

weather.msfc.nasa.gov/tempo/



Tropospheric Emissions:
Monitoring of Pollution
Hourly Measurement of Pollution



Smithsonian Astrophysical
Observatory



<http://tempo.si.edu/>



TEMPO Mission Update

NACAA Fall Membership Meeting
October 18, 2023

Aaron Naeger
& TEMPO Team

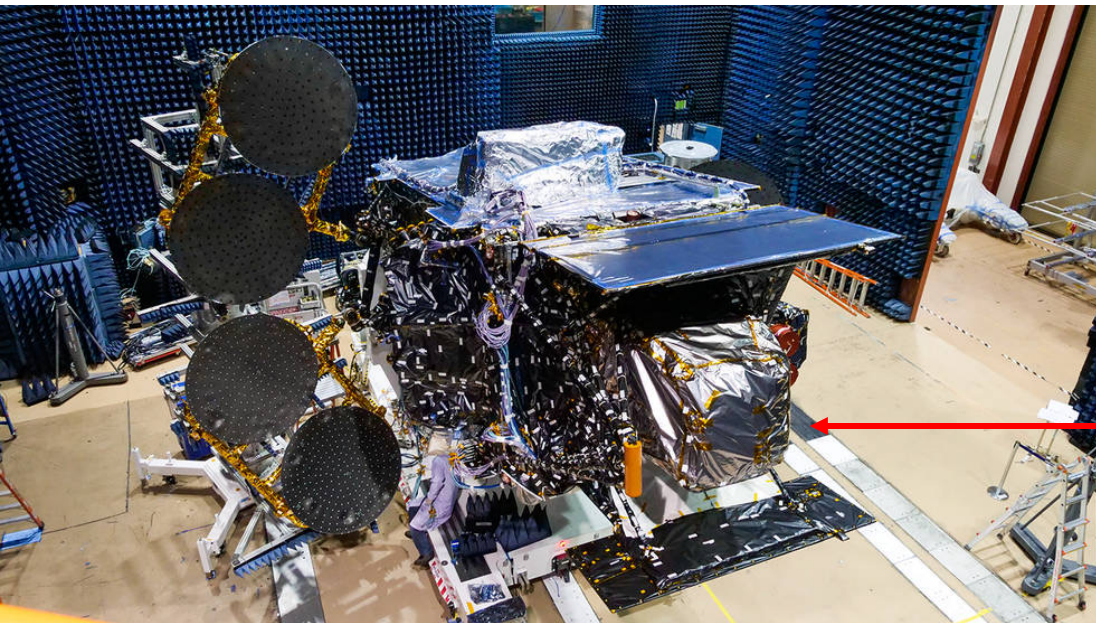
TEMPO Mission Applications Lead
NASA Marshall Space Flight Center

U.S. Government sponsorship acknowledged.





TEMPO Mission Status, Timeline, & Products



Intelsat 40E satellite carrying
TEMPO instrument



TEMPO Quick Facts



Smithsonian

Launched April 2023

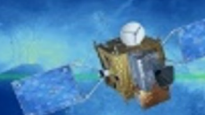
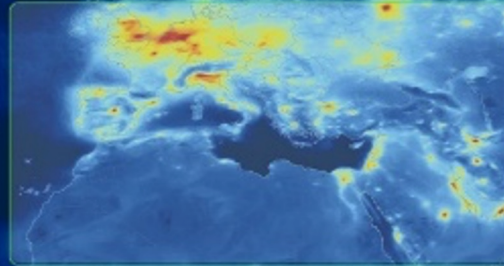
TEMPO (hourly)
Tropospheric Emissions:
Monitoring of Pollution



Sentinel-5P (once per day)

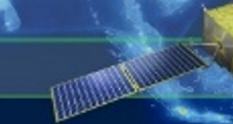
Launch 2024

Sentinel-4 (hourly)



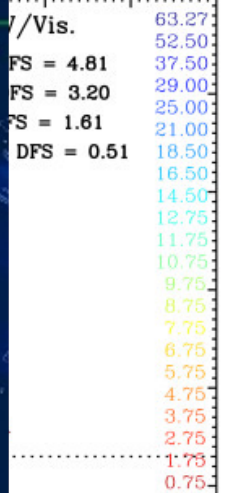
Launched Feb 2020

GEMS (hourly)
Geostationary Environmental
Monitoring Spectrometer



GaoFen-5 (once per day)

Equator



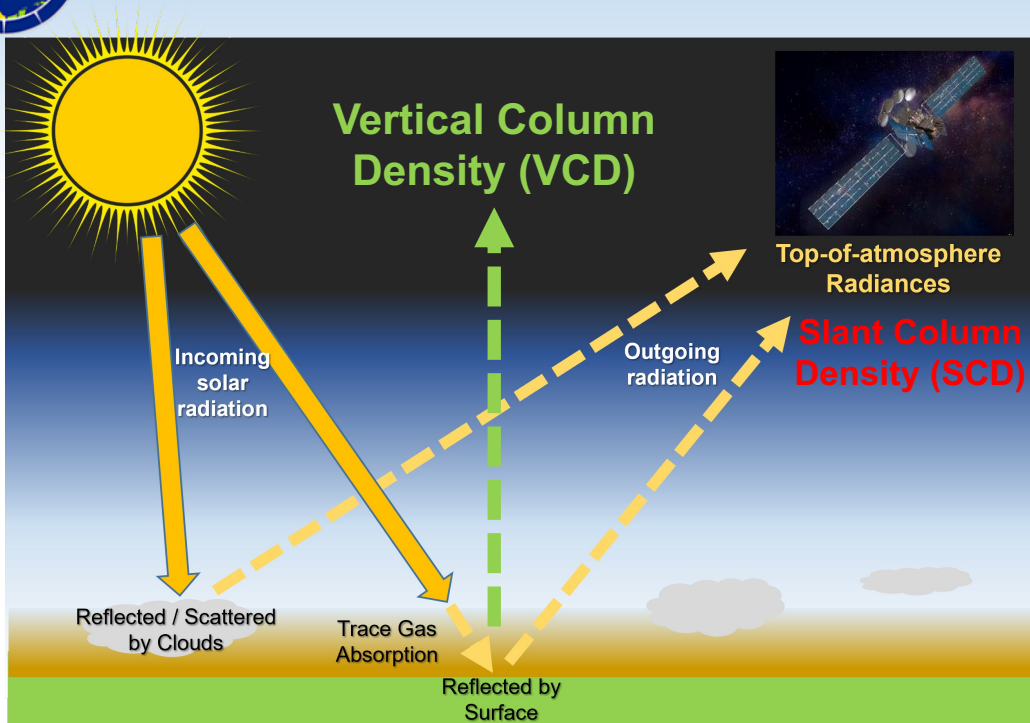
Averaging Kernels (Norm. to 1 km) Averaging Kernels (Norm. to 1 km)

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Product Name	Product Precision	Air Quality Relevant Precision	Frequency
Total Column O ₃	3%		1 hour
Tropospheric Column O ₃	10 ppbv	10 ppb	1 hour
0-2 km O ₃ selected scenes	10 ppbv	10 ppb	2 hours
Total Column NO ₂	1.0×10^{15} molecules cm ⁻²	0.4 ppb	1 hour
Tropospheric NO ₂	1.0×10^{15} molecules cm ⁻²	0.4 ppb	1 hour
Tropospheric HCHO	1.0×10^{16} molecules cm ⁻²	4.0 ppb	3 hours

AQ relevant precision (ppb) assumes all gas molecules are contained over an area from the surface to 1 km

TEMPO NO₂ product will be of high accuracy and precision

- ❑ TEMPO operational trace gas retrievals based on 2-step approach
 - 1) Derive **slant column densities (SCD)** – integrated number density of gas molecules in mean photon path from sun to instrument – by spectral fitting to measured radiances in known trace gas absorption windows
 - 2) Calculation of **vertical column densities (VCD)** using Air Mass Factors calculated offline with a radiative transfer model accounting for surface, atmospheric, and viewing geometry conditions

- ❑ VCDs provide information on trace gas concentrations in the vertical column above the TEMPO footprint



TEMPO L2+ Products: Baseline + SNWG TEMPO NRT



Level	Product	Key Variables	Resolution (km ²) **	Frequency/ Size
L2	Cloud	Cloud Fraction, Cloud Pressure	2.0 x 4.75	Hourly, granule
	O ₃ (Ozone) profile	O₃ profile, Tropospheric O₃ column, Total O₃ column, Stratosphere O₃ column, Cloud Fraction, O₃ a priori, O₃ Averaging Kernel	>= 8.0 x 4.75	Hourly, granule
	Total O ₃	Total column O₃, Cloud Fraction, Aerosol Index	2.0 x 4.75	Hourly, granule
	NO₂ (Nitrogen Dioxide)	Tropospheric Vertical Column Density (VCD), Total VCD, Slant Column Density (SCD), Cloud Fraction, Air Mass Factor (AMF), Data Quality Flag	2.0 x 4.75	Hourly, granule
	HCHO (Formaldehyde)	Total VCD, SCD, Cloud Fraction, AMF, Data Quality Flag	2.0 x 4.75	Hourly, granule
	Aerosol	Ultraviolet & Visible Aerosol Optical Depth (AOD), Aerosol Optical Centroid Height (AOCH), Aerosol Absorption Index (AAI)	8.0 x 4.75 (TBD)	Hourly, granule
L3	Same as L2 (Gridded)	Same as L2	~2 x 2 (TBD)	Hourly, scan

**** Center of Field of Regard**

Near real-time (NRT) products: Latency 2 - 3 hours

Baseline (Offline) products: Latency 3 - 6 hours (except O₃ profile ~24 hours)

SNWG: Satellite

Needs Working Group



TEMPO L2+ Products: Additional



Level	Product	Key Variables	Resolution (km ²) **	Frequency/ Size
L2	C ₂ H ₂ O ₂ (Glyoxal)	SCD, Total VCD, Cloud Fraction, AMF, Data Quality Flag	2.0 x 4.75	Hourly, granule
	H ₂ O (Water Vapor)		2.0 x 4.75	
	BrO (Bromine)		2.0 x 4.75	
	SO₂ (Sulfur Dioxide)	SCD, VCD (Total, Planetary Boundary Layer, & Lower / Middle / Upper Tropospheric, Lower Stratospheric)	2.0 x 4.75	Hourly, granule
	TEMPO/GOES-R Synergistic	Aerosol, Fire / Hotspot, Cloud & Mask, Lightning, Snow / Ice, Precipitable Water, etc.	2.0 x 4.75	Hourly, granule
L3	Same as L2 (Gridded)	Same as L2	~2 x 2 (TBD)	Hourly, scan
L4	UVB	UV irradiance, erythemal irradiance, UVI	TBD	Hourly, scan

**** Center of Field of Regard**

Level 3 product stitches together TEMPO Level 2 product granules for each scan



Mission Phases & Operational Timeline

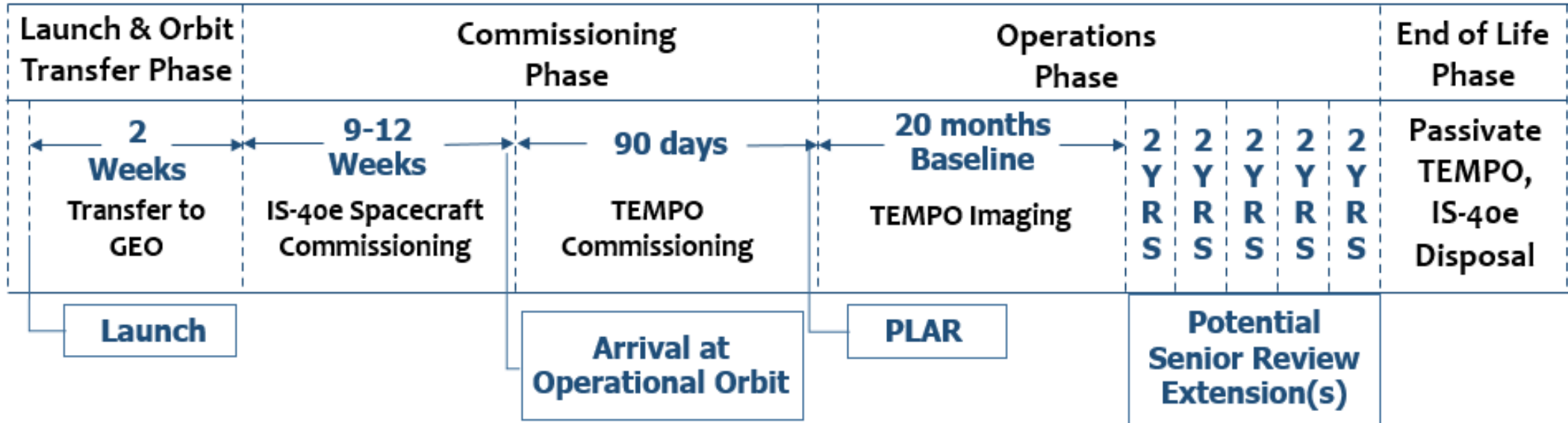


Launched:
April 7, 2023

Powered On:
June 7

Commissioning:
June 7 – Oct. 18

Nominal Operations:
Oct. 19 – May 2025



- Currently in commissioning phase of mission June – Sept. 2023
- First light:** July 31 – August 2 with first Earth imaging on August 2
- Nominal operation: ~6 months after launch (Oct 2023)
- Baseline mission length: 20 months (Oct 2023 – May 2025) **w/ potential 10+ year lifetime**
- Public release of Baseline products at ASDC: Level 1b data ~Feb 2024, **Level 2 & 3 data ~April 2024**
- Archive of baseline “offline” products will start from commissioning phase ~Aug 2023
- Initial public release of NRT products at ASDC ~Jan 2025**

ASDC: Atmospheric Science Data Center

Baseline TEMPO data format: **NetCDF**



Data Distribution, Visualization, Analysis Tools



ASDC (Atmospheric Science Data Center) is the DAAC (Distributed Active Archive Center) for the TEMPO mission

TEMPO data will be publicly available via Earthdata Search

TEMPO imagery will be available in Worldview

TEMPO visualization and analysis capabilities in ArcGIS

EPA RSIG3D Gateway

TEMPO Scan Operations

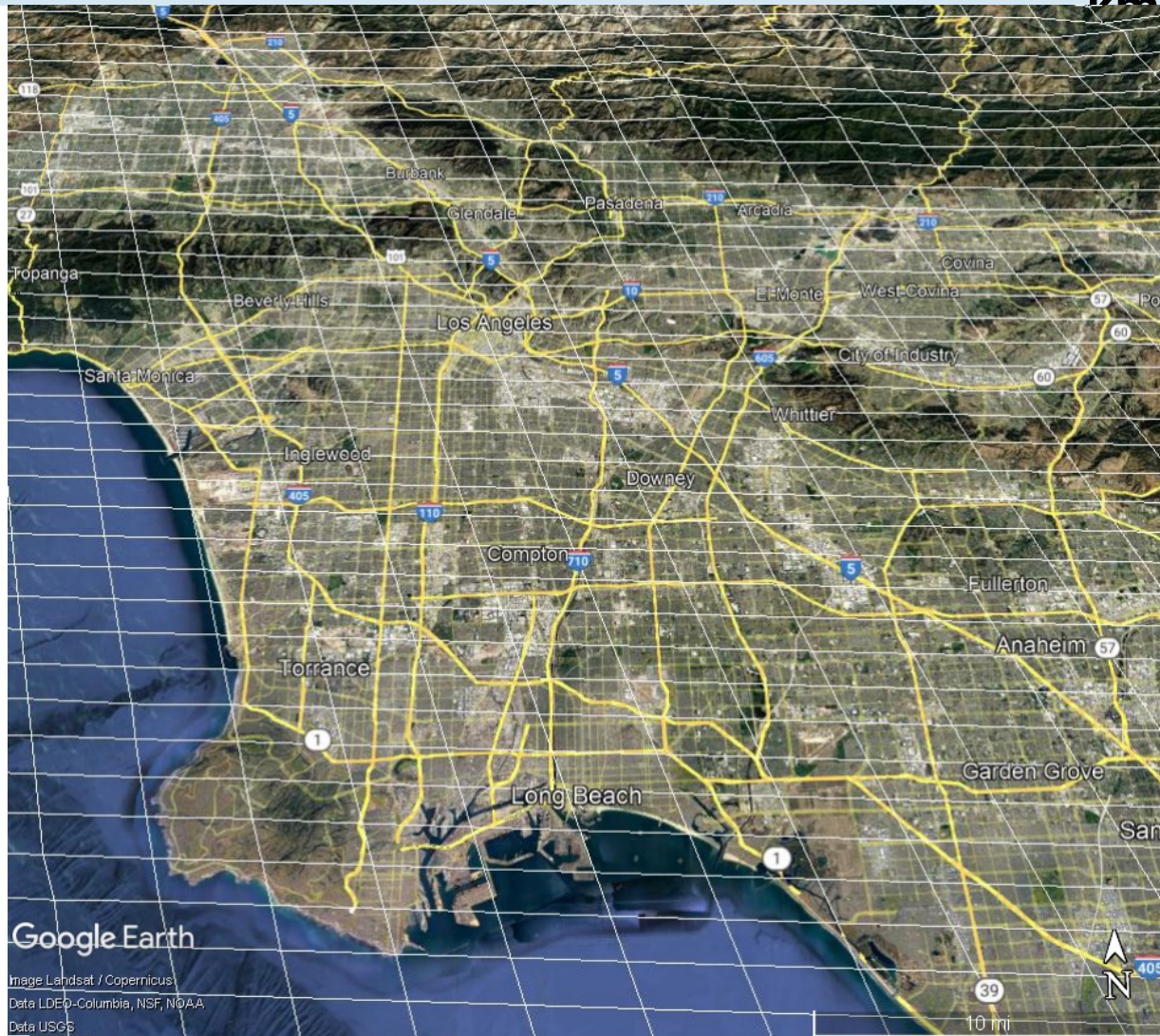
Proxy TEMPO Tropospheric NO₂ 20130809 1000 UTC



- ❑ TEMPO will perform standard (nominal) East-West hourly daytime scans consisting of ~1226 mirror steps across the Field of Regard (FoR) over greater North America.
- ❑ Sub-hourly scans will also be performed:
 - 1) Optimized scans across the East and West during sunrise and sunset periods, respectively, when SZA is too high ($> 80^\circ$) over portions of the FoR for collecting measurements of pollutants
 - 2) **Special operations for dedicated experiments (wildland fires, volcanic eruptions, dust storms, industrial accidents) over a portion or slice of the TEMPO FoR (e.g., ≤ 10 minutes)**



Footprint Size over TEMPO FoR



Location	N/S (km)	E/W (km)	GSA (km ²)	VZA (°)
36.5°N, 100°W	2.1	4.8	10.1	42.4
Washington, DC	2.3	5.1	11.3	48.0
Seattle	3.2	6.2	16.8	61.7
Los Angeles	2.1	5.6	11.3	48.0
Boston	2.5	5.5	13.0	53.7
Miami	1.8	4.9	8.6	33.2
San Juan	1.7	5.6	9.2	37.4
Mexico City	1.6	4.7	7.7	23.9
Can. oil sands	4.1	5.6	20.8	67.0
Juneau	6.1	9.1	33.3	75.3

Can resolve features at even finer spatial scales than nominal footprint size via oversampling of TEMPO data! As high as 1 km resolution possible by multi-week (e.g., monthly) oversampling!

