



Tropospheric Emissions:
Monitoring of Pollution
Hourly Measurement of Pollution



Smithsonian Astrophysical
Observatory



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



Strengths & Limitations of Satellite Data: TEMPO Perspective & Early Results

HAQAST Utah

Session 3B: Comparing Models & Observations:
Strengths & Limitations of Satellite Data

October 19, 2023

Aaron Naeger

& TEMPO Team

TEMPO Mission Applications Lead
NASA Marshall Space Flight Center





Mission Phases & Operational Timeline

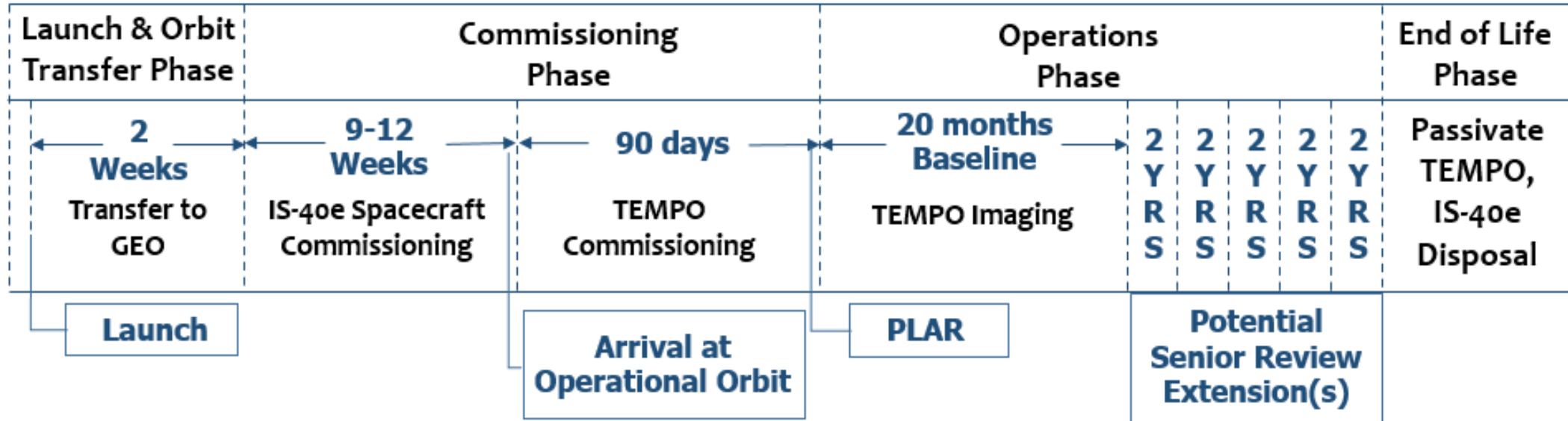


Launched:
April 7, 2023

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**



TEMPO L2+ Products: Baseline + SNWG TEMPO NRT



Level	Product	Key Variables	A Priori	Resolution (km ²)**	Frequency/Size
L2	Cloud	Cloud Fraction, Cloud Pressure	GEOS-CF	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	Climatology + GEOS-CF	>= 8.0 x 4.75	Hourly, granule
	Total O ₃	Total column O₃, Cloud Fraction, Aerosol Index	Climatology	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)	GEOS-CF	2.0 x 4.75	Hourly, granule
	HCHO (Formaldehyde)	Total VCD, SCD, Cloud Fraction, AMF, Data Quality Flag	GEOS-CF	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**

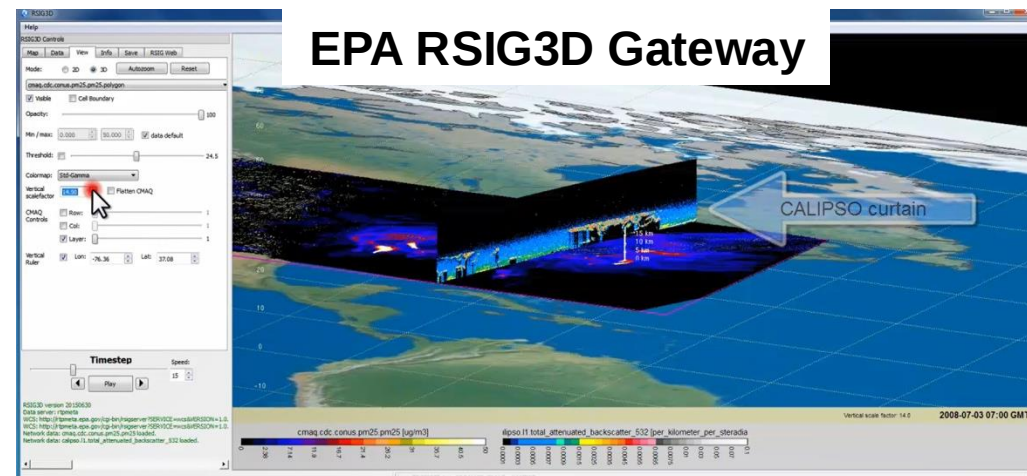
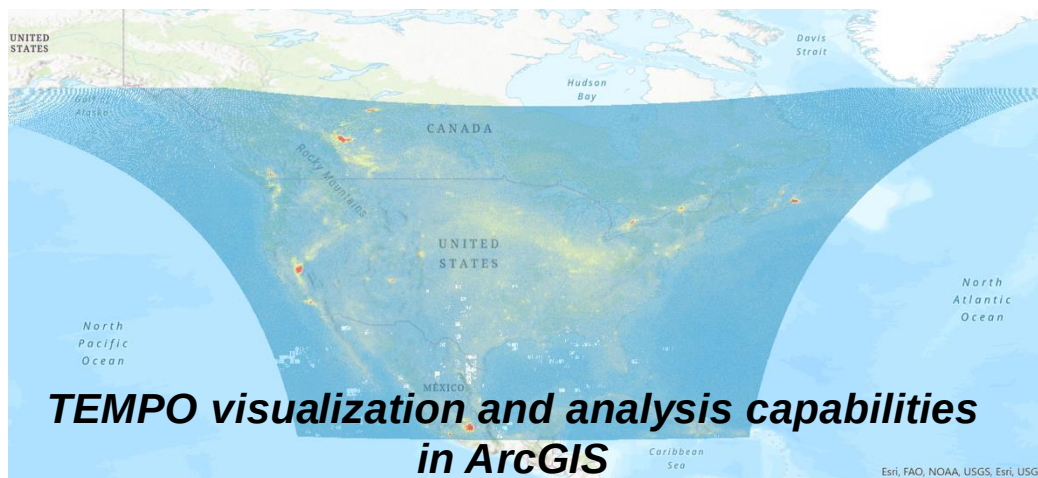
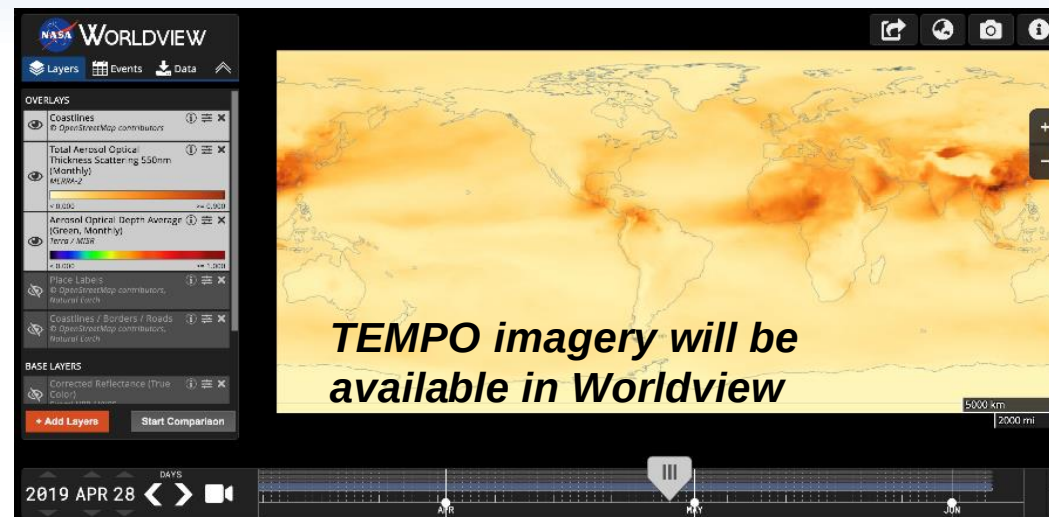
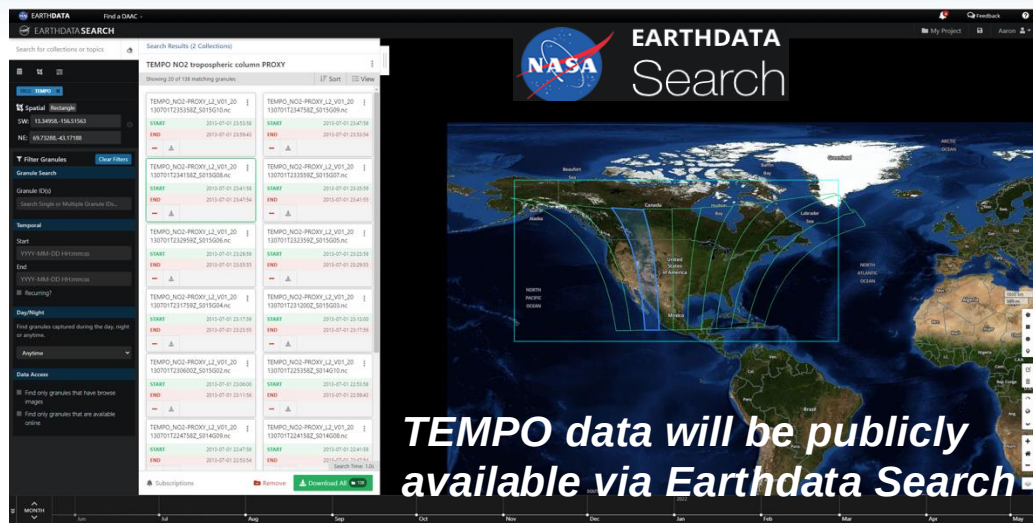
Level 3 product stitches together TEMPO Level 2 product granules for each scan



