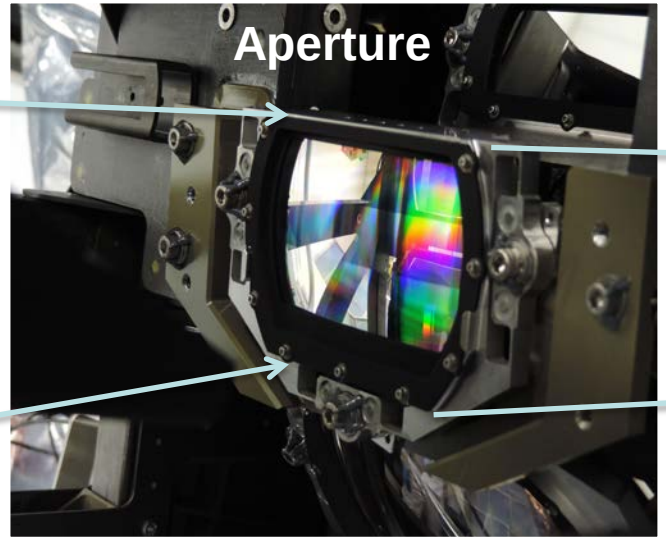
While a single example, this source of uncertainty is very common, especially for morning conditions when NO2 columns are generally most shallow and measurement geometry is challenging

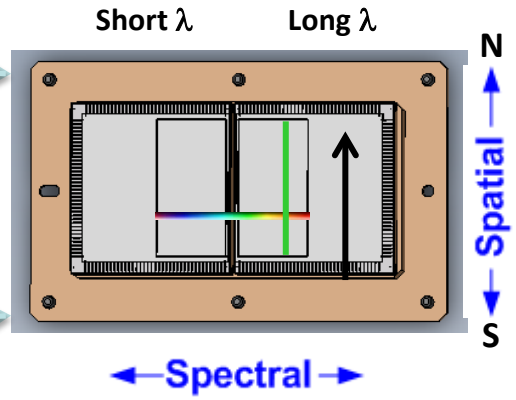
TEMPO Instrument Overview



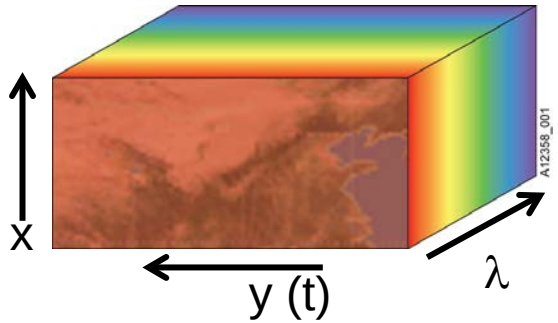
- Wavelength range = UV~293 – 494 nm and VIS 538 – 741 nm
- Spectral resolution = ~0.6 nm @Full Width Half Maximum (0.54-0.63 nm)
- Two 2048 (spatial) x 1024 (spectral) pixel CCD detectors
- Step/stare 2-axis scan mechanism
- Each mirror step is a ~2.85 s snapshot of all 2K N/S cross-track pixels.
- 60 minute E→W scan of FOR in 1226 mirror steps
- Orbit = geostationary (35786 km), 91.0˚ W above equator
- Calibration wheel with transmissive diffusers for daily solar calibration
- Instrument Control Electronics (ICE) mounted below spacecraft deck
- Images co-added on board before data downlink
- **Mass**: 137 Kg **Power**: 138W **Volume:** 1.4m x 1.1m x 1.2 m