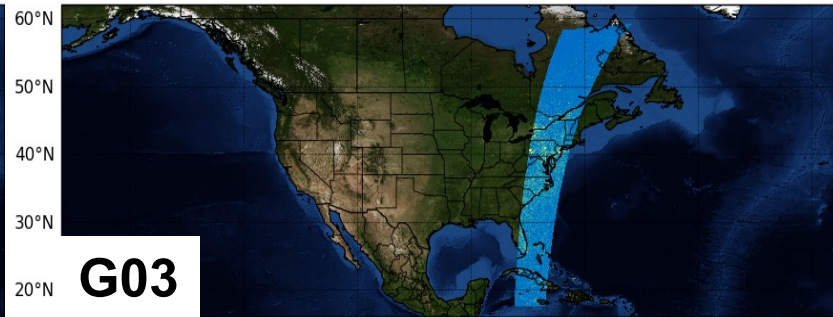
Proxy TEMPO Tropospheric NO₂ 20130829 1600 UTC



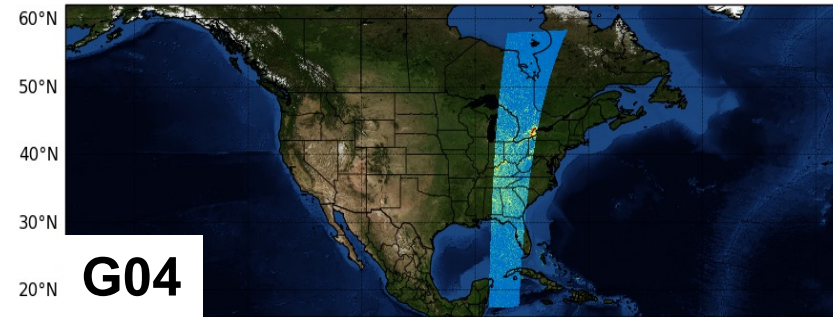
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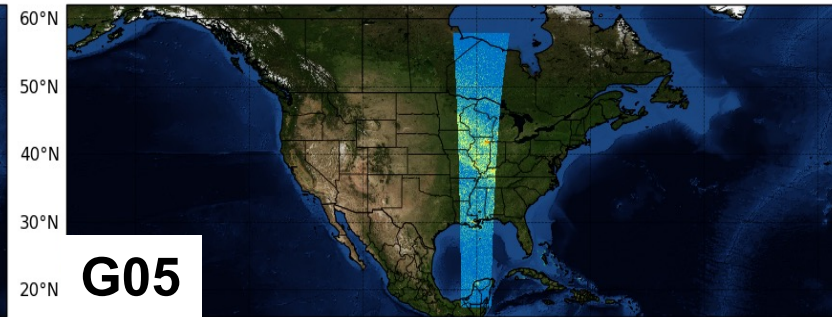
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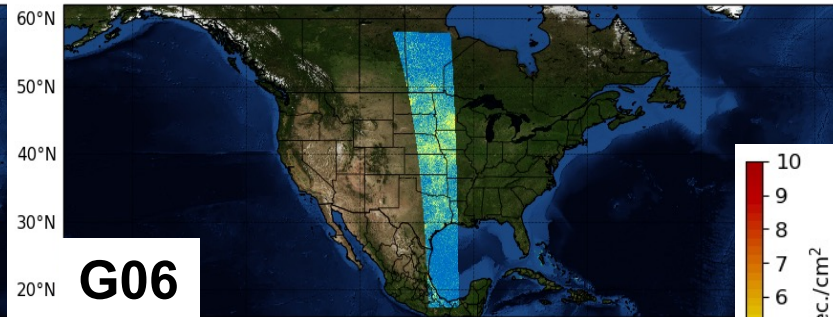
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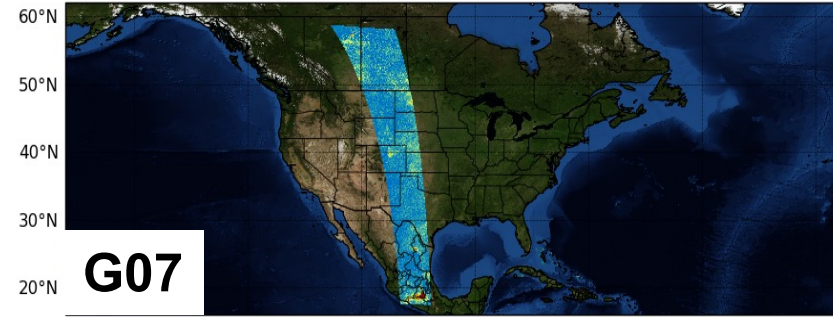
Proxy TEMPO Tropospheric NO₂ 20130829 1623 UTC



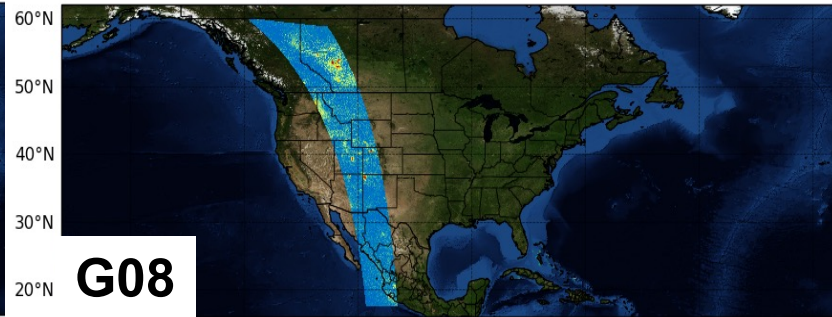
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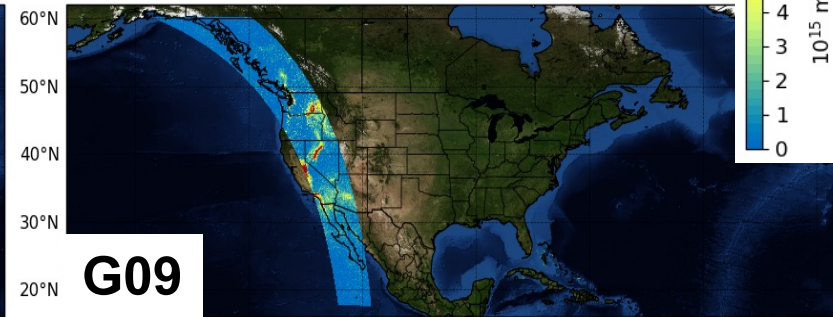
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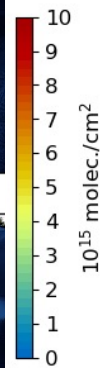
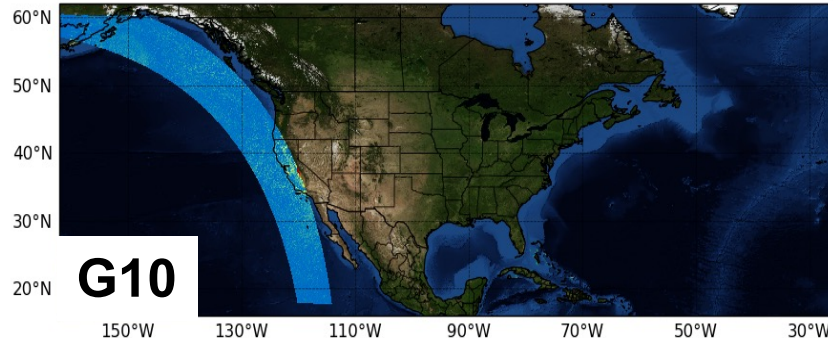
Proxy TEMPO Tropospheric NO₂ 20130829 1641 UTC



Proxy TEMPO Tropospheric NO₂ 20130829 1647 UTC



Proxy TEMPO Tropospheric NO₂ 20130829 1653 UTC



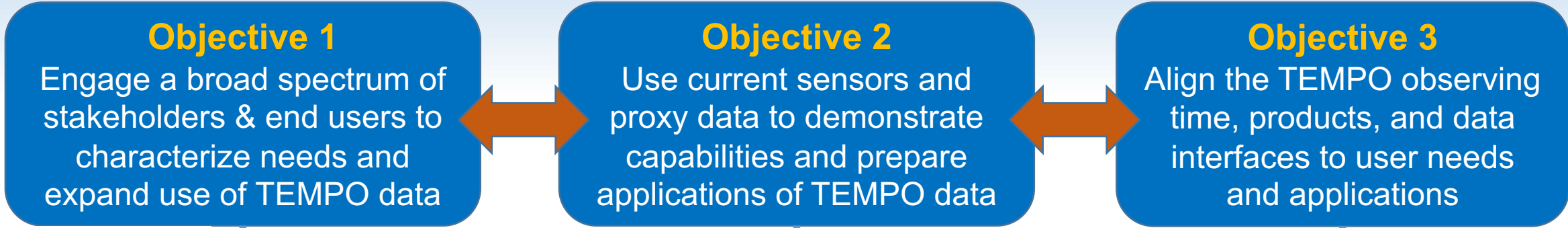
- TEMPO L2 data files will be distributed in granules across the FoR
 - Nominal hourly scans will consist of 10 granules containing ~120 mirror steps (complete FoR ~1226 mirror steps)
 - Enable more efficient distribution of TEMPO data, especially near real-time data



TEMPO Capabilities & Applications



TEMPO Early Adopters (EA) Program



Join EA Program

EAs are individuals or groups who:

- Have an interest or need for using TEMPO data
- Have an existing or new application for TEMPO data
- Work with end-users and understand their decision-making process

Prepare users for operational TEMPO data

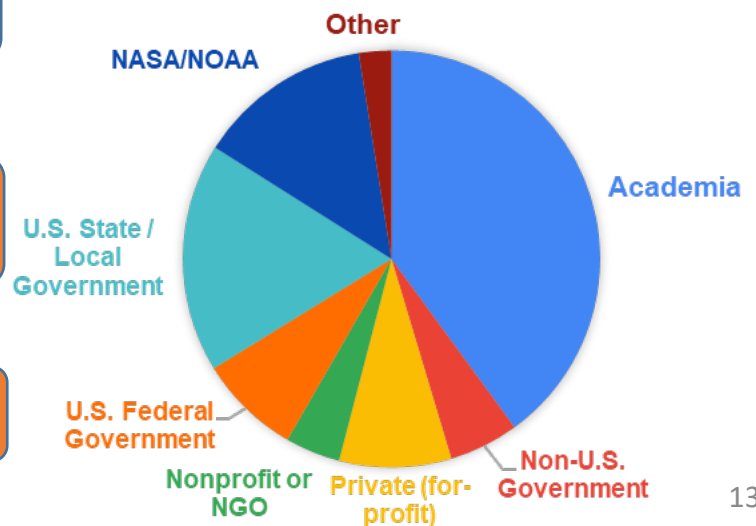
Enhance and accelerate applications of TEMPO data

Maximize the value of TEMPO data for societal benefit

Extend TEMPO mission lifetime

> 500 EAs (as of Sept. 2023)

EARLY ADOPTERS BY AFFILIATION



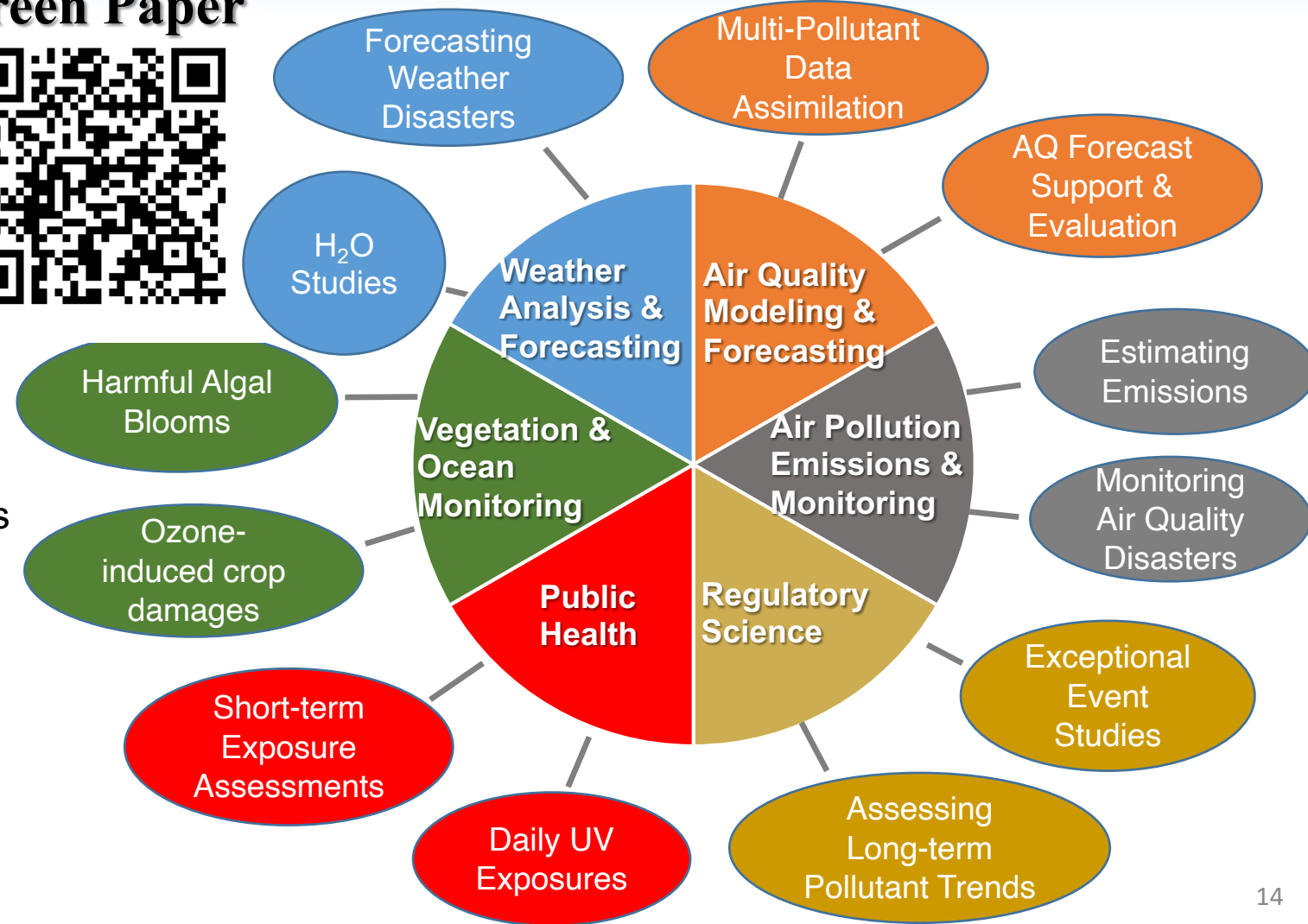
Subset of TEMPO EA Studies

- ❑ **Observing NO₂ pollution inequality**
 - TEMPO will provide new insight into emission sources and drivers of pollution inequality at intra-urban scales.
- ❑ **Ozone along Colorado Front Range**
 - Use suite of trace gases from TEMPO to better understand and monitor ozone production during exceedance events.
- ❑ **O&G activities in Western U.S.**
 - Use TEMPO data to better assess ozone production related to oil & natural gas facilities
- ❑ **Dust storm monitoring**
 - TEMPO aerosol data will help characterize U.S. dust storms.
- ❑ **Assimilation of TEMPO in regional air quality forecasting system**
 - Apply WRF-Chem/DART for NRT forecasting with chemical data assimilation