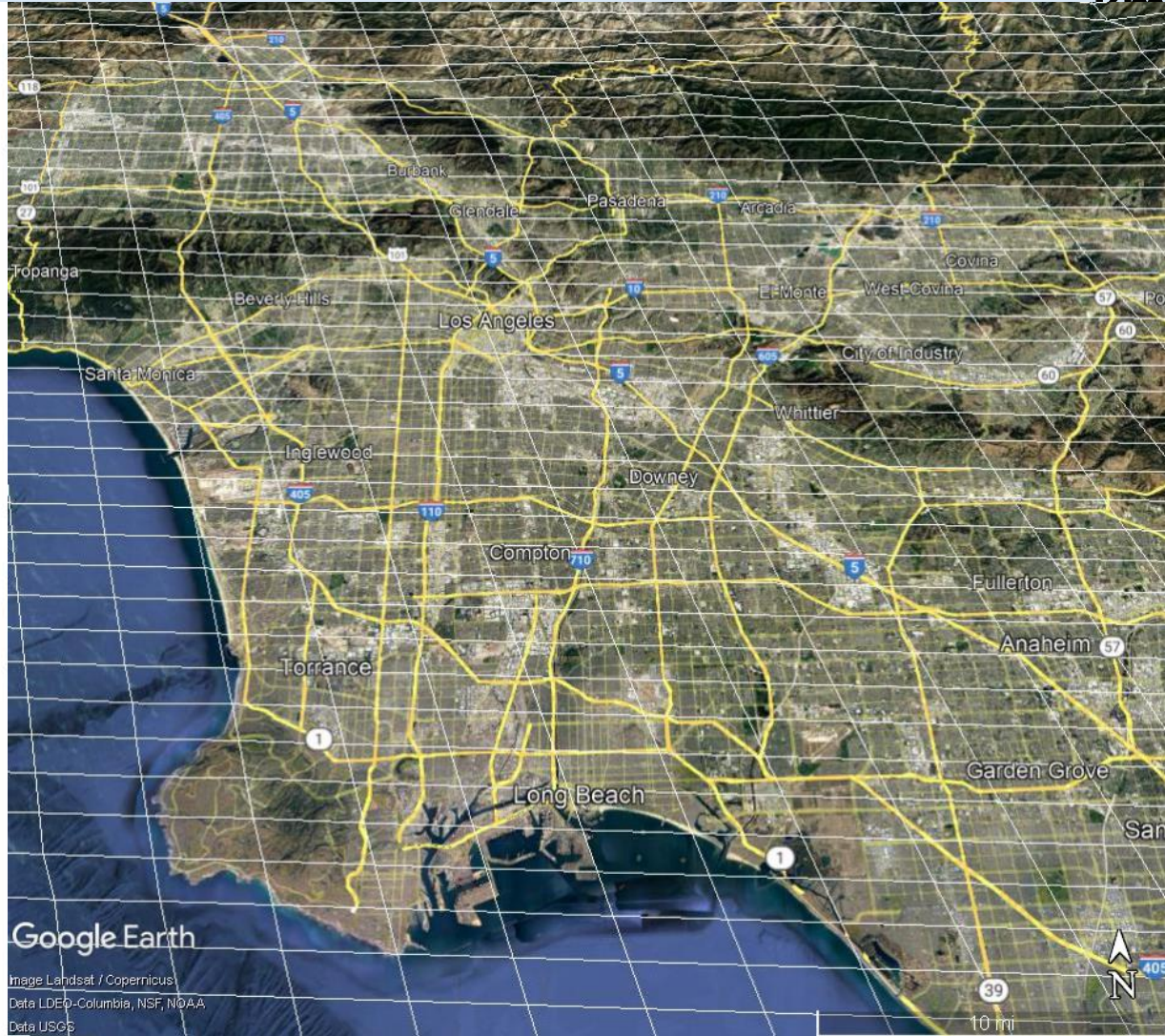
Data Distribution, Visualization, Analysis Tools



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



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!