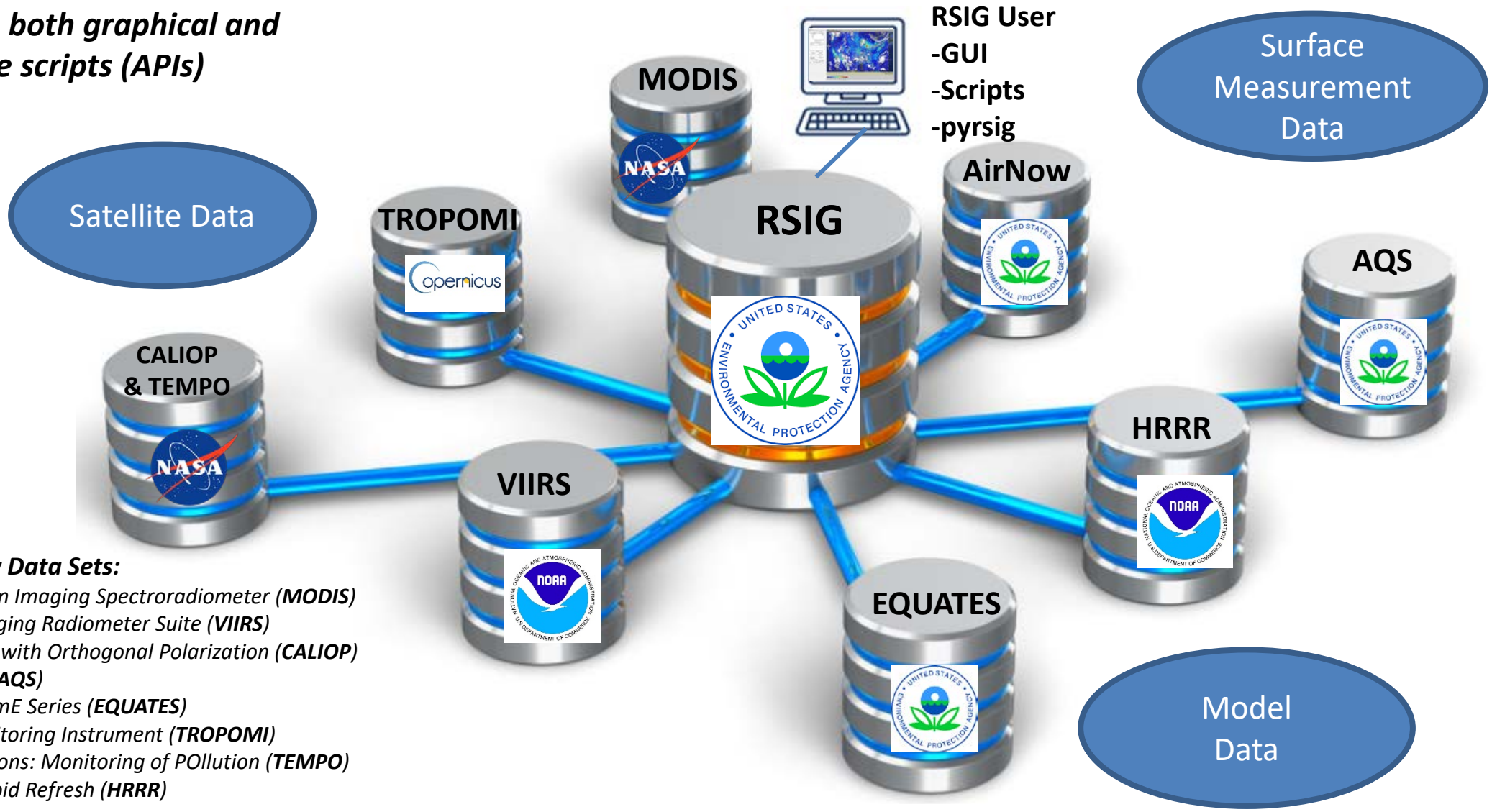
Downlink, spatial bin, image reconstruction



RSIG Server is a Web of Servers

www.epa.gov/rsig

-RSIG access both graphical and programable scripts (APIs)



Popular Air Quality Data Sets:

- *Moderate Resolution Imaging Spectroradiometer (**MODIS**)*
- *Visible Infrared Imaging Radiometer Suite (**VIIRS**)*
- *Cloud-Aerosol Lidar with Orthogonal Polarization (**CALIOP**)*
- *Air Quality System (**AQS**)*
- *EPA's Air QUAlity TimE Series (**EQUATES**)*
- *TROPOspheric Monitoring Instrument (**TROPOMI**)*
- *Tropospheric Emissions: Monitoring of POllution (**TEMPO**)*
- *High-Resolution Rapid Refresh (**HRRR**)*