TEMPO Green Paper



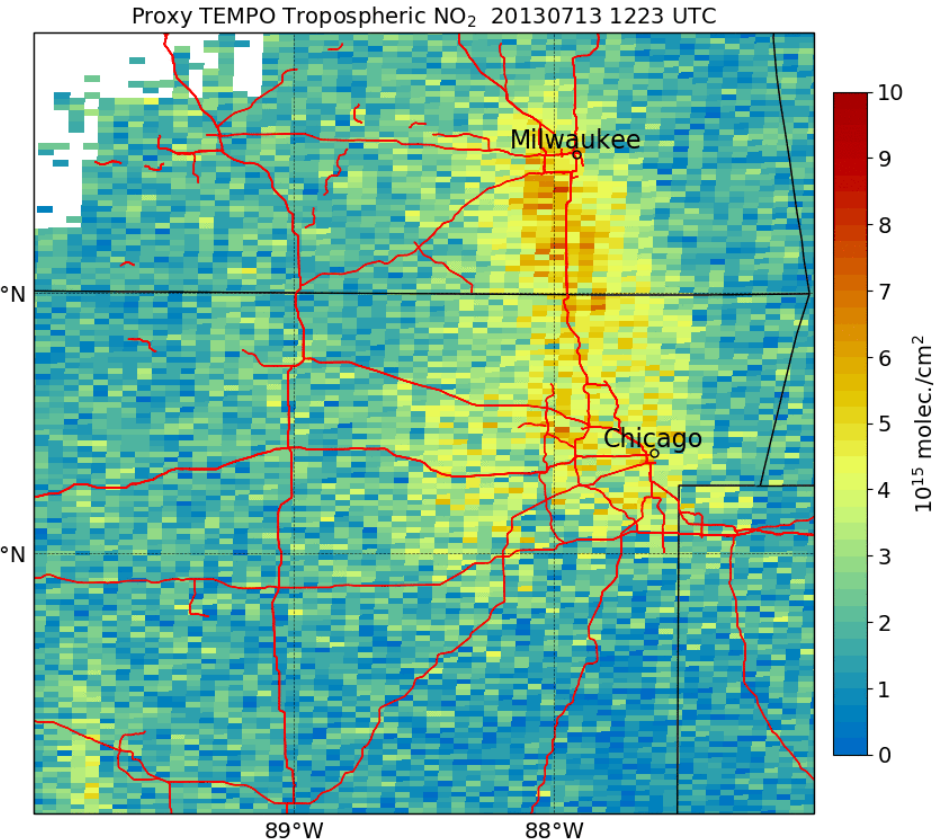
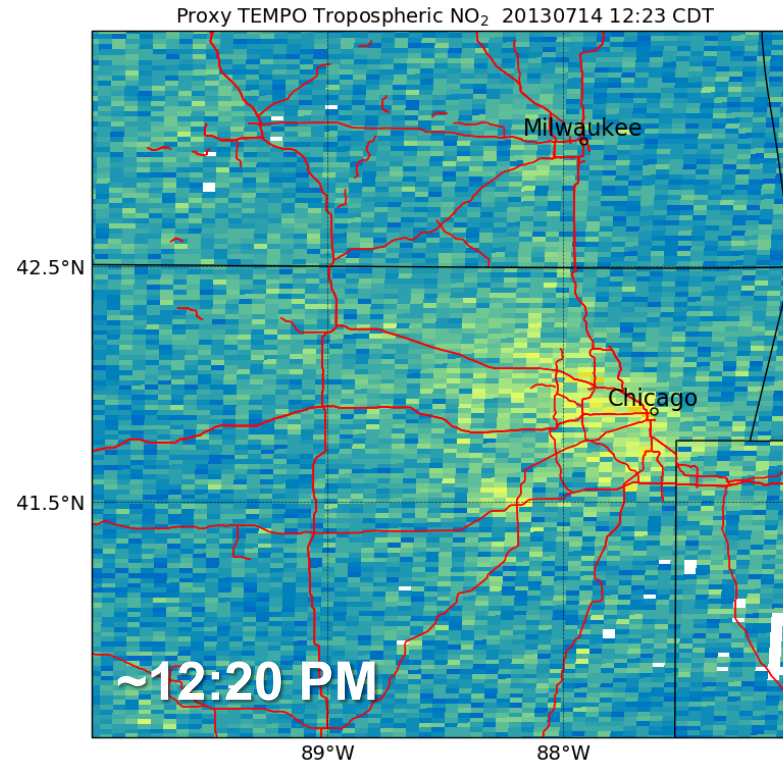
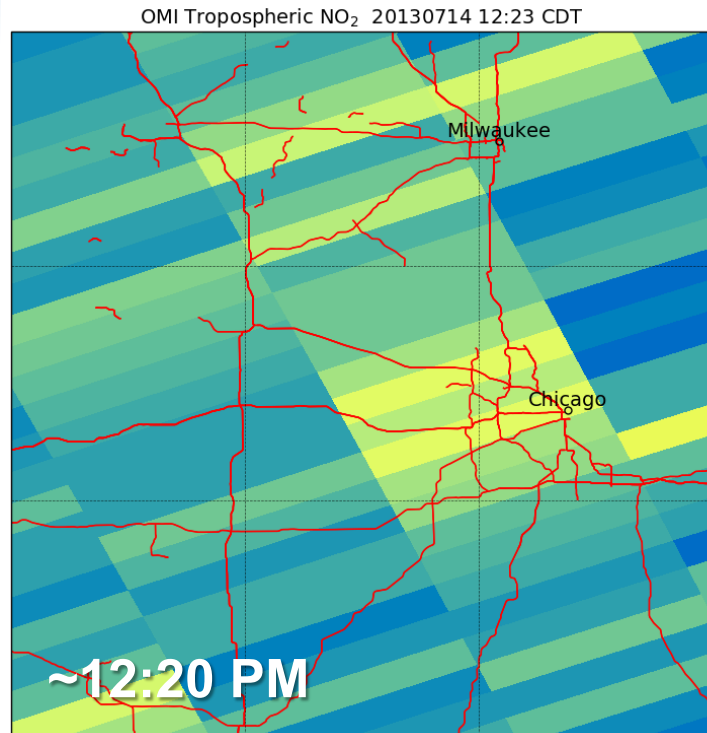
TEMPO data will enable new and enhanced health and air quality applications



Monitoring NO₂ Along Traffic Corridors

OMI July 14, 2013 TEMPO Proxy

July 13 - 14 TEMPO Proxy



- ❑ Current low-earth orbiting (LEO) air quality instruments (OMI, TROPOMI) only provide mid-day observations of NO₂, missing the morning and evening rush hour traffic
- ❑ **TEMPO will observe the evolution of NO₂ from morning to evening along traffic corridors**

***Proxy data not intended to support operational decisions or scientific research studies**

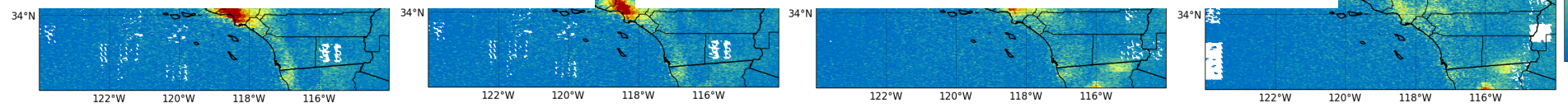
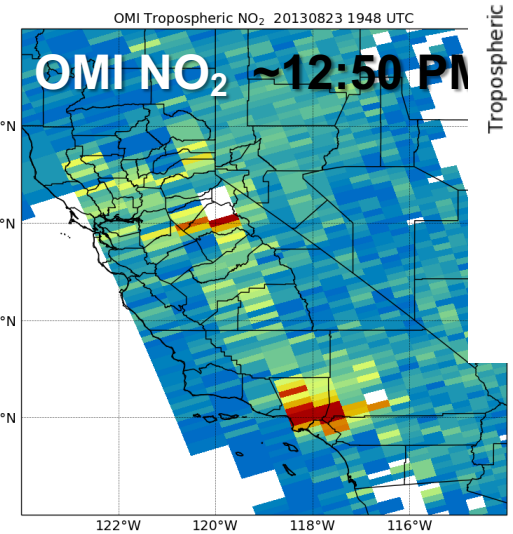
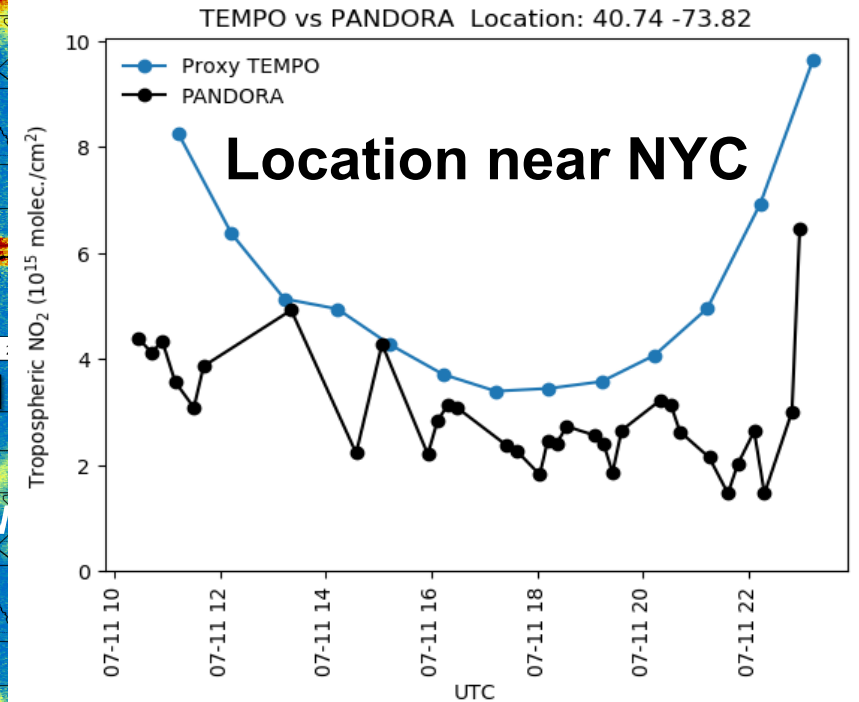
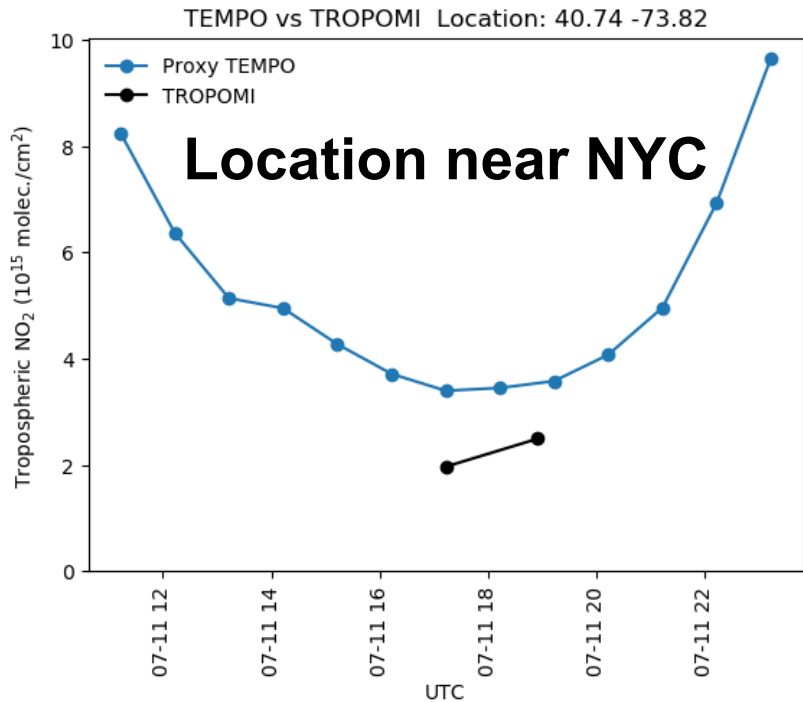
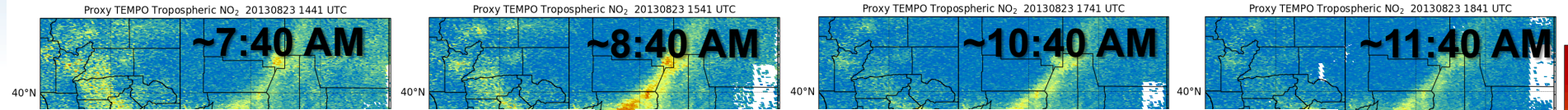
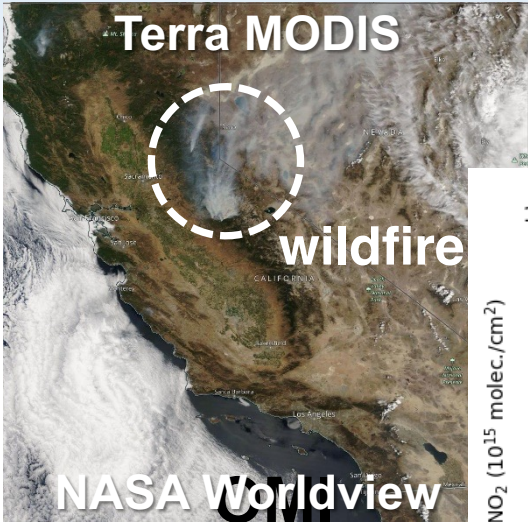


Aug. 23, 2013

Monitoring NO₂ in Complex Scenes



TEMPO Proxy Level 2 NO₂ data

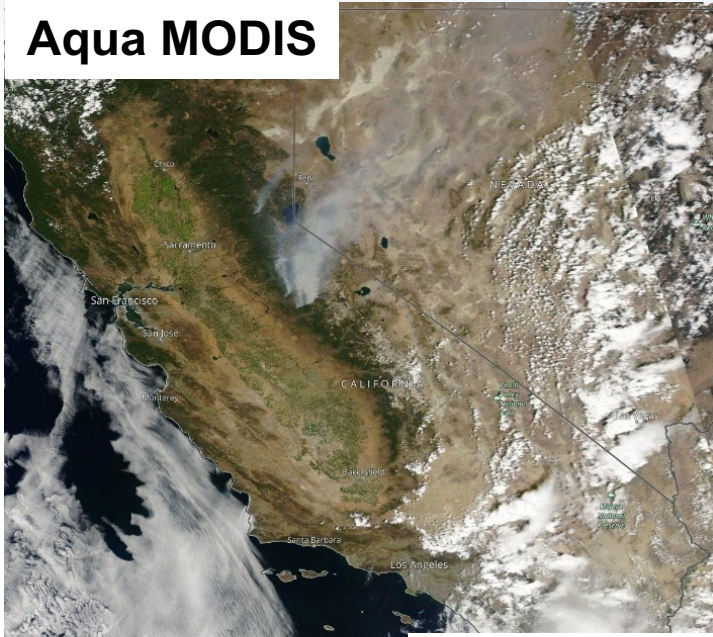


***Proxy data not intended to support operational decisions or scientific research studies**

□ TEMPO will observe rapidly varying NO₂ columns within wildfire smoke plumes and across urban areas and traffic corridors.

Multi-Pollutant Monitoring with TEMPO

Aqua MODIS

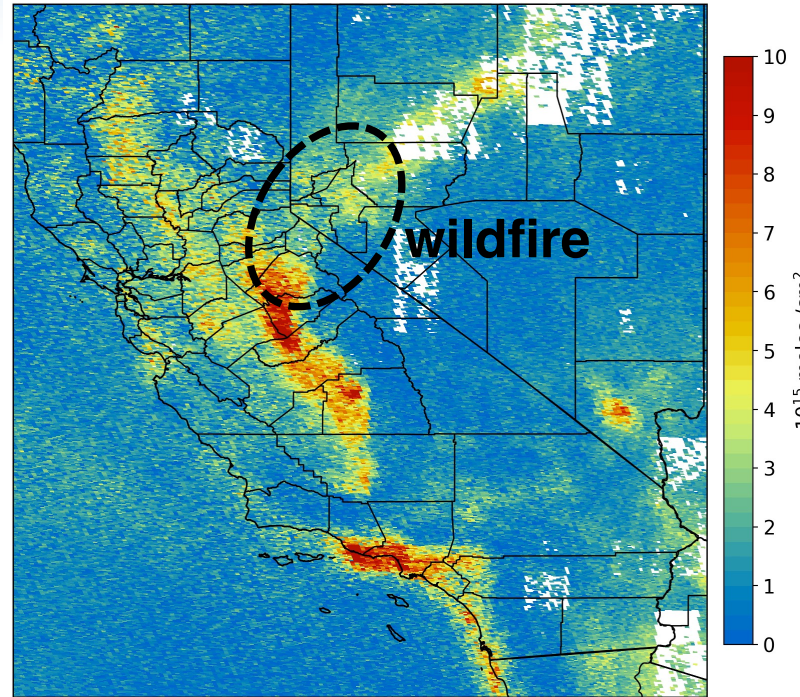


29 Aug. 2013

Worldview

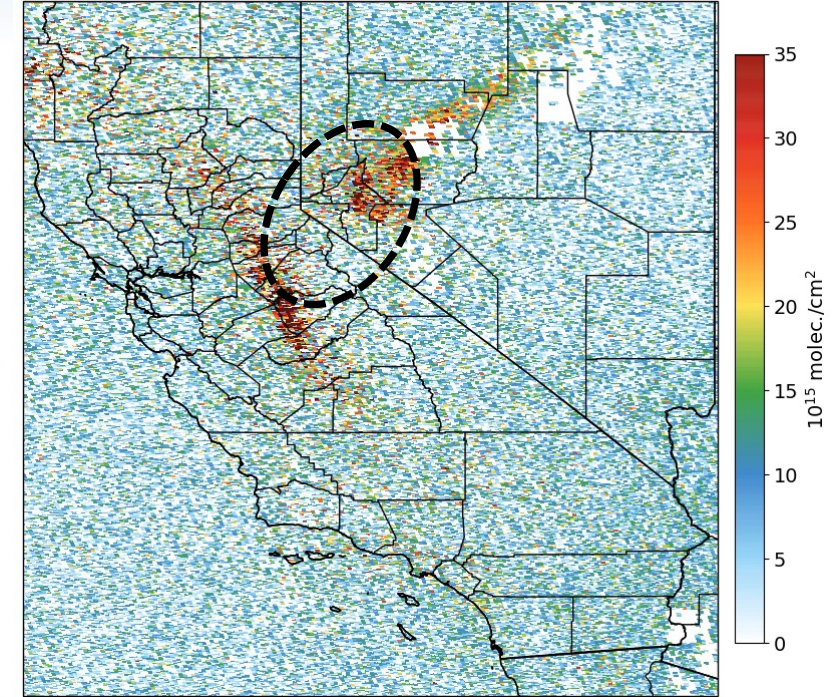
Tropospheric NO₂ VCD

Proxy TEMPO Tropospheric NO₂ 20130828 1441 UTC



Total HCHO VCD

Proxy TEMPO Total HCHO 20130828 1441 UTC



28 – 31 Aug. 2013

- Multi-pollutant information from TEMPO will help better diagnose emission sources, pollutant transport, and health impacts
- HCHO/NO₂ ratios can help infer ozone sensitivity to precursors