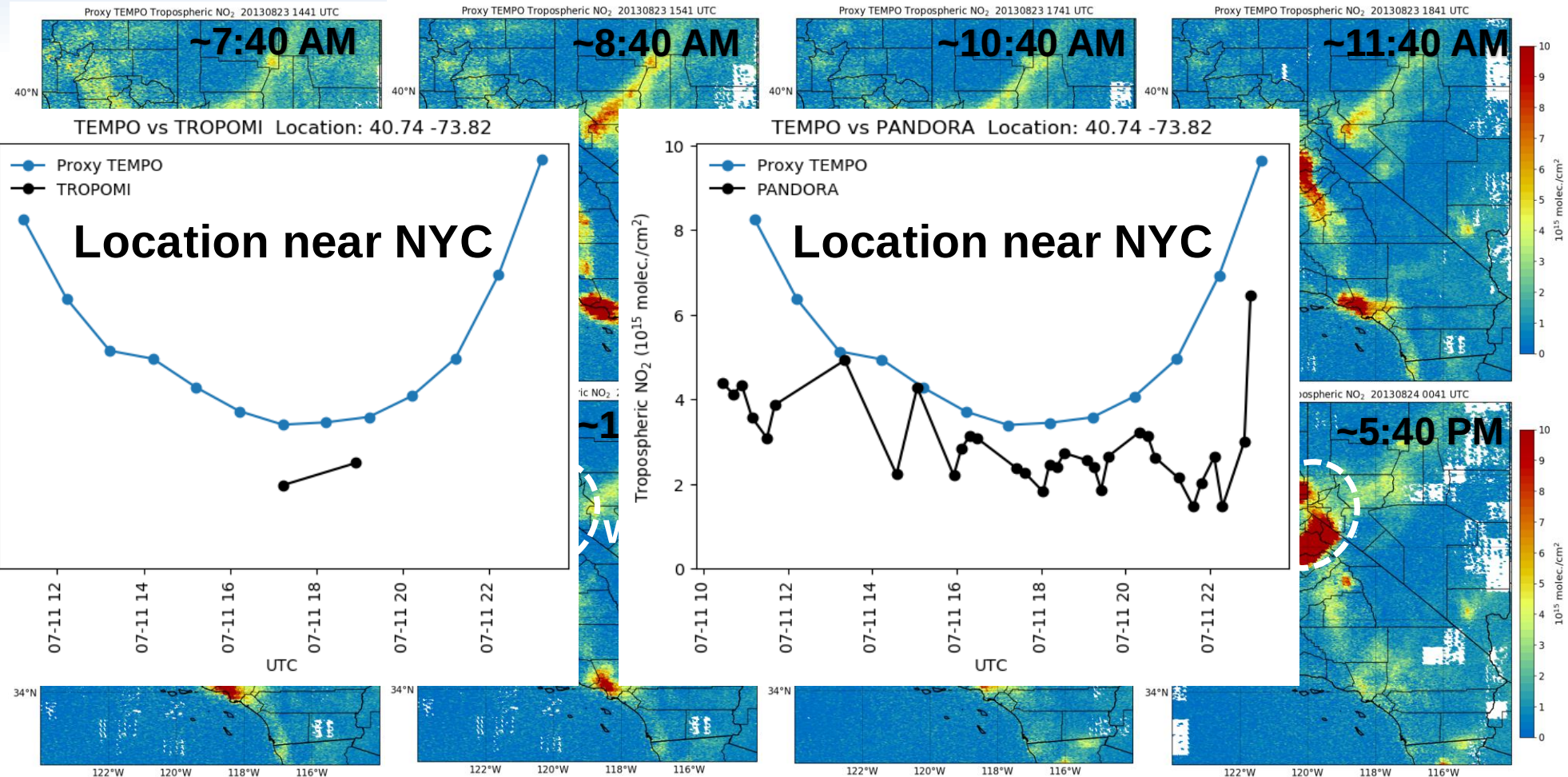
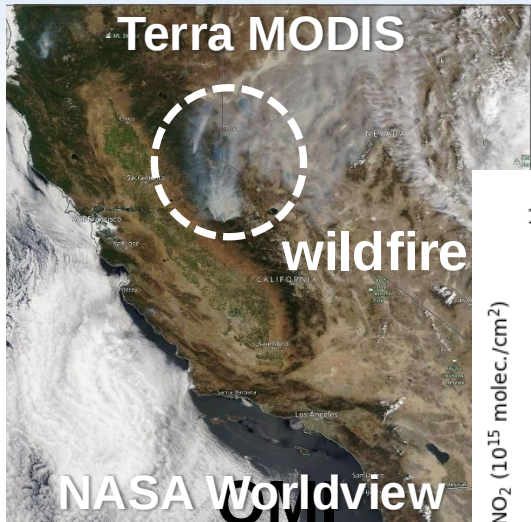