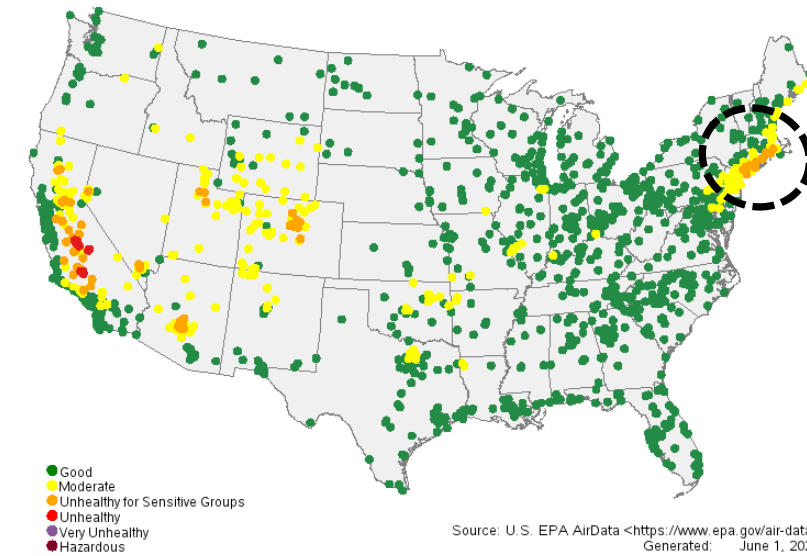
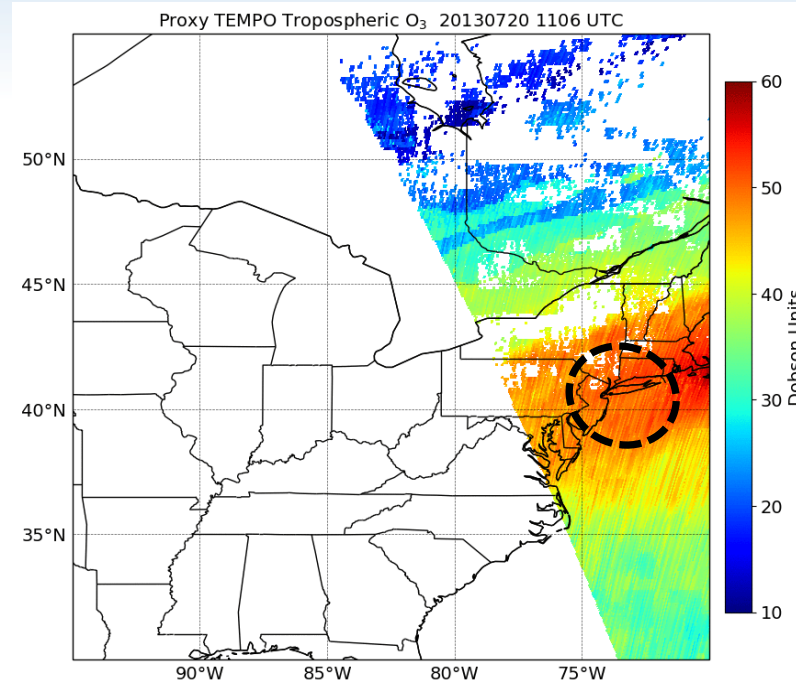
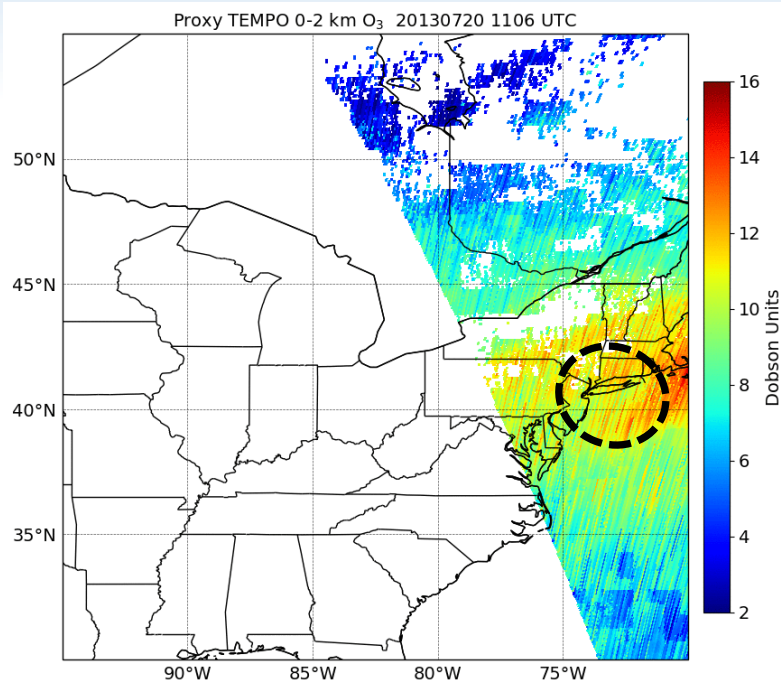
***Proxy data not intended to support operational decisions or scientific research studies**

0-2 km (PBL) O₃

Tropospheric O₃

20 July 2013 Use Case

Ozone AQI Values by site on 07/20/2013



- ❑ TEMPO instrument will be sensitive to O₃ in the lower troposphere as shown by the proxy data
- ❑ O₃ profile will offer new capabilities to track and predict (assimilation) O₃ concentrations and transport from the stratosphere to the planetary boundary layer (PBL)
- ❑ Unprecedented monitoring of **O₃ pollution within the layer of air where people live and breathe**
- ❑ TEMPO O₃ data will help fill the gaps in surface monitor coverage, especially the large gaps in the western region



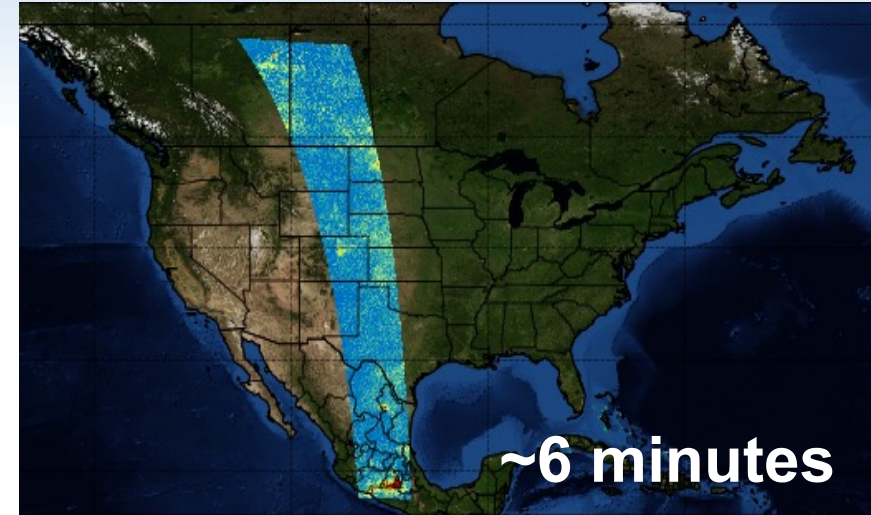
TEMPO Special Operations & Stakeholder Experiments



TEMPO Special Operations



- ❑ Up to 25% of TEMPO's observing time will be devoted to special operations over a slice of the FoR (e.g., ≤ 10 min frequency)
- ❑ Special experiments will commence during the nominal operations (Oct 2023 – onward)
- ❑ Focus areas include **air quality disasters** (e.g., wildfires, volcanoes), **research studies** (e.g., agriculture, lightning NO_x), & field campaigns



Selection of special experiments in **TEMPO Green Paper**

- ❖ **Formation of ozone along the Colorado Front Range**
- ❖ **High Resolution Scanning over the New York City area**
- ❖ Study of Winter Air Pollution in Toronto
- ❖ Utah Summer Ozone Study
- ❖ **Coastal & Oceanic Atmospheric Pollution Experiment 2 Gulf of Mexico Cruise**
- ❖ **Air Quality Impacts from Oil and Gas Activities in the Western U.S.**
- ❖ Monitoring Volcanic Activity and Air quality Impacts from Mexican Volcanoes
- ❖ Lightning NO_x
- ❖ Agricultural soil NO_x emissions and air quality in California

*** Experiments Focused on Regulatory Science ***

Green Paper here!





Formation of Ozone Along CO Front Range

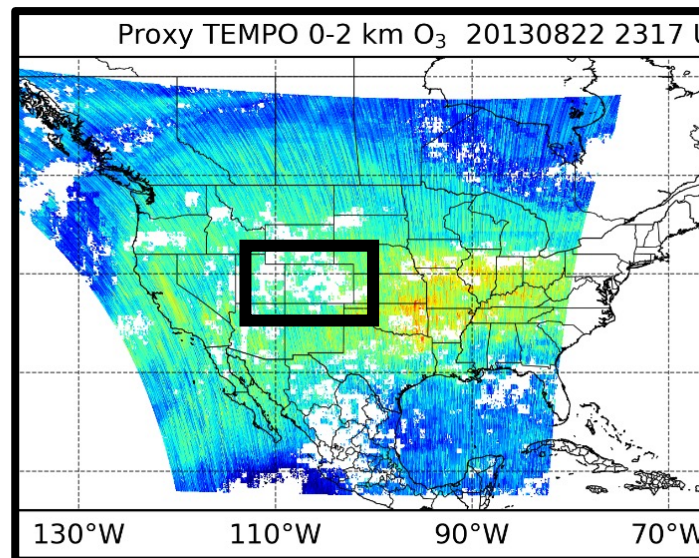
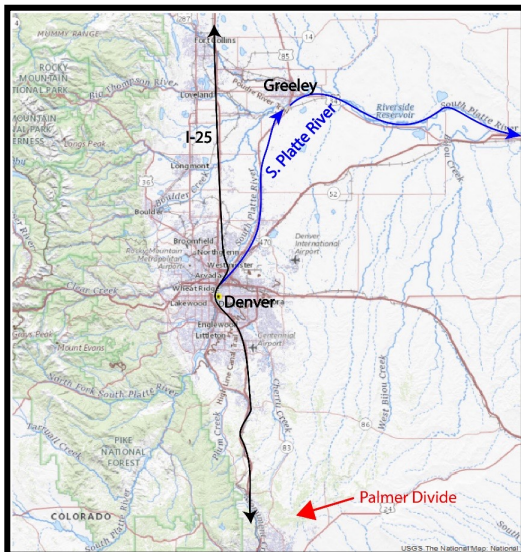
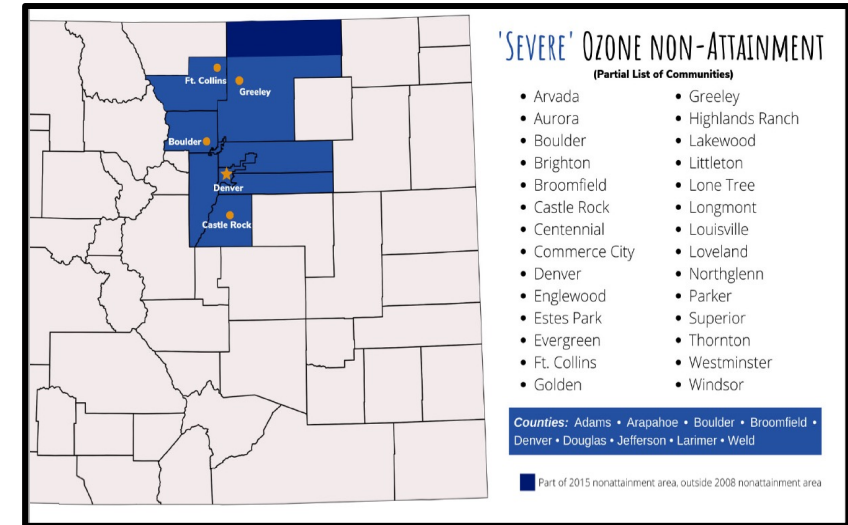


- ❑ **Problem:** O₃ nonattainment area across Colorado Front Range is now classified as severe with repeated downgrades since 2008
 - Contributing factors to O₃ nonattainment area include urban sources, traffic emissions, O&G operations, topography
 - Population density in CO is highest along Front Range
 - CDPHE aims to use TEMPO data to monitor the evolution of O₃ precursors and O₃ accumulation along Front Range
- ❑ **Goal:** Use TEMPO data for better documentation of these processes and greater understanding of air pollution episodes

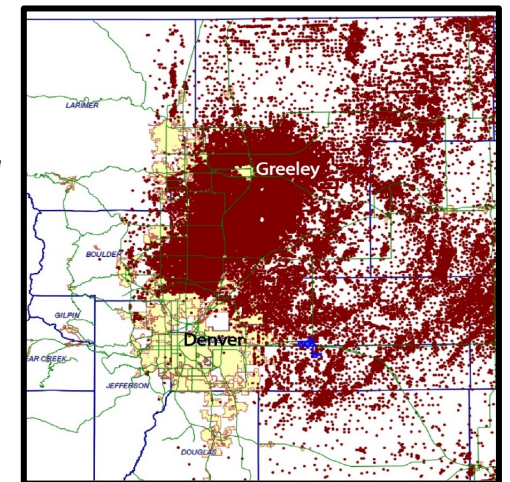
Investigators: Dan Welsh, Katie Broyles, Scott Landes



COLORADO
Department of Public Health & Environment



Location of oil & gas wells (red dots)



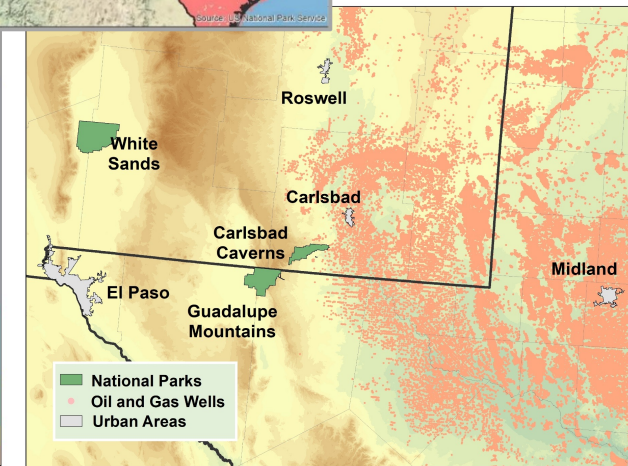
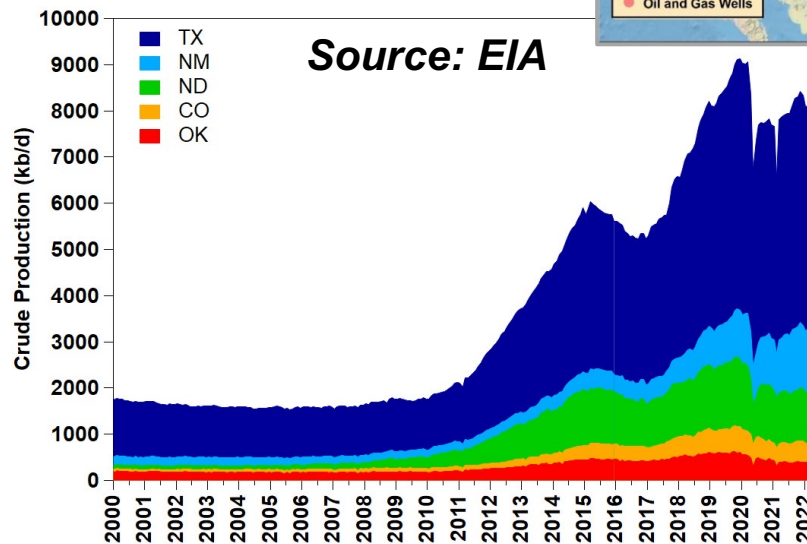
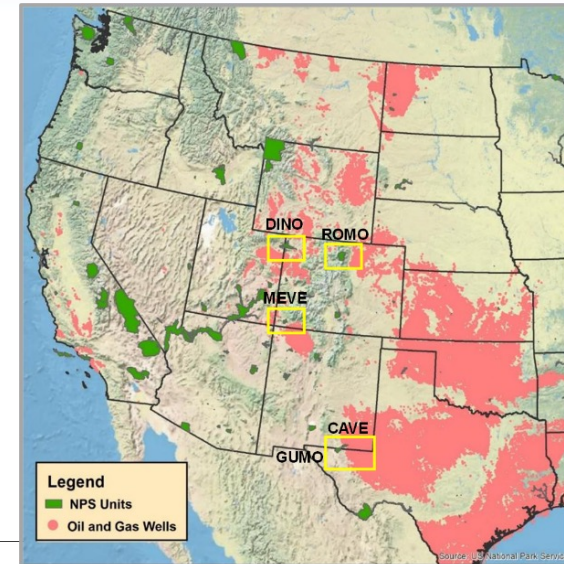


Air Quality Impacts from O&G in the Western U.S.



- ❑ **Problem:** Widespread air quality impacts from O&G activity emissions across multiple basins have been observed at National Park Service (NPS) units and their surrounding communities
 - Carlsbad, NM area, including Carlsbad Caverns National Park (CAVE), has been struggling with degrading air quality and associated negative health effects on communities.
- ❑ **Goal:** Use high-frequency TEMPO data to demonstrate the widespread impacts of pollution episodes in the region and assist in facilitating emission control strategies to improve air quality

Investigators: **Barkley Sive, Lisa Devore**



8-hr O ₃ DV Years	CAVE	Carlsbad, NM	DFW	Houston
2014-2016	67	67	80	79
2015-2017	66	68	79	81
2016-2018	71	74	76	78
2017-2019	74	79	77	81
2018-2020	73	78	76	79
2019-2021	74	77	76	77
2020-2022*	77	77	77	74

*Preliminary and incomplete



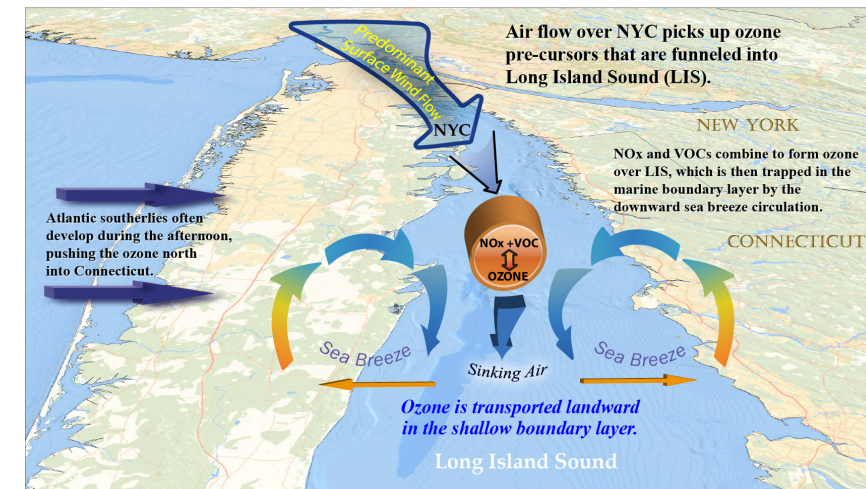
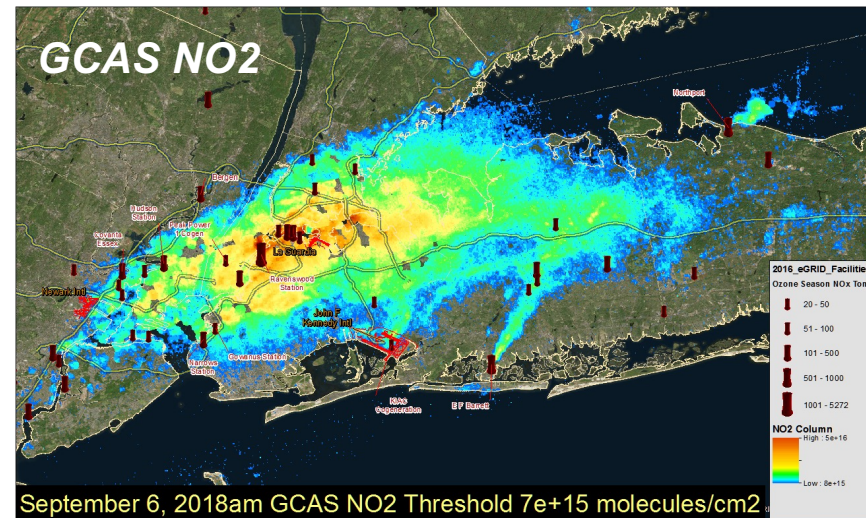
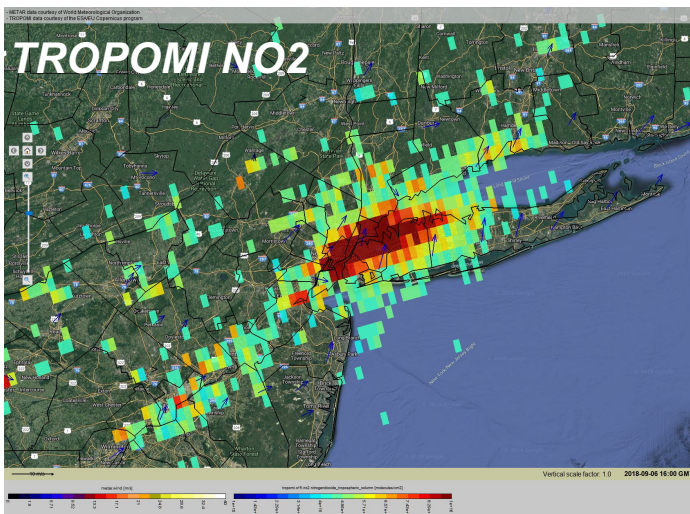
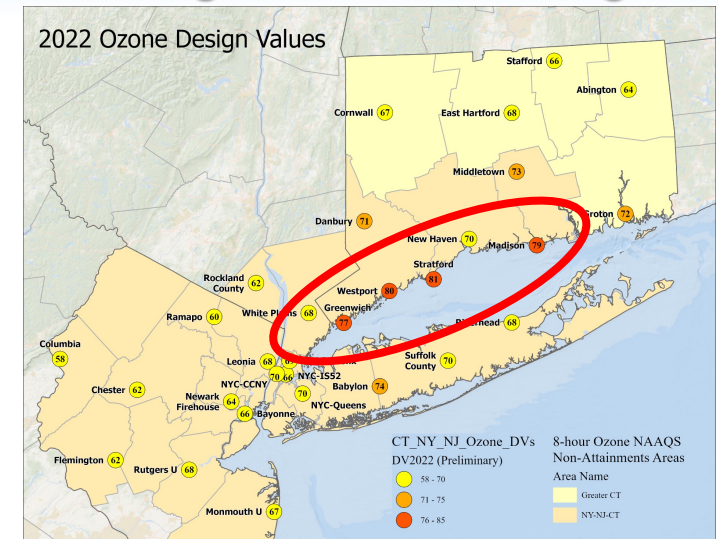
High Resolution Scanning over NYC Area



Connecticut
Department of Energy &
Environmental Protection

Investigator: **Michael Geigert**

- ❑ **Problem:** Connecticut coastal sites continue to record the highest ozone design values on the east coast.
 - Ozone precursors from NYC are funneled into the Long Island Sound (LIS) and trapped in the marine boundary layer and then transported into Connecticut by Atlantic southerlies.
 - To develop better NOx control strategies, we need to know where emissions come from on high ozone days.
- ❑ **Goal:** Use TEMPO data in conjunction with oversampling techniques to characterize point emission sources and monitor strength and movement of NO2 plumes across land/sea interface

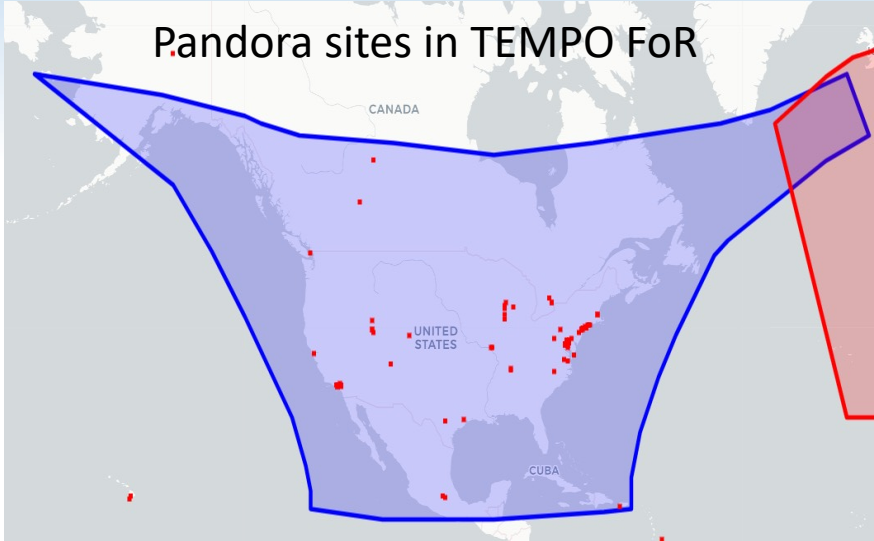




TEMPO Field Campaigns & Initial Results



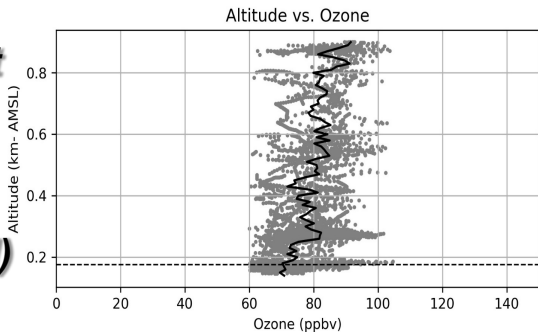
TEMPO Validation and Supplementary Data



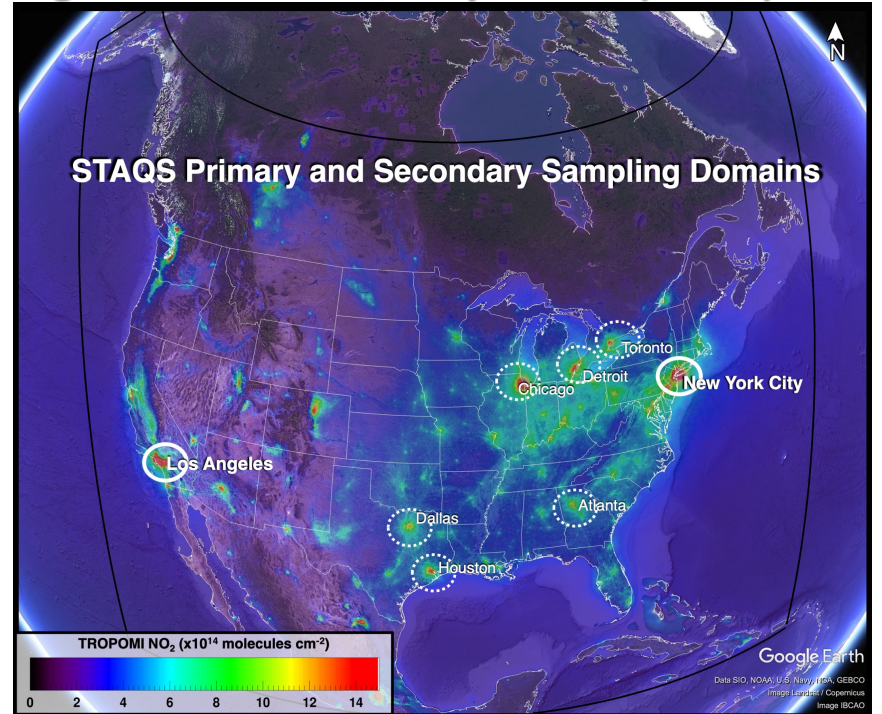
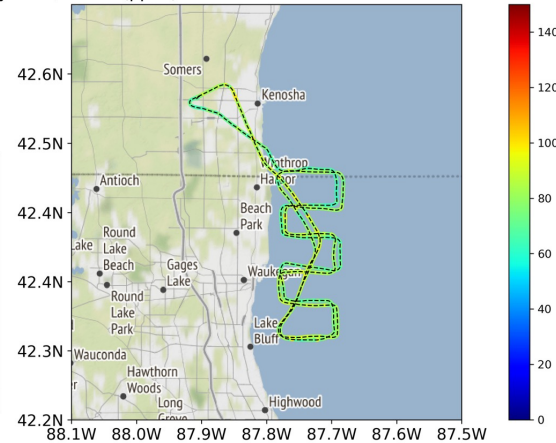
- ❑ Network of ground-based NASA Pandora spectrometers will be used to validate and characterize TEMPO products of O₃, NO₂, HCHO, and SO₂ (experimental)
- ❑ EPA's AirNow network will supplement TEMPO's observations by connecting space to ground observations and develop top-down approaches for estimating emissions and surface-level pollution

Synergistic TEMPO Air Quality Science (STAQS) Mission

O₃ from Searey aircraft around Chicago sampling domain of STAQS
PI: M. Newchurch (UAH)



Searey Data, Ozone (ppbv) - 2023-08-02 14:59:48 to 2023-08-02 16:50:25



- ❑ In July – Aug. 2023, STAQS mission seeks to integrate TEMPO satellite data with traditional air quality monitoring for TEMPO validation and improved understanding of air quality science

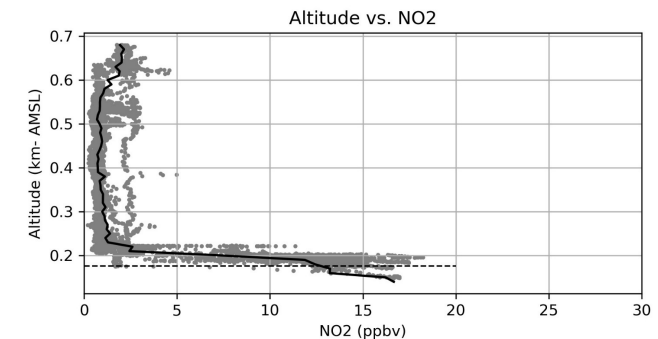
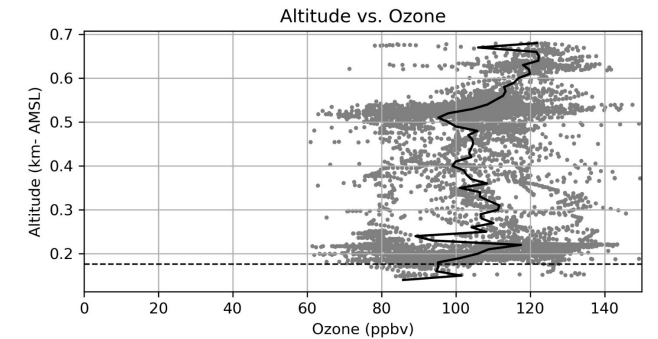
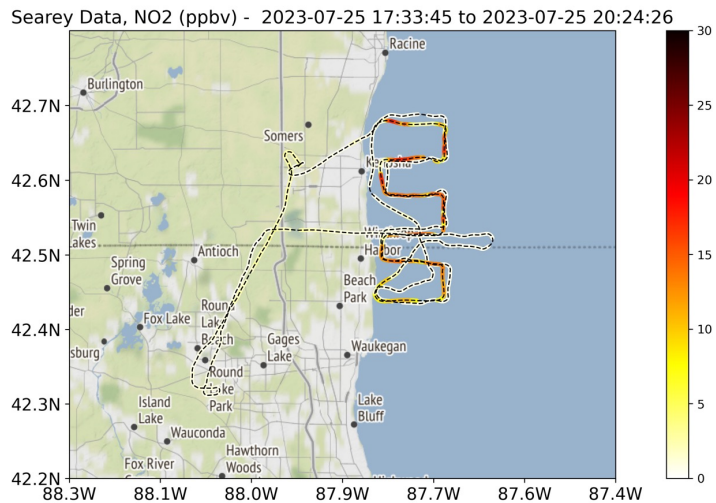
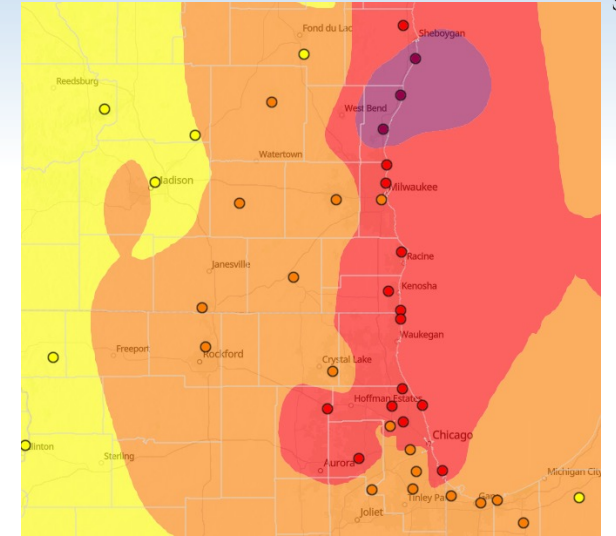
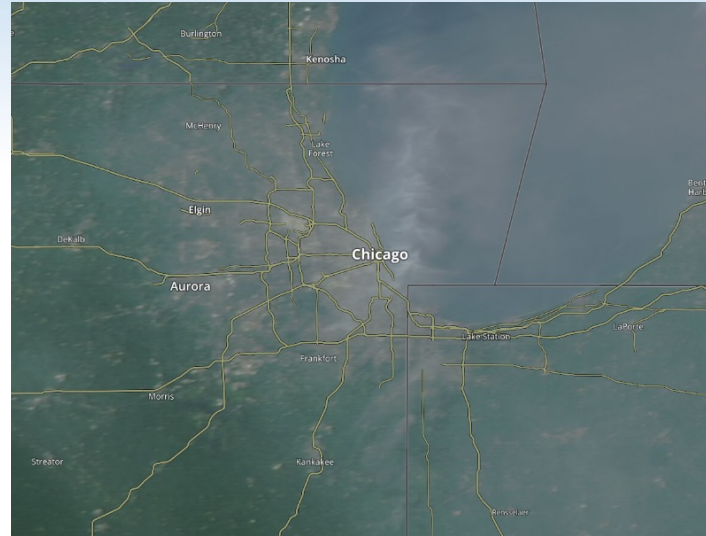
Interested in connecting with the STAQS team?
 laura.m.judd@nasa.gov and john.t.sullivan@nasa.gov



Synergistic TEMPO Air Quality Science Mission



- ❑ Severe smoke event from Canadian wildfires impacted Chicago area on July 25, 2023 during STAQS campaign
- ❑ Searey aircraft flew through the smoke and observed enhanced NO_2 and O_3 concentrations
- ❑ Huge spike in NO_2 within 100 meters of lake surface