Aug. 23, 2013

Monitoring NO₂ in Different Sources



TEMPO Proxy Level 2 NO₂ data

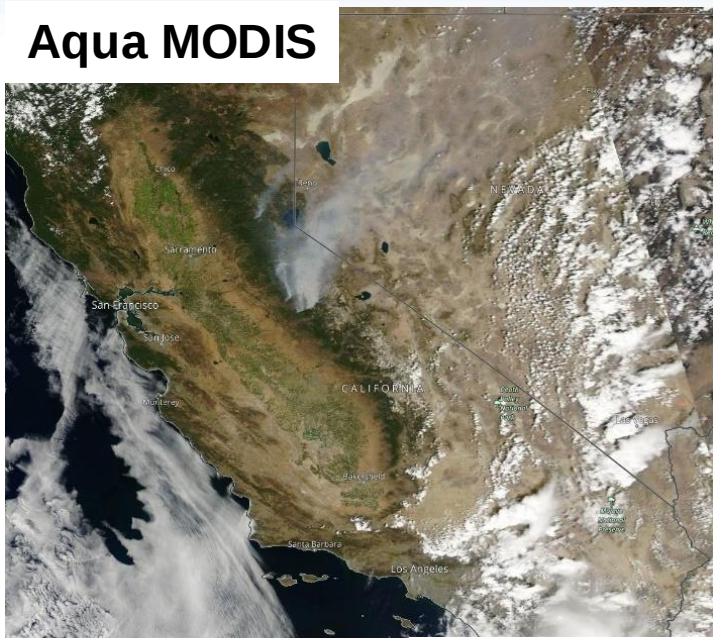


***Proxy data not intended to support operational decisions or scientific research studies**

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

Multi-Pollutant Observations from TEMPO

Aqua MODIS

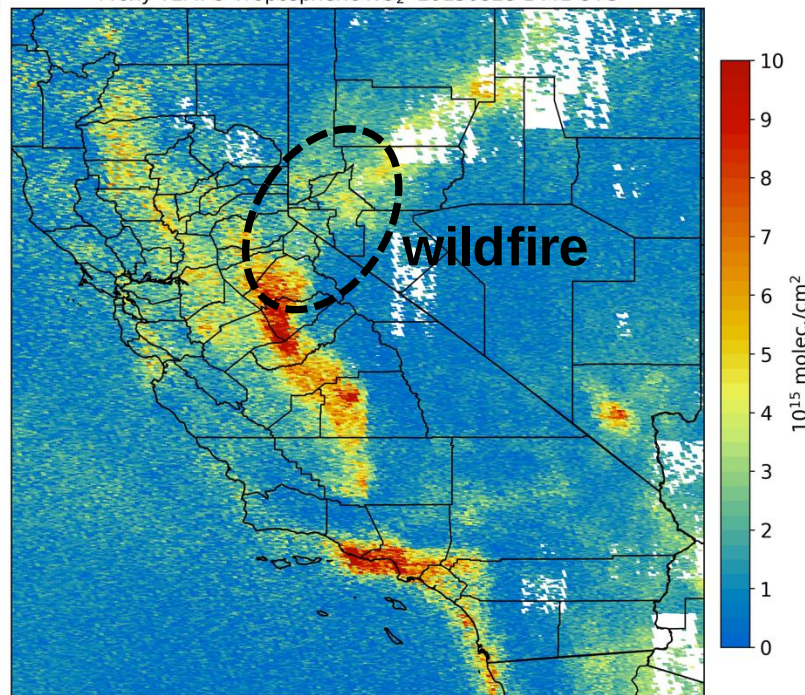


29 Aug. 2013

Worldview

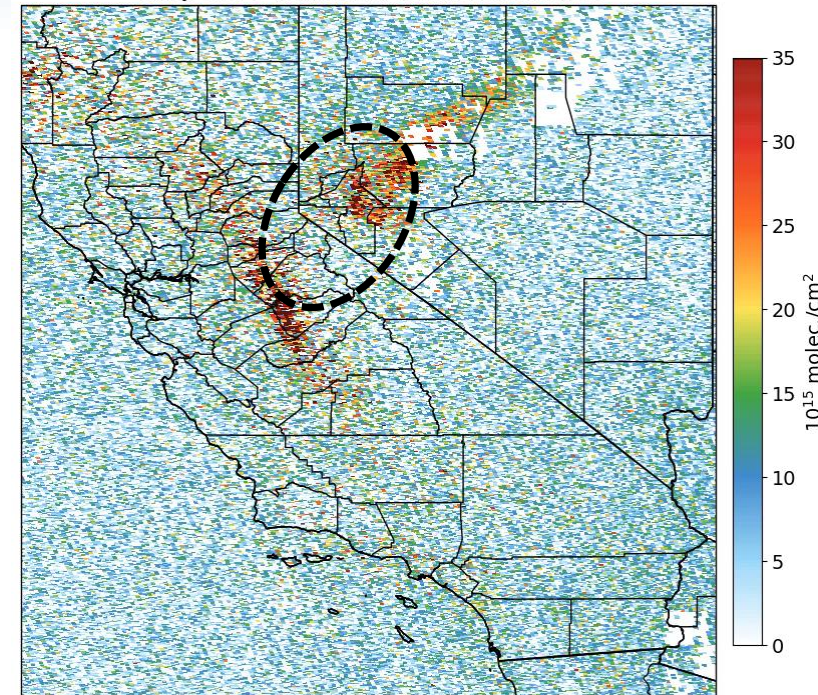
Tropospheric NO₂ VCD

Proxy TEMPO Tropospheric NO₂ 20130828 1441 UTC



Total HCHO VCD

Proxy TEMPO Total HCHO 20130828 1441 UTC



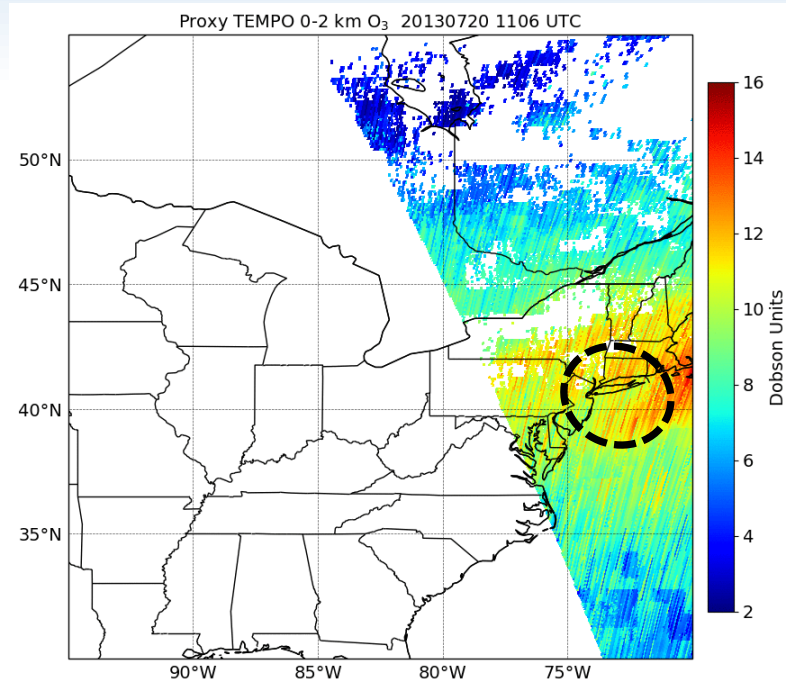
28 – 31 Aug. 2013

- ❑ Multi-pollutant information from TEMPO will help better diagnose emission sources and pollutant transport, **ultimately enhancing health studies**
- ❑ More frequent scans from TEMPO will help better diagnose ozone sensitivity to precursors using HCHO/NO₂ ratios

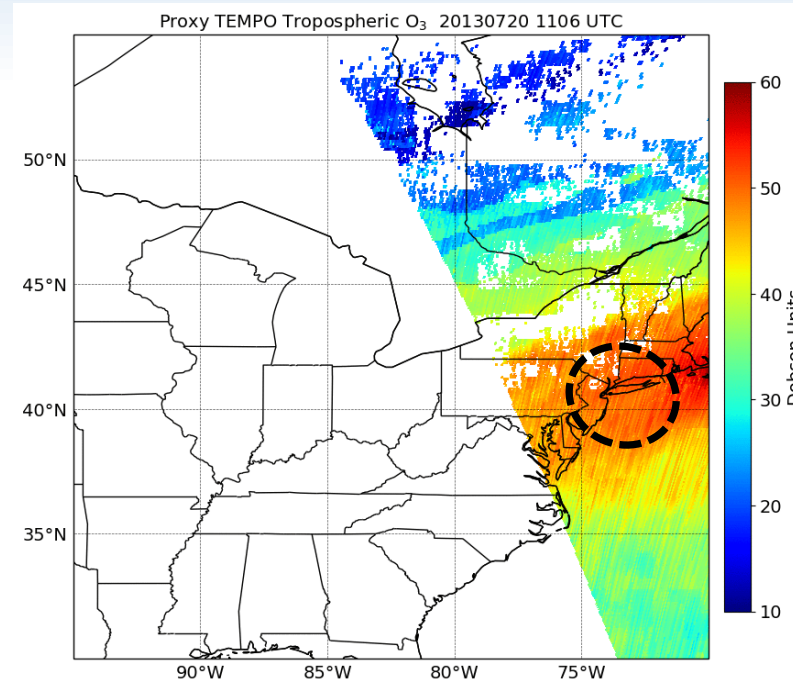
***Proxy data not intended to support operational decisions or scientific research studies**

Monitoring Tropospheric Ozone Pollution

0-2 km (PBL) O₃

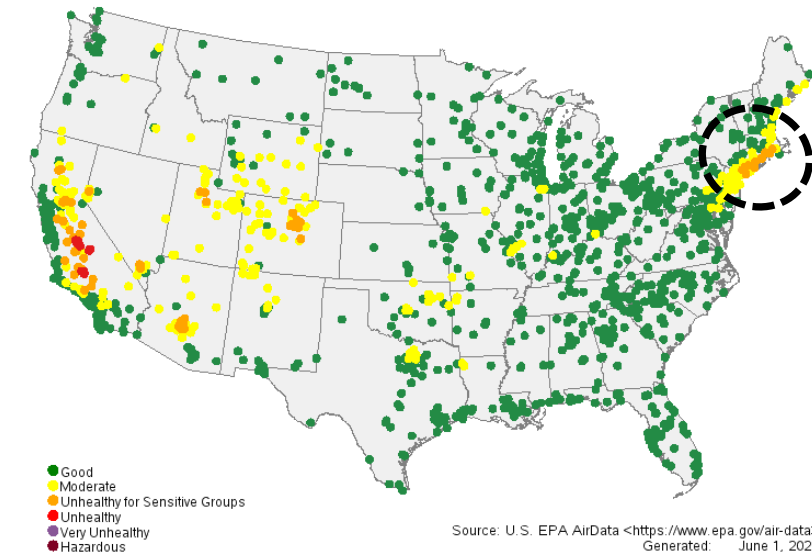


Tropospheric O₃



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
- ❑ 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 Early Adopters, Special Operations, & Stakeholder Experiments