TEMPO First Light on Aug 2, 2023

TEMPO performed six daytime hourly scans across the Field of Regard





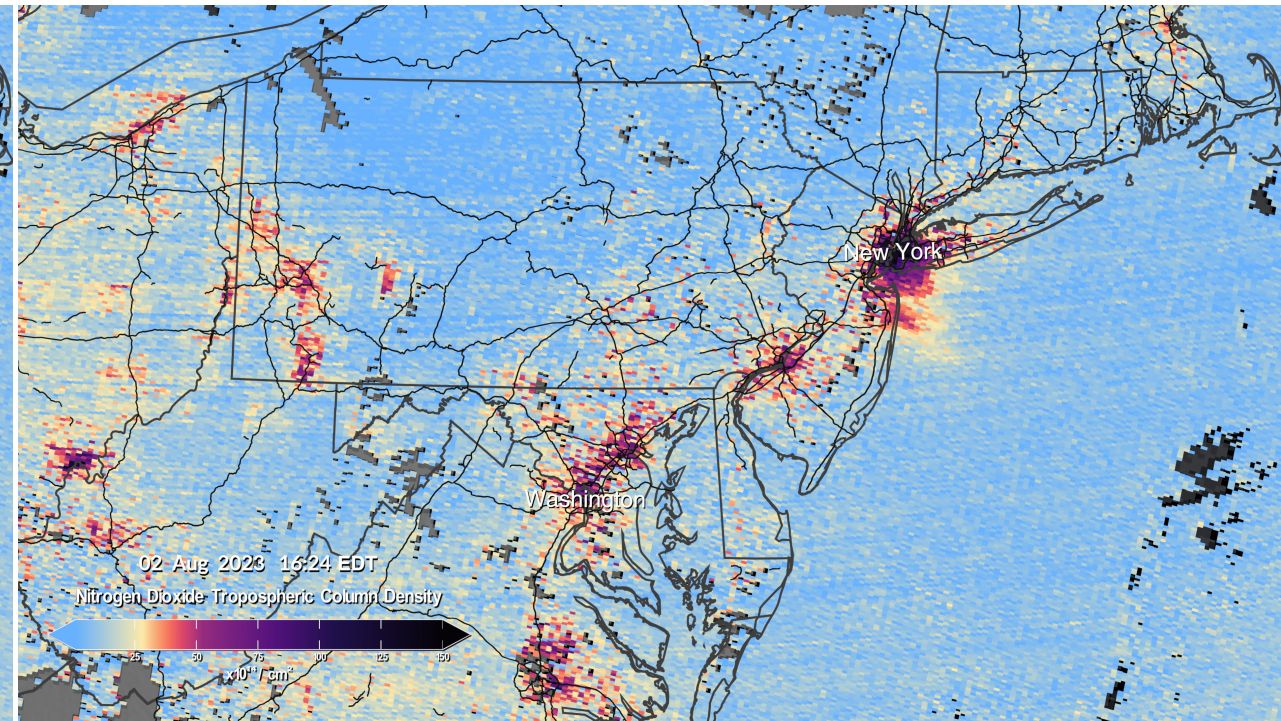
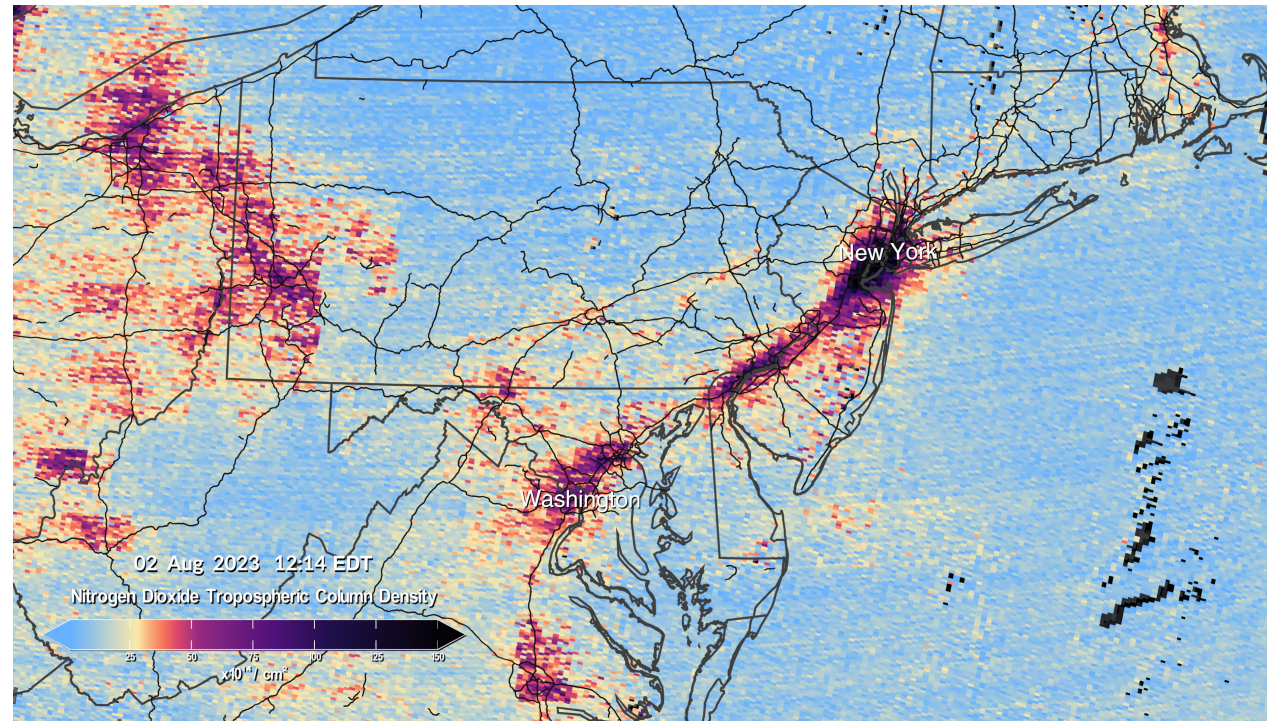
TEMPO First Light on Aug 2, 2023



Nitrogen Dioxide Tropospheric Columns

12:14 PM

4:24 PM



Credit: NASA Scientific Visualization Studio



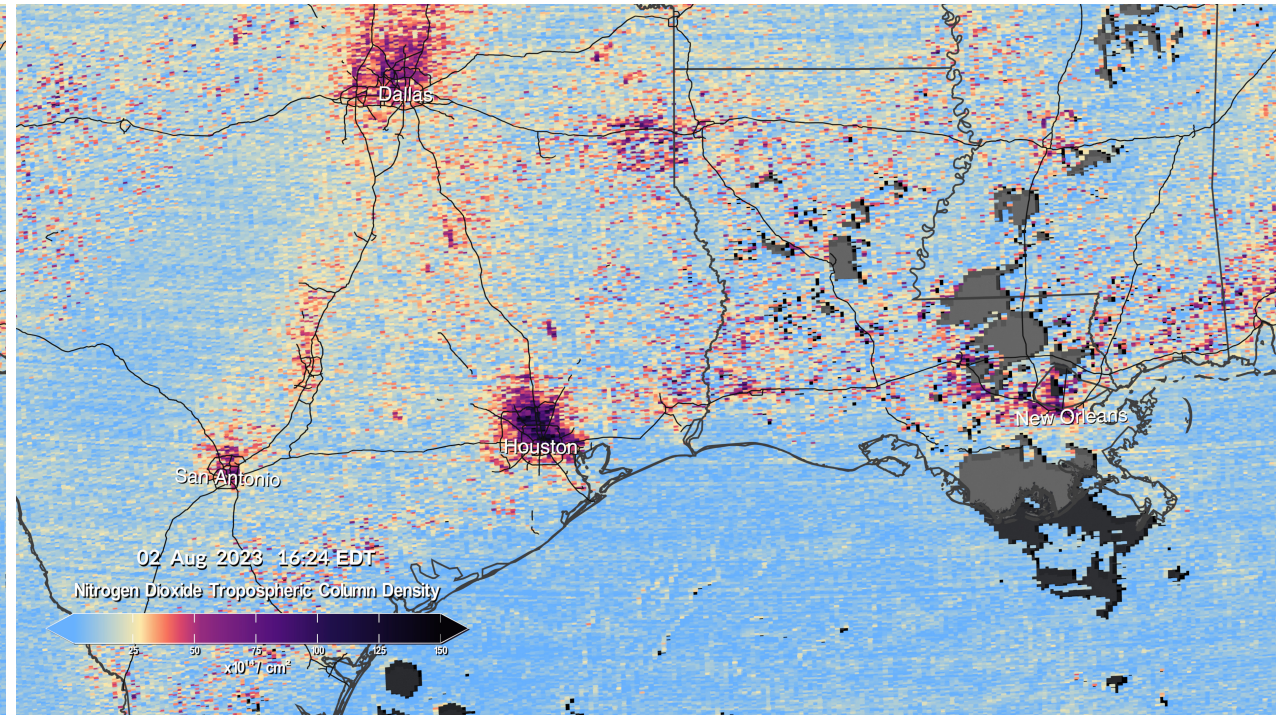
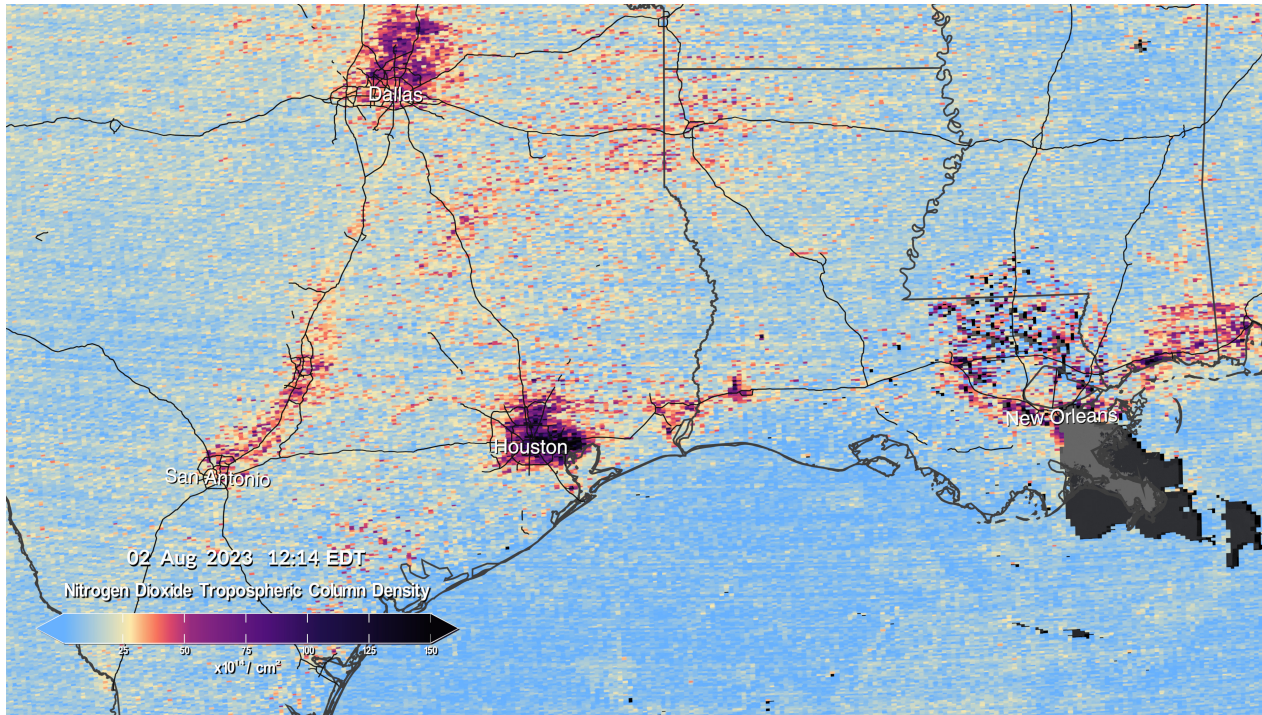
TEMPO First Light on Aug 2, 2023



Nitrogen Dioxide Tropospheric Columns

11:14 AM

3:24 PM



Credit: NASA Scientific Visualization Studio



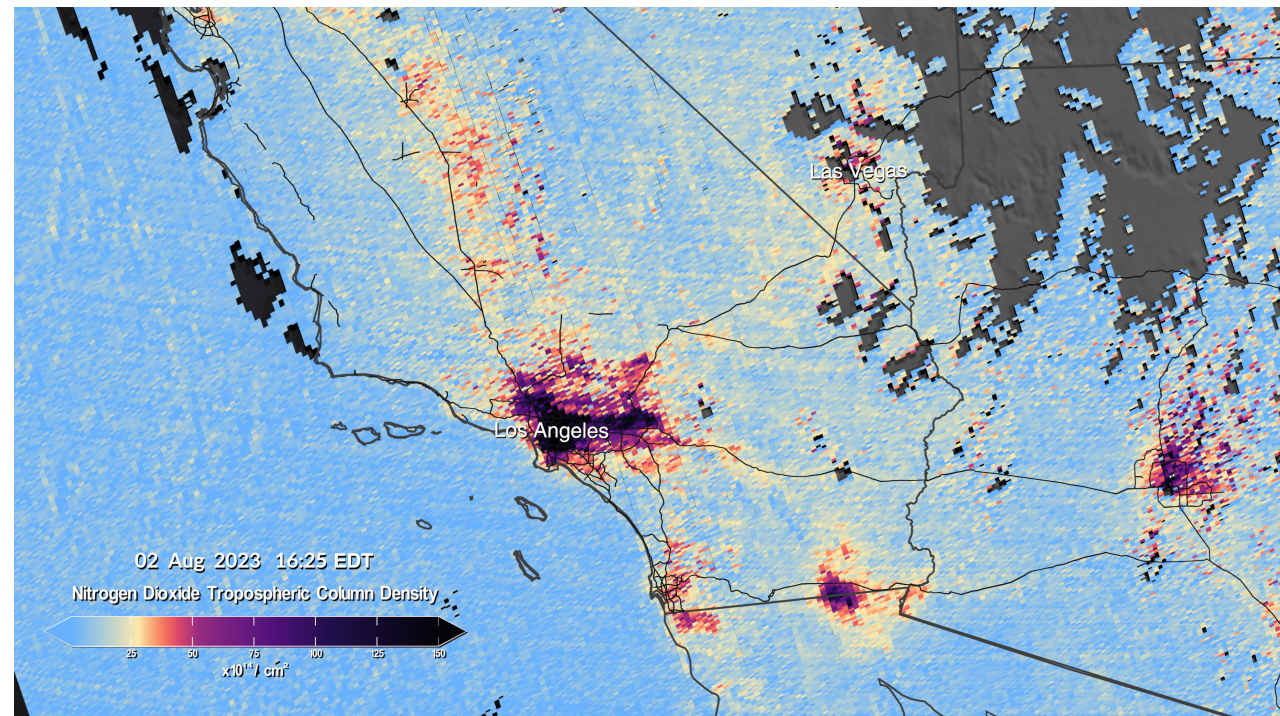
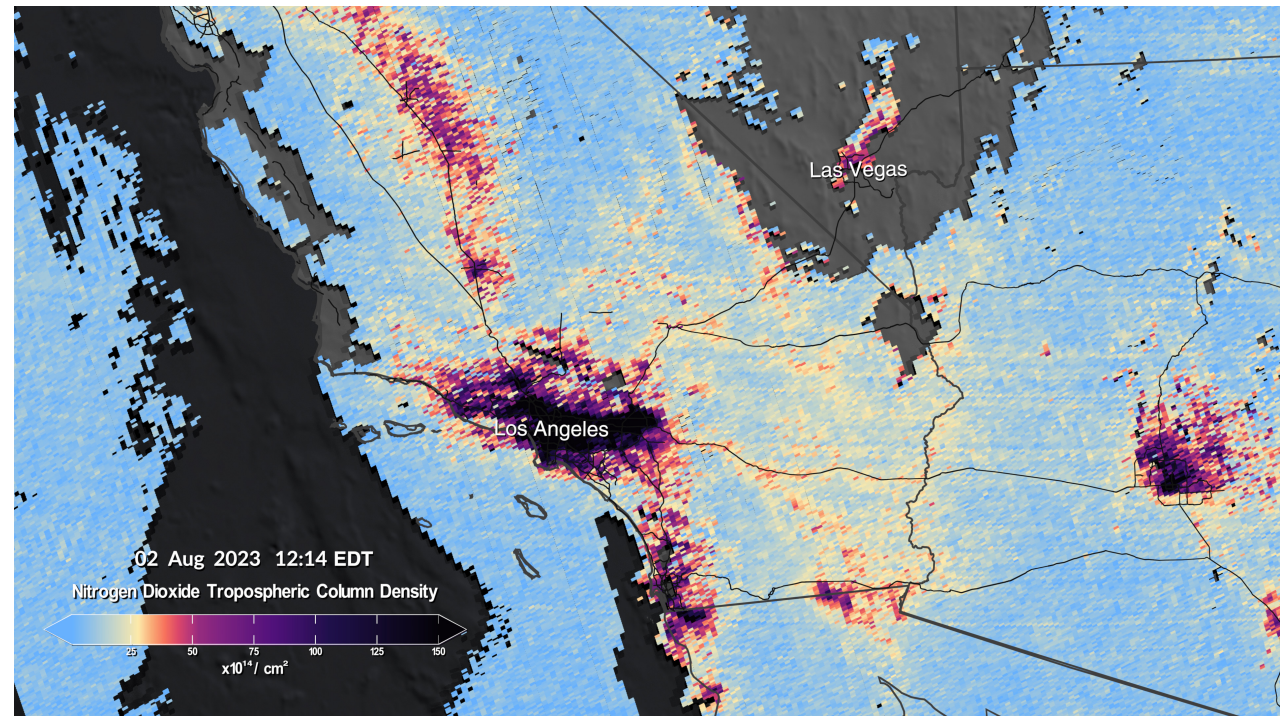
TEMPO First Light on Aug 2, 2023



Nitrogen Dioxide Tropospheric Columns

9:14 AM

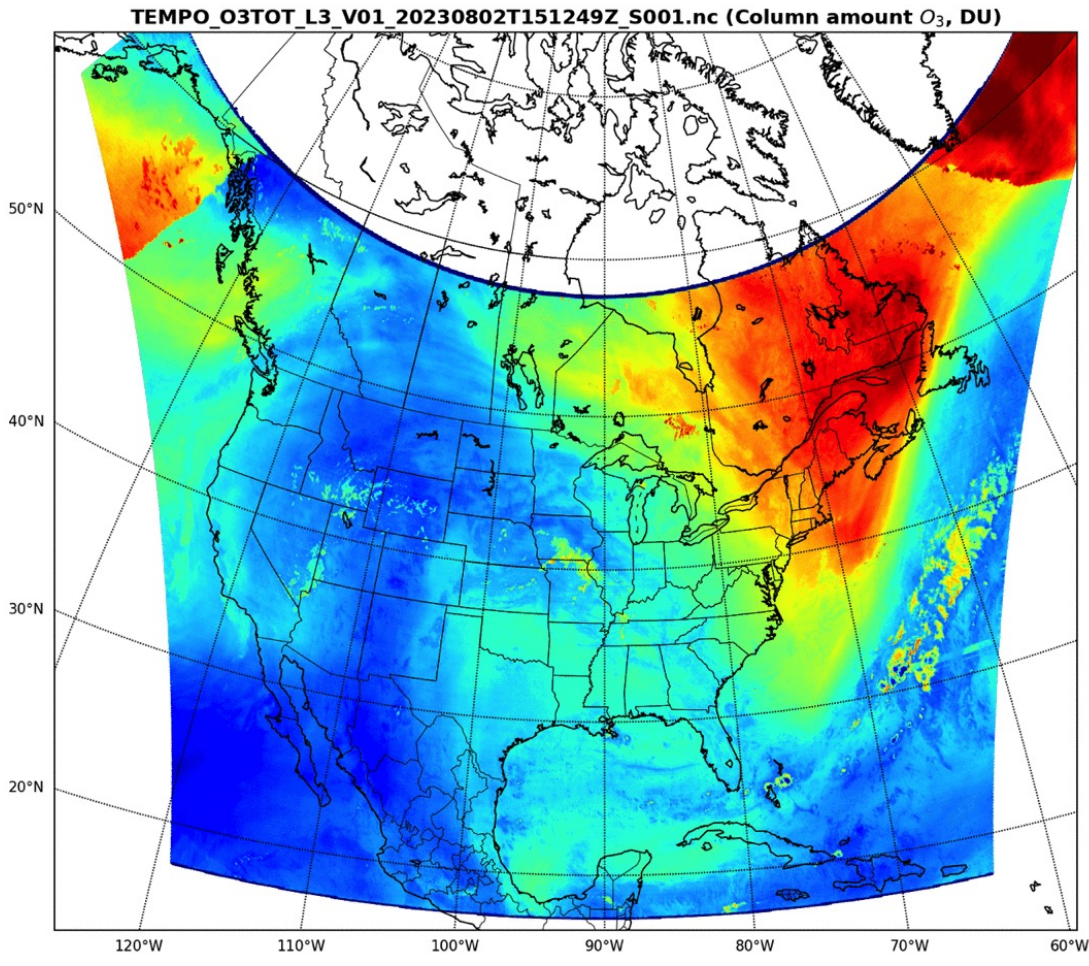
1:25 PM



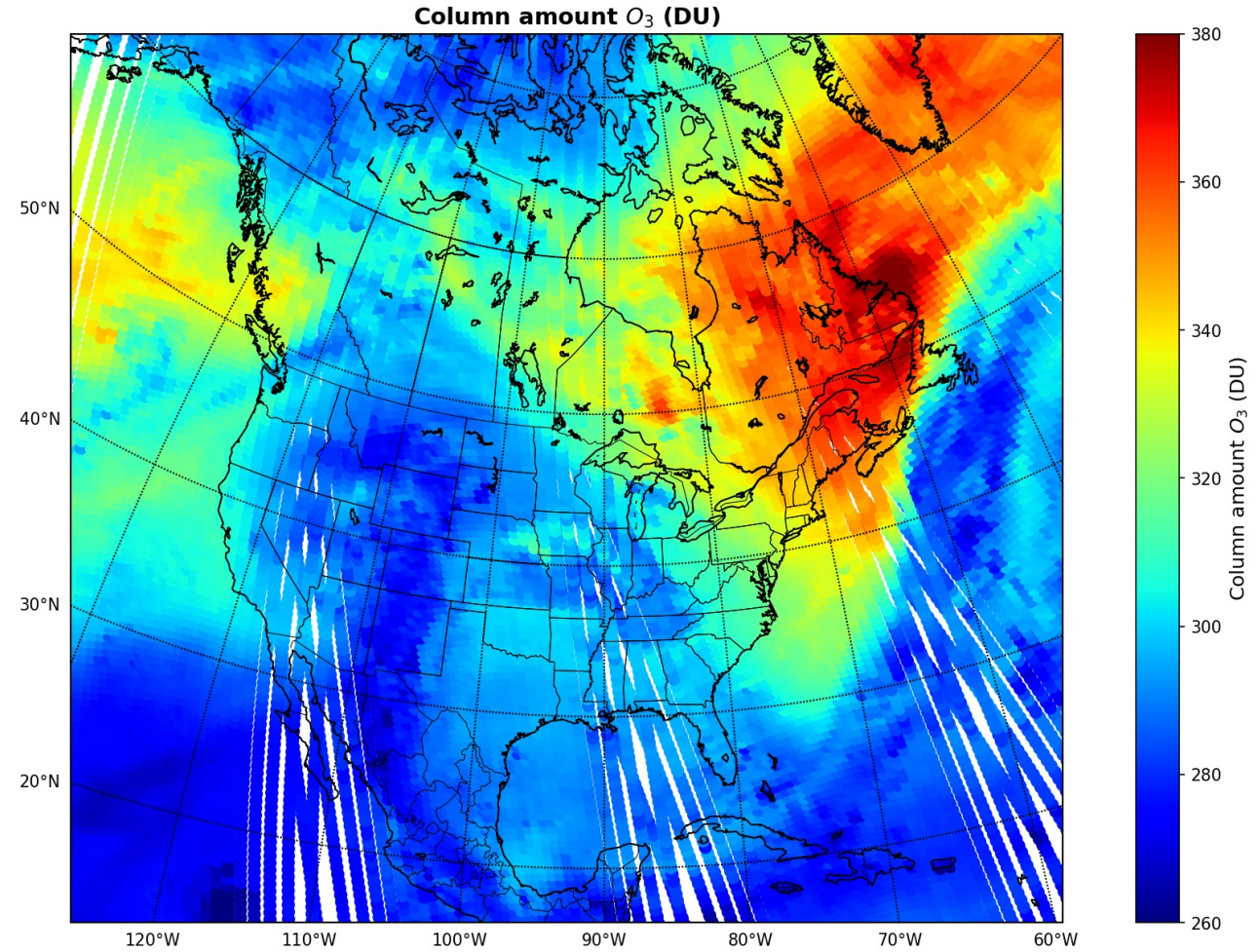
Credit: NASA Scientific Visualization Studio



Total Ozone: First Results Aug 2, 2023



TEMPO



OMPS

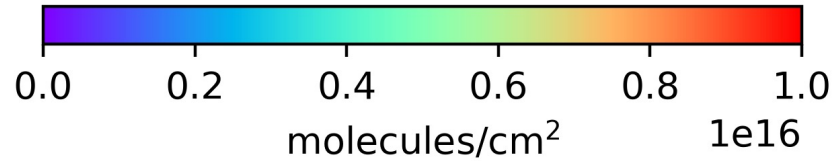
Courtesy of Xiong Liu



TEMPO Commissioning Phase Oct 6, 2023

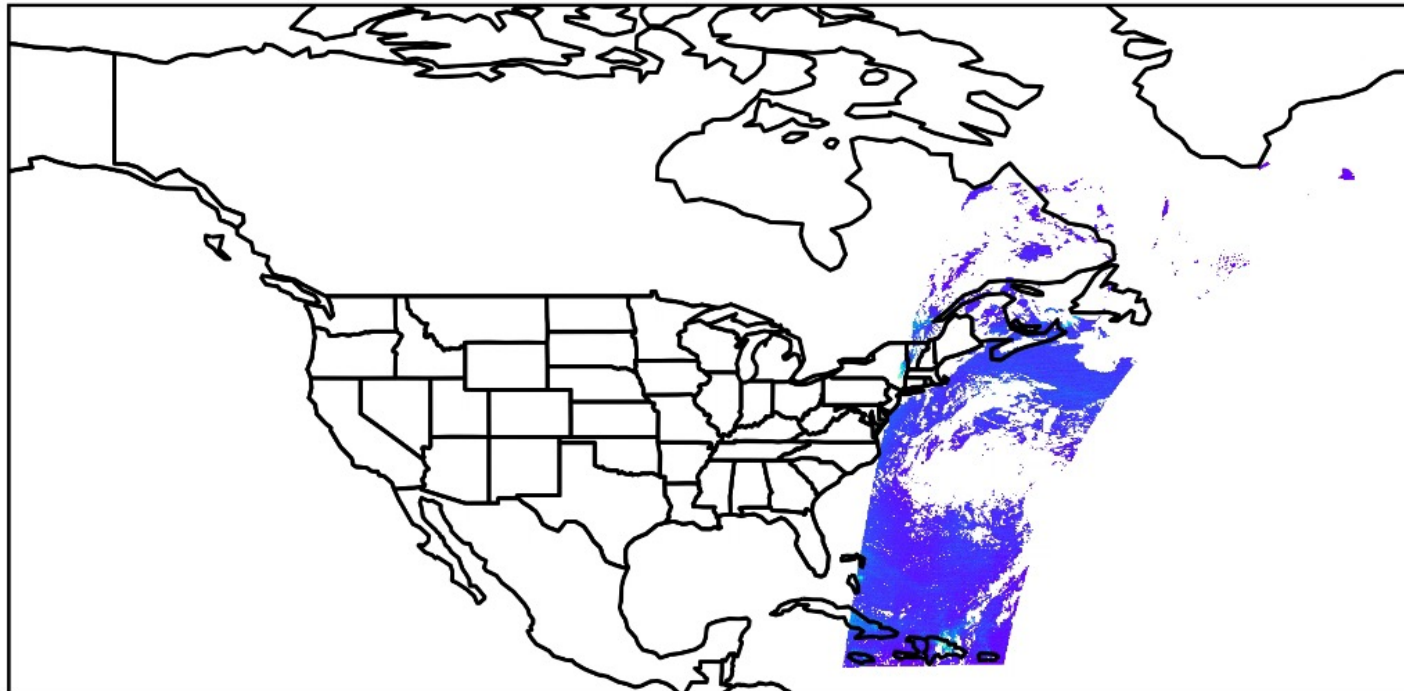


TEMPO_NO2_L3_V01_20231006T111622Z_S002



Courtesy of Caroline Nowlan

Tropospheric NO₂



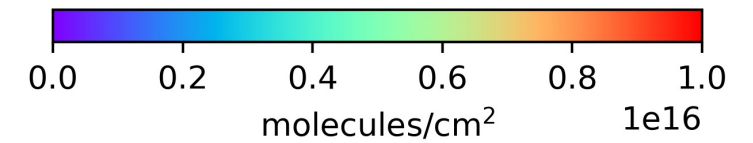
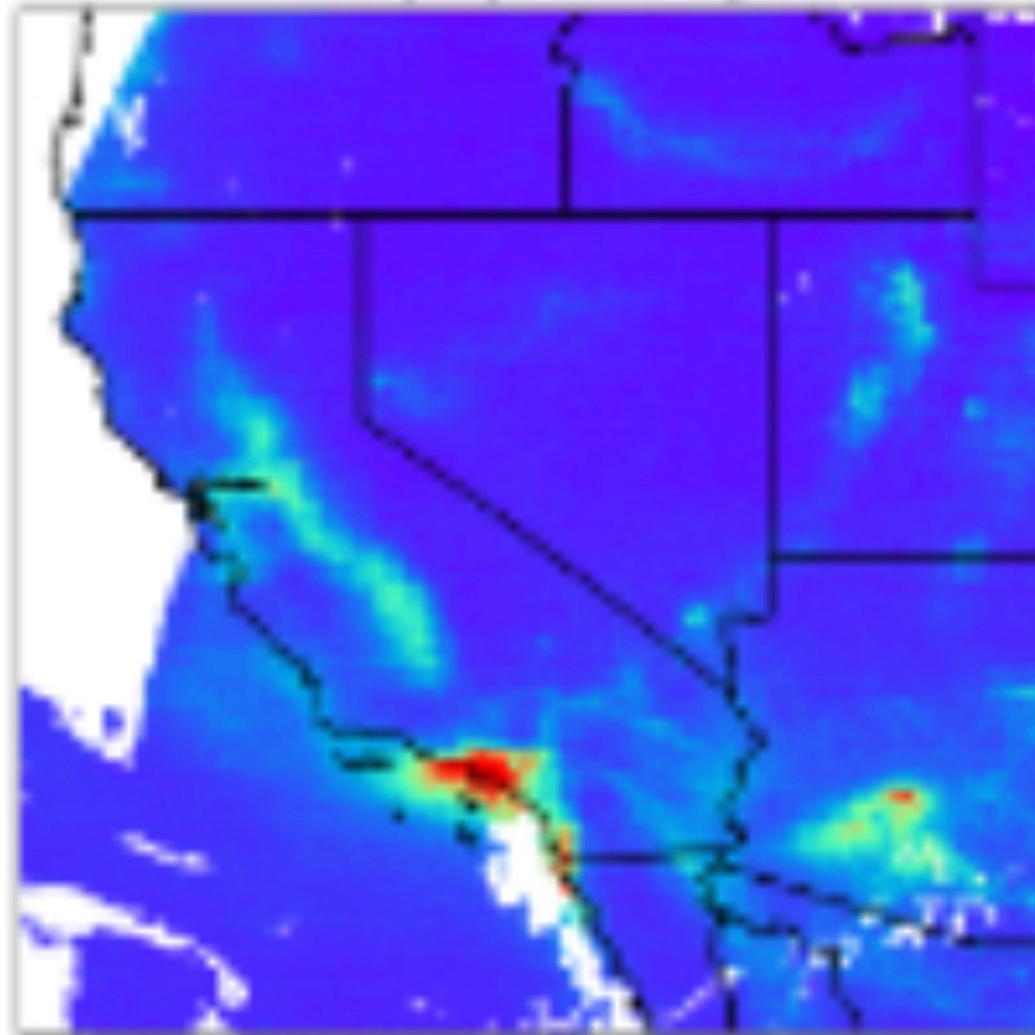


TEMPO Commissioning Phase Oct 6, 2023



TEMPO_NCO_L3_V01_20231006T135642Z_S006

Tropospheric NO₂



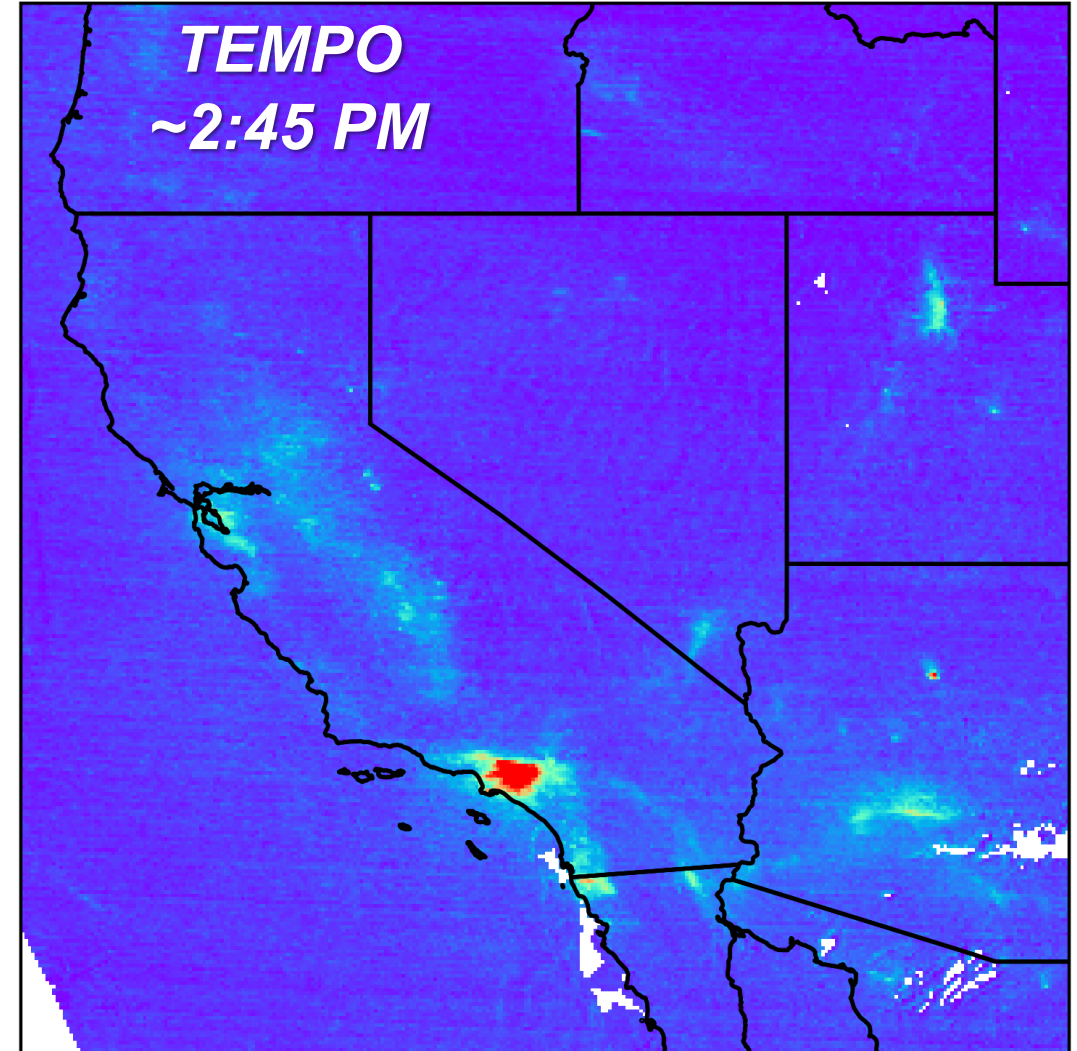
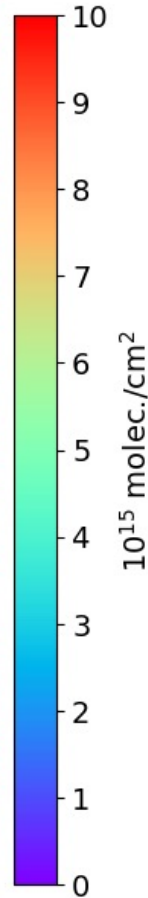
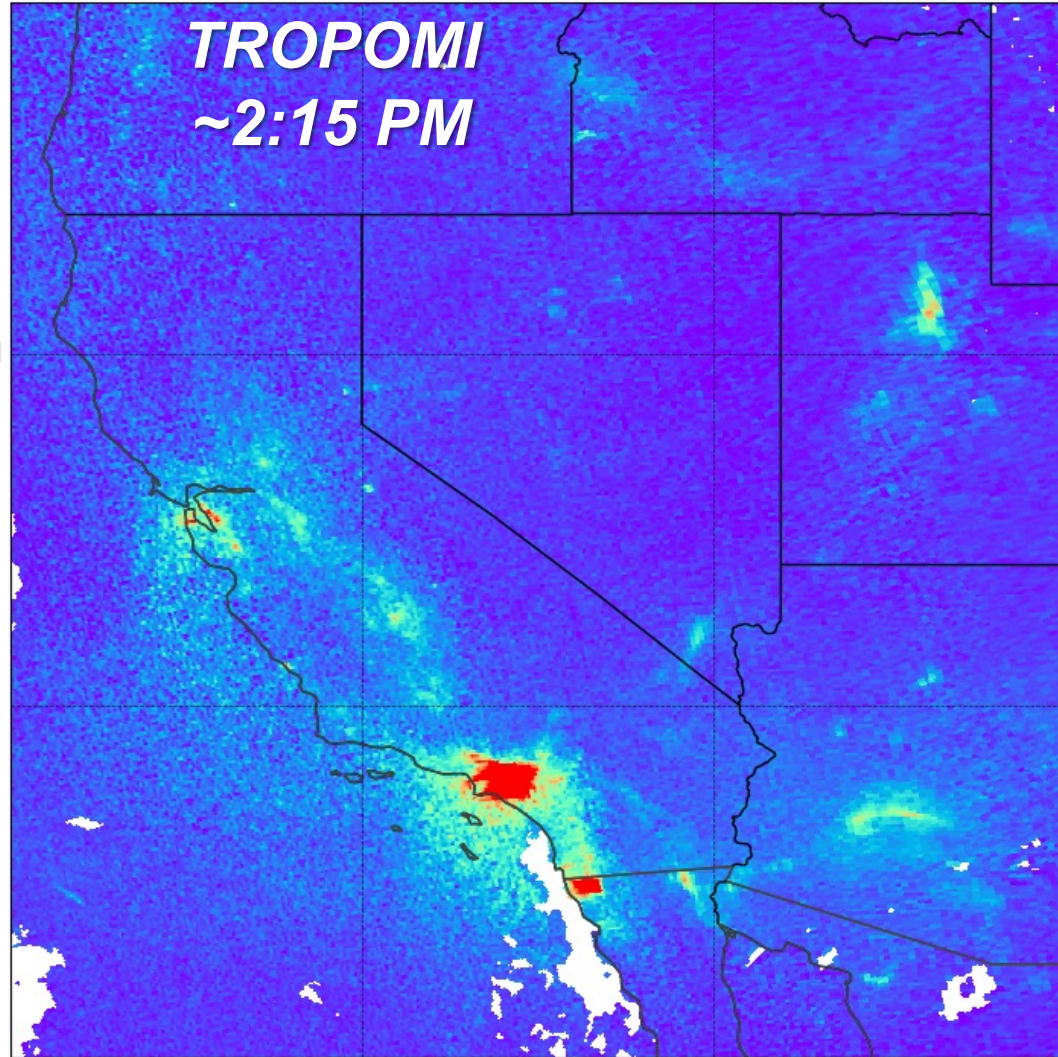