TEMPO Early Adopters (EA) Program



Objective 1

Engage a broad spectrum of stakeholders & end users to characterize needs and expand use of TEMPO data

Objective 2

Use current sensors and proxy data to demonstrate capabilities and prepare applications of TEMPO data

Objective 3

Align the TEMPO observing time, products, and data interfaces to user needs and applications



Join EA Program

Prepare users for operational TEMPO data

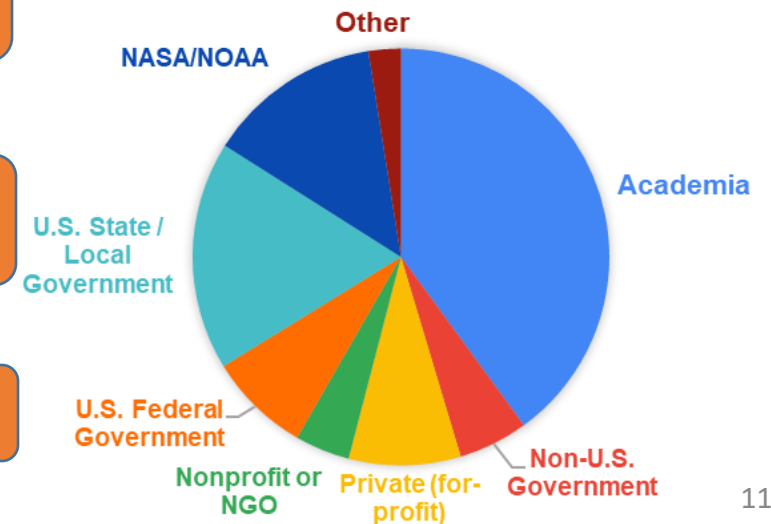
Enhance and accelerate applications of TEMPO data

Maximize the value of TEMPO data for societal benefit

Extend TEMPO mission lifetime

> 500 EAs (as of Sept. 2023)

EARLY ADOPTERS BY AFFILIATION



EAs are individuals or groups who:

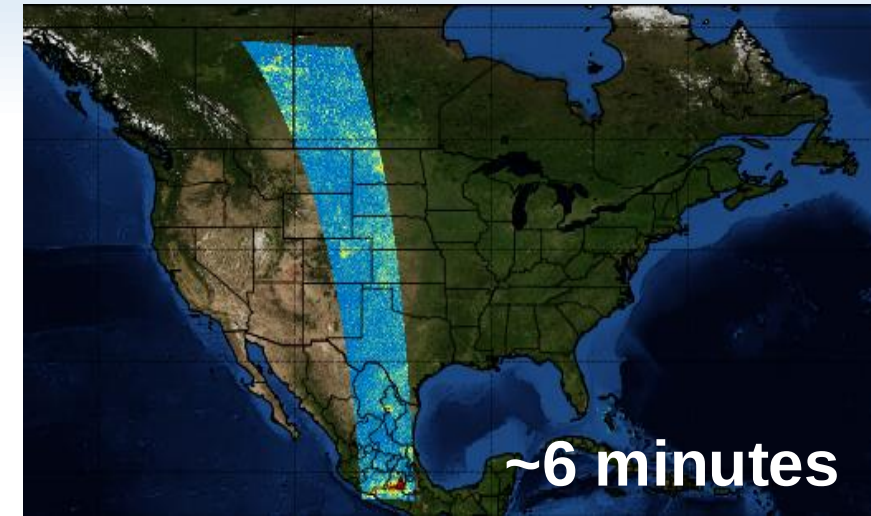
- ☐ Have an interest or need for using TEMPO data
- ☐ Have an existing or new application for TEMPO data
- ☐ Work with end-users and understand their decision-making process



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 AQ Management ***

**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

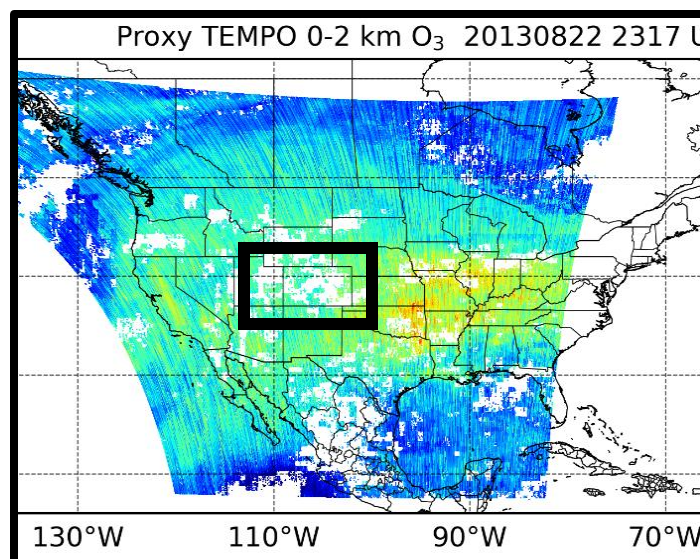
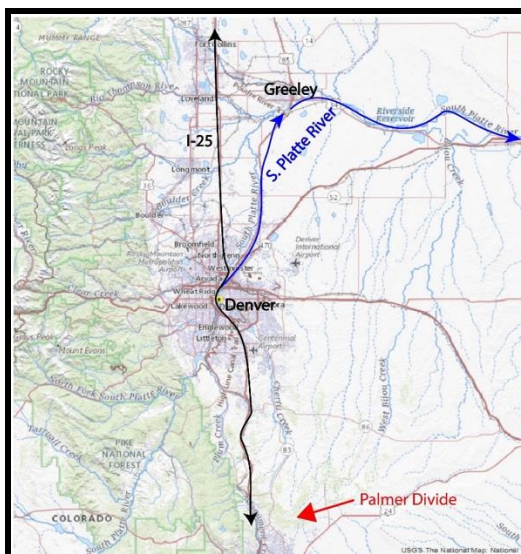
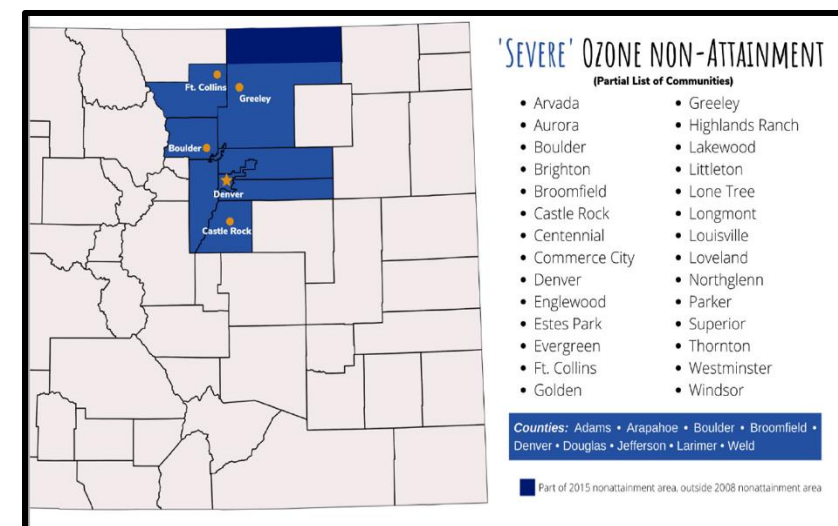
- Contributing factors to O₃ nonattainment area include urban sources, traffic emissions, O&G operations, topography
- Population density in CO is highest along Front Range
- CDPHE aims to use TEMPO data to monitor the evolution of O₃ precursors and O₃ accumulation along Front Range

❑ **Goal:** Use TEMPO data for better documentation of these processes and greater understanding of air pollution episodes

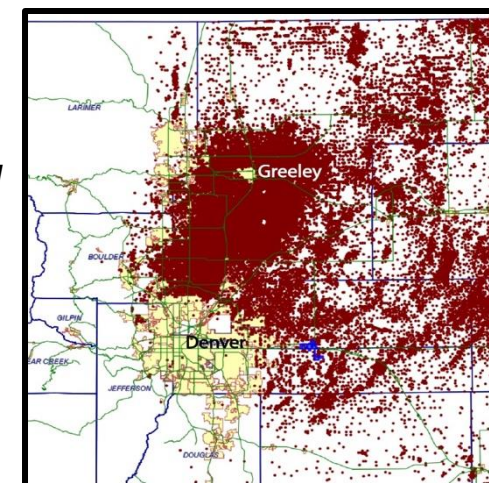
Investigators: Dan Welsh, Katie Broyles, Scott Landes



COLORADO
Department of Public Health & Environment



Location of oil & gas wells (red dots)



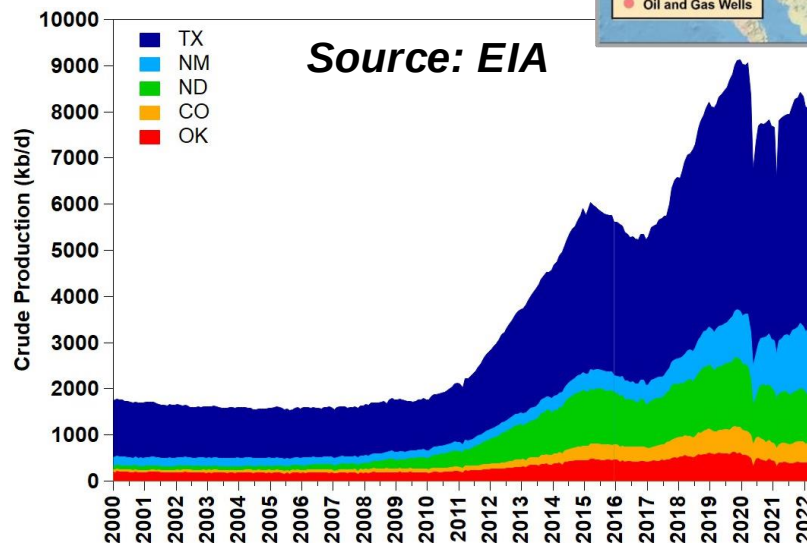
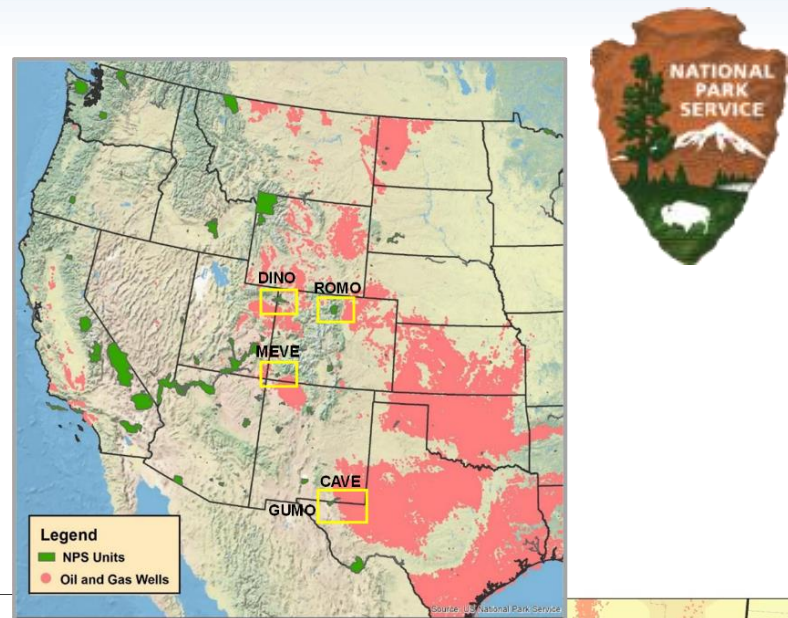


Air Quality Impacts from O&G in the Western U.S.



- ❑ **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



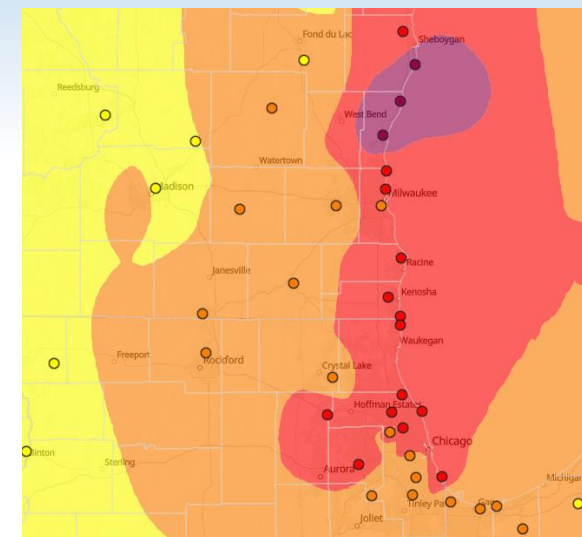
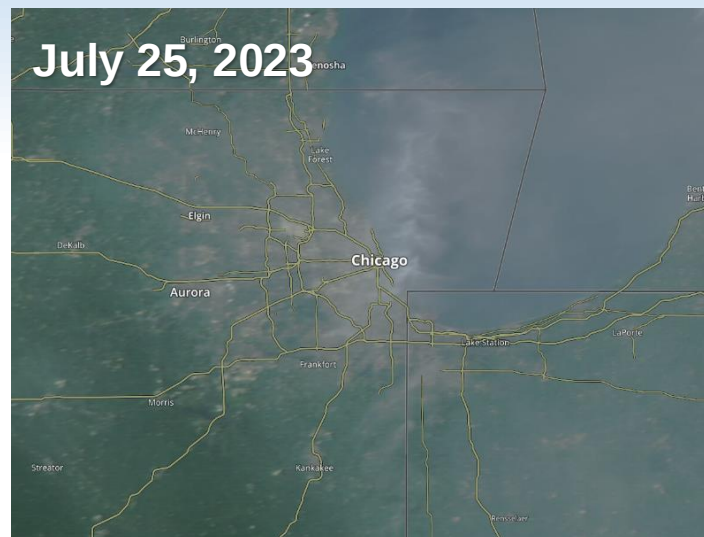
TEMPO Field Campaigns & Initial Results



Synergistic TEMPO Air Quality Science Mission



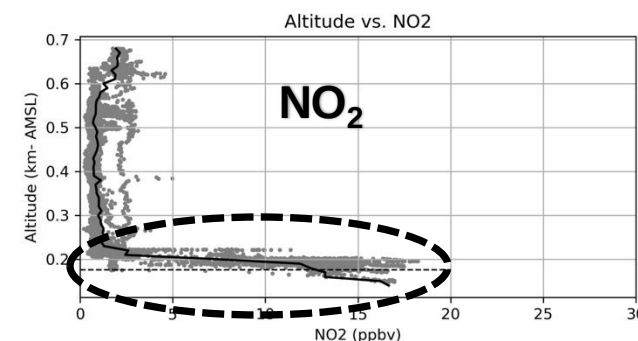
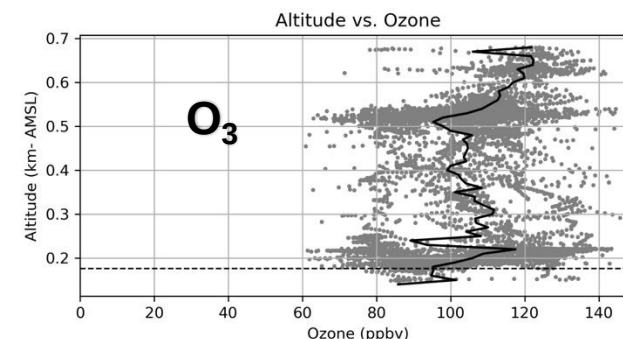
- ❑ Severe smoke event from Canadian wildfires impacted Chicago area on July 25, 2023 during STAQS campaign
- ❑ Searey aircraft flew through the smoke and observed enhanced NO_2 and O_3 concentrations
- ❑ **Huge spike in NO_2 within 100 meters of lake surface**



Searey Data, NO_2 (ppbv) - 2023-07-25 17:33:45 to 2023-07-25 20:24:26



Searey Data, Ozone (ppbv) - 2023-07-25 17:33:45 to 2023-07-25 20:24:26

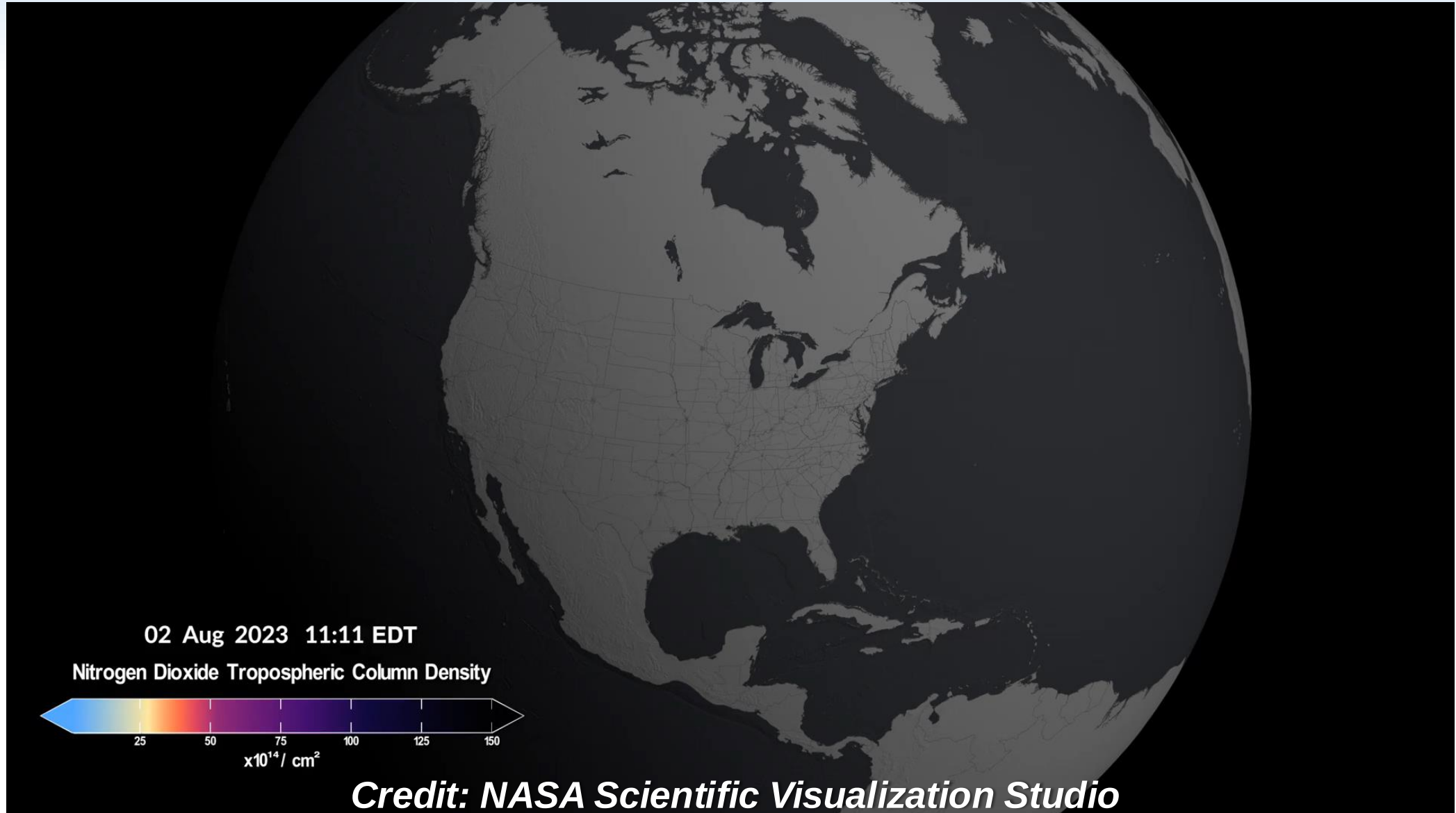


Searey data Courtesy of Mike Newchurch (UAH)



TEMPO First Light on Aug 2, 2023

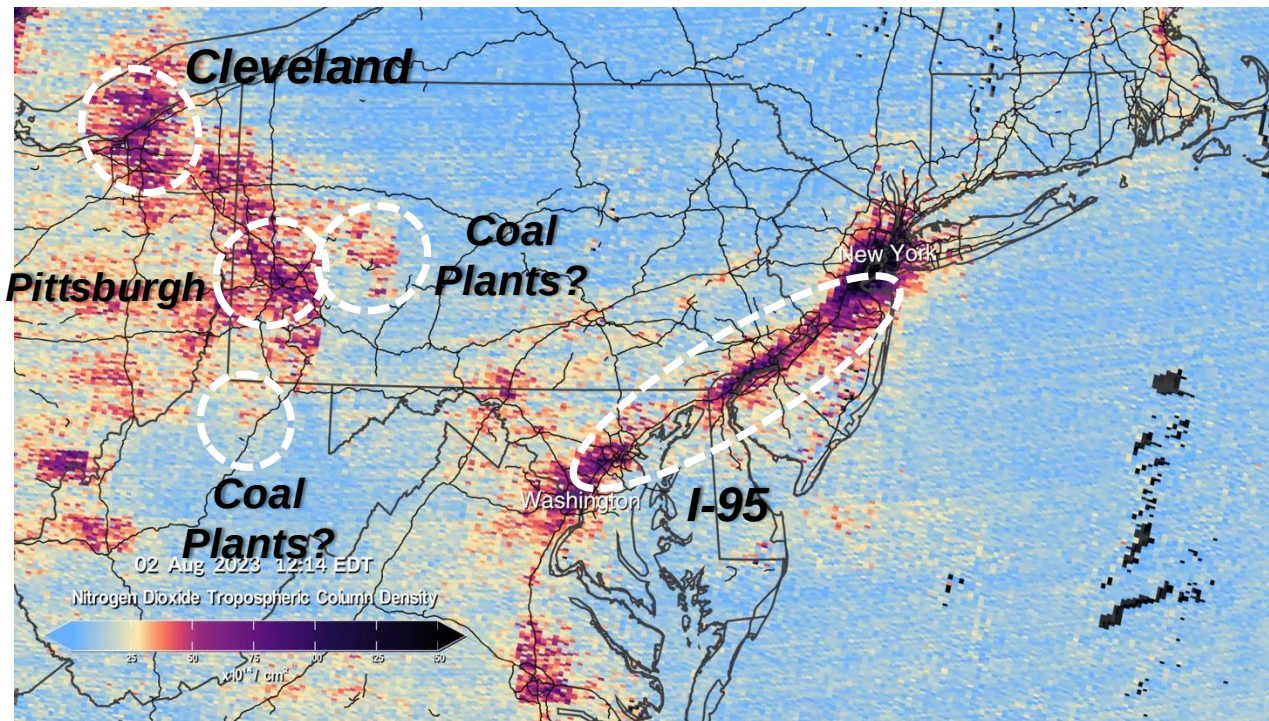
TEMPO performed six daytime hourly scans across the Field of Regard



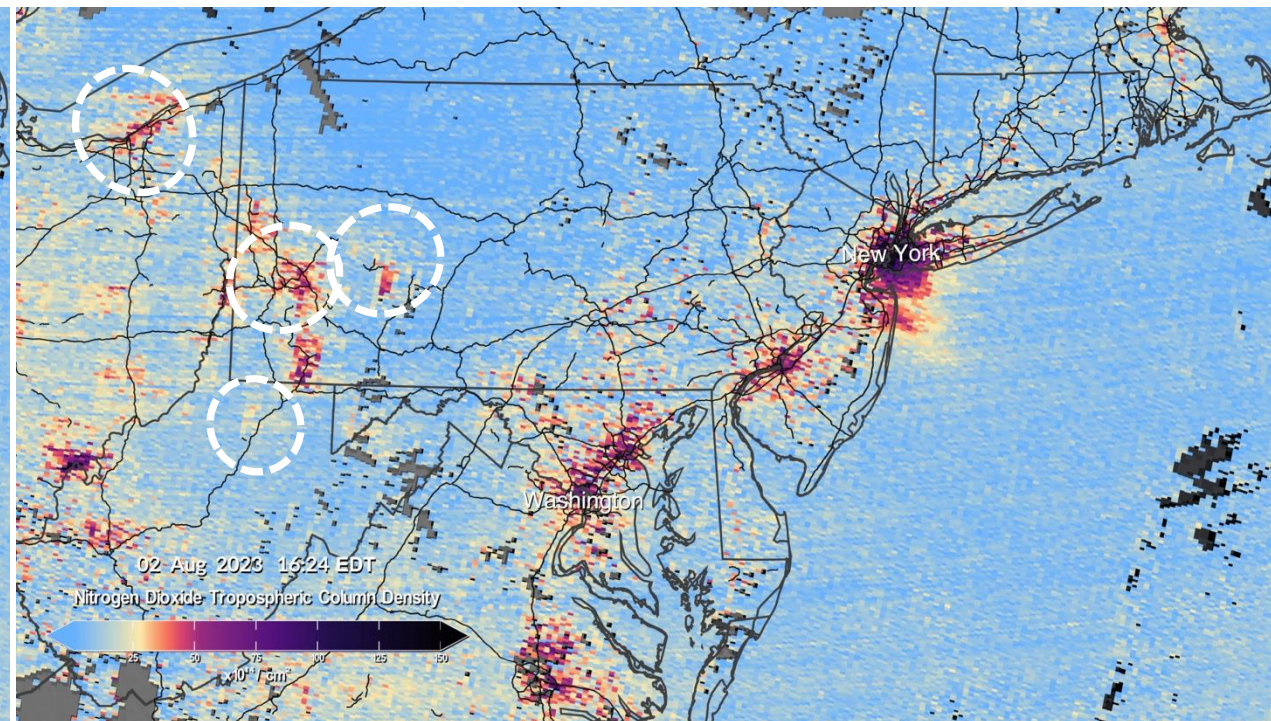
TEMPO First Light on Aug 2, 2023

Nitrogen Dioxide Tropospheric Columns

12:14 PM



4:24 PM

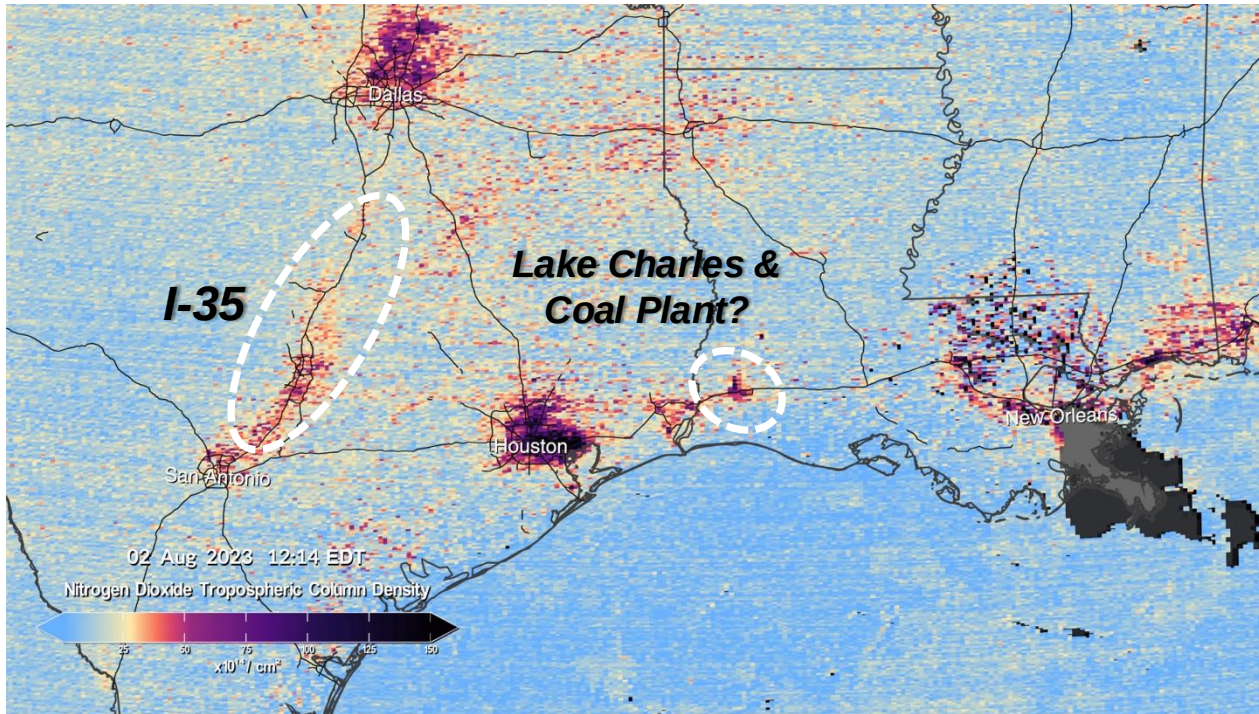


Credit: NASA Scientific Visualization Studio