TEMPO Commissioning Phase Oct 6, 2023



S5P TROPOMI L3 Tropospheric NO₂ 20231006

Tropospheric NO₂



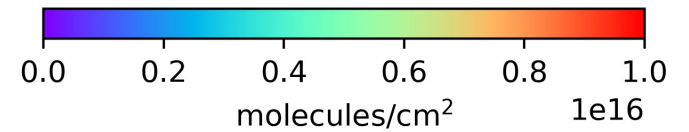
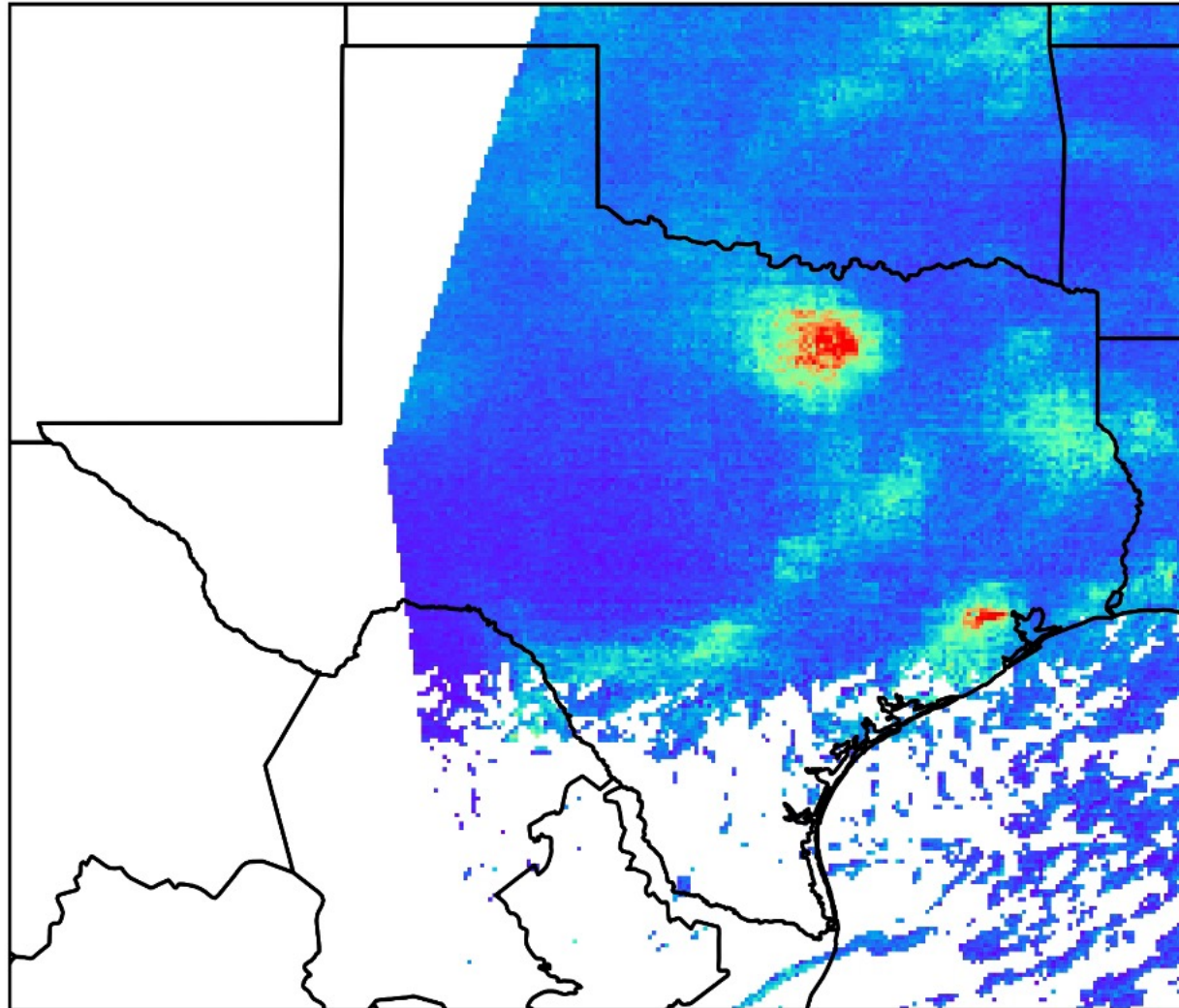


TEMPO Commissioning Phase Oct 8, 2023



TEMPO_NO2_L3_V01_20231008T123558Z_S004

Tropospheric NO₂

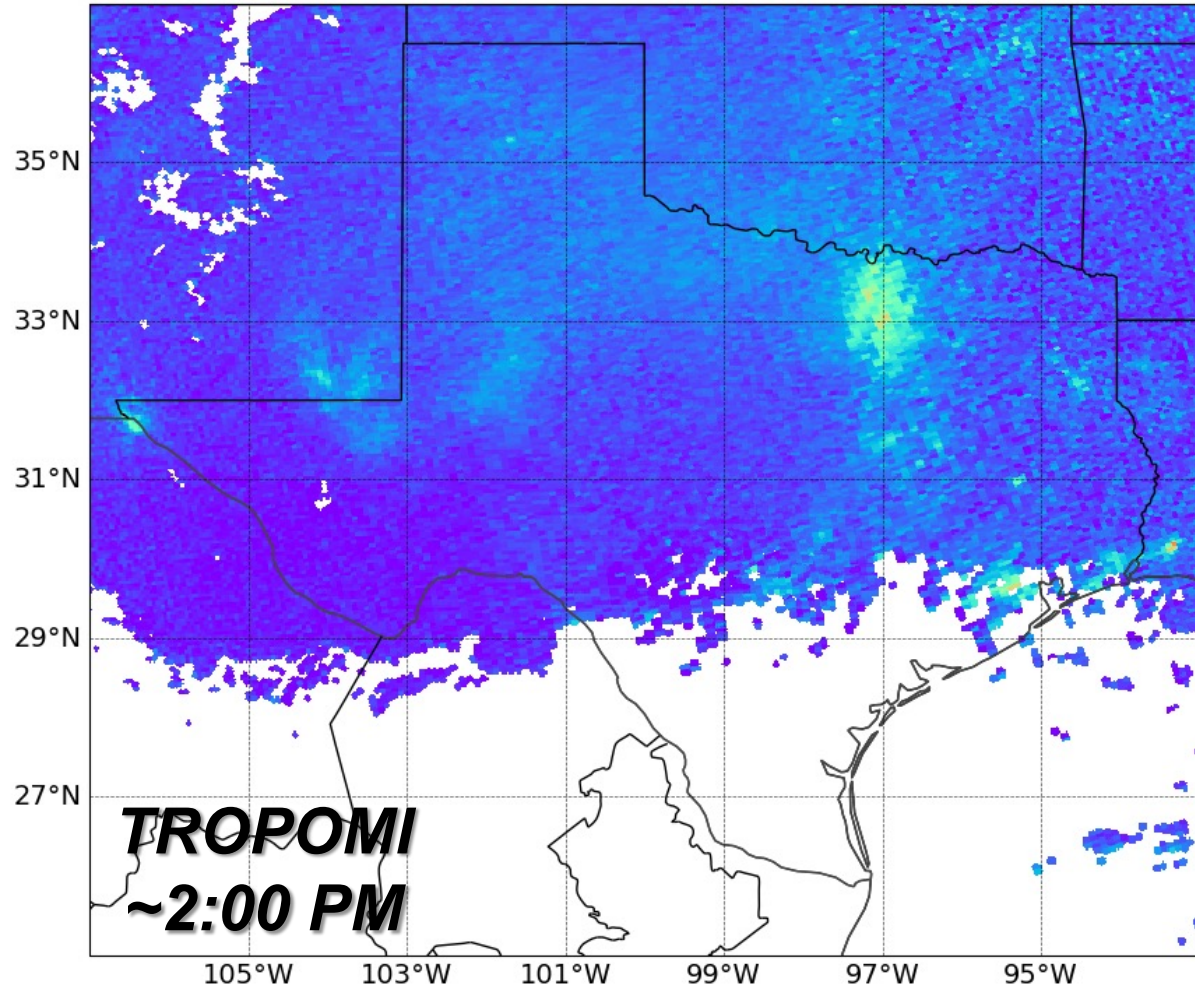




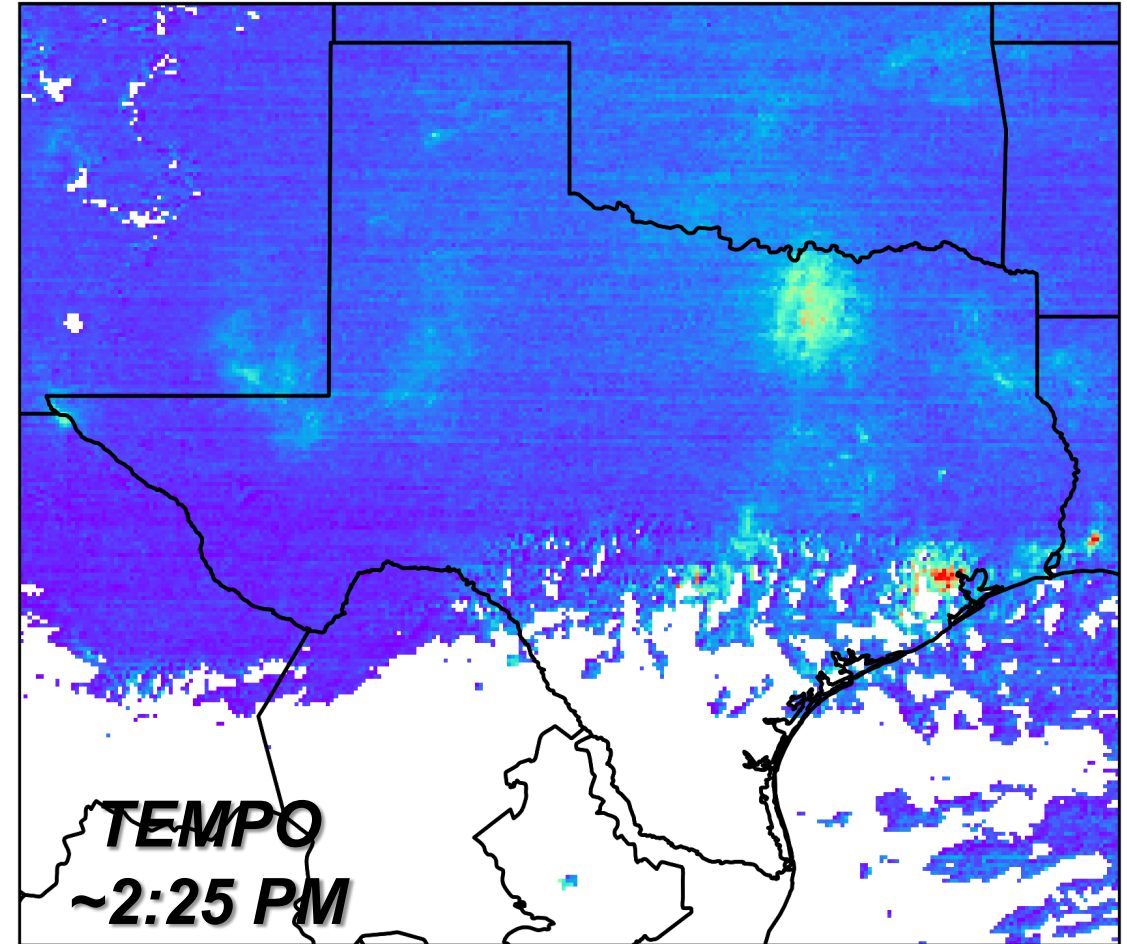
TEMPO Commissioning Phase Oct 8, 2023



S5P TROPOMI L3 Tropospheric NO₂ 20231008



Tropospheric NO₂



in



Summary of TEMPO Strengths (Non-Exhaustive)



- ❑ **O₃ profile will** offer new capabilities to **monitor and distinguish ozone concentrations from the stratosphere to the planetary boundary layer (PBL)**
- ❑ TEMPO will **observe small-scale emission sources** that have not been adequately resolved by current satellite missions, **capability to quantify sub-urban emissions and pollutant gradients**
- ❑ TEMPO will **monitor rapidly evolving pollutants from episodic events such as wildland fires**
- ❑ Tracking criteria air pollutants associated with interstate and international transport
- ❑ **Diurnal information on HCHO / NO₂ ratios for new understanding of sensitivity of local O₃ production and assessments of O₃ production regimes**
- ❑ **Supporting surface monitor site analysis and selection of new site locations**
- ❑ **Robust monitoring of industrial operations, regulatory monitors may miss peak emissions!**
- ❑ Hourly scans for observing gaps in cloud cover, mitigate impact of clouds on monitoring air quality using satellite data
- ❑ Aerosol optical depth and aerosol layer height for aerosol plume monitoring and PM_{2.5} estimates
- ❑ **Near real-time NO₂, HCHO, and aerosol products for air quality monitoring & forecasting!**



Challenges Remain!

- ❑ **Space-borne spectrometers like TEMPO provide vertical column measurements, not nose-level concentration measurements**
 - Ancillary data and methods required to estimate nose-level concentrations
- ❑ Challenges associated with accessing, processing, and properly interpreting satellite data, especially noisy products such as HCHO and SO₂
 - Large increase in data volume with TEMPO
- ❑ Adapting previous retrieval methods for low-earth orbiting instruments (TROPOMI) to account for new challenges associated with geostationary satellites
 - Changing solar geometry throughout the day, surface reflectivity, and a priori input for retrievals
- ❑ First-ever O₃ PBL retrieval from space will be challenging, sensitivity to O₃ in the PBL will require intensive evaluation



What Will TEMPO Offer Air Quality Managers?

by Aaron R. Naeger, Michael J. Newchurch, Tom Moore, and Kelly Chance

A preview of NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) Mission, planned for launch in November 2022, which promises to revolutionize current capabilities in monitoring air pollution in the troposphere.



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Contribute to the Green Paper!





Thank You!

Questions / Comments

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@NaegerAaron

TEMPO Special Observations

[TEMPO Green Paper \(pdf\)](#)

[Experiment Request Form](#)

[Management Plan](#)



The TEMPO mission plans to use as much as 25% of the observing time for non-standard or “special” operations with sub-hourly temporal resolution (e.g., ≤ 10 minutes) over selected slices of the Field of Regard (FoR). A special focus of the special operations will be disaster events, such as wildfires, dust storms, volcanic eruptions, and industrial accidents, along with unique chemistry experiments aimed at further enhancing our understanding of rapidly varying emissions and air pollutants in complex environments. Special operations can be performed during the commissioning phase of the mission from June – September 2023 when instrument testing and calibration are conducted. It is possible to initiate the special scan operations in about 2-3 hours after notice of an impending or occurring event with considerable flexibility in the specifications of temporal frequency and swath width. The management plan document provides additional details on the planning and coordination activities of the TEMPO special operations.

**Special
Experiment
Request**



- To make request for using a portion of TEMPO’s special observation time, investigators must complete the Experiment Request Form available on the TEMPO Early Adopters site
- Once approved as a suitable experiment for the special operations, the abstract of the experiment will be added to the living TEMPO Green Paper
- Inclusion of the experiment in the Green Paper does not guarantee that special operations will be committed to the experiment, but it is critical first step for adding it to the pipeline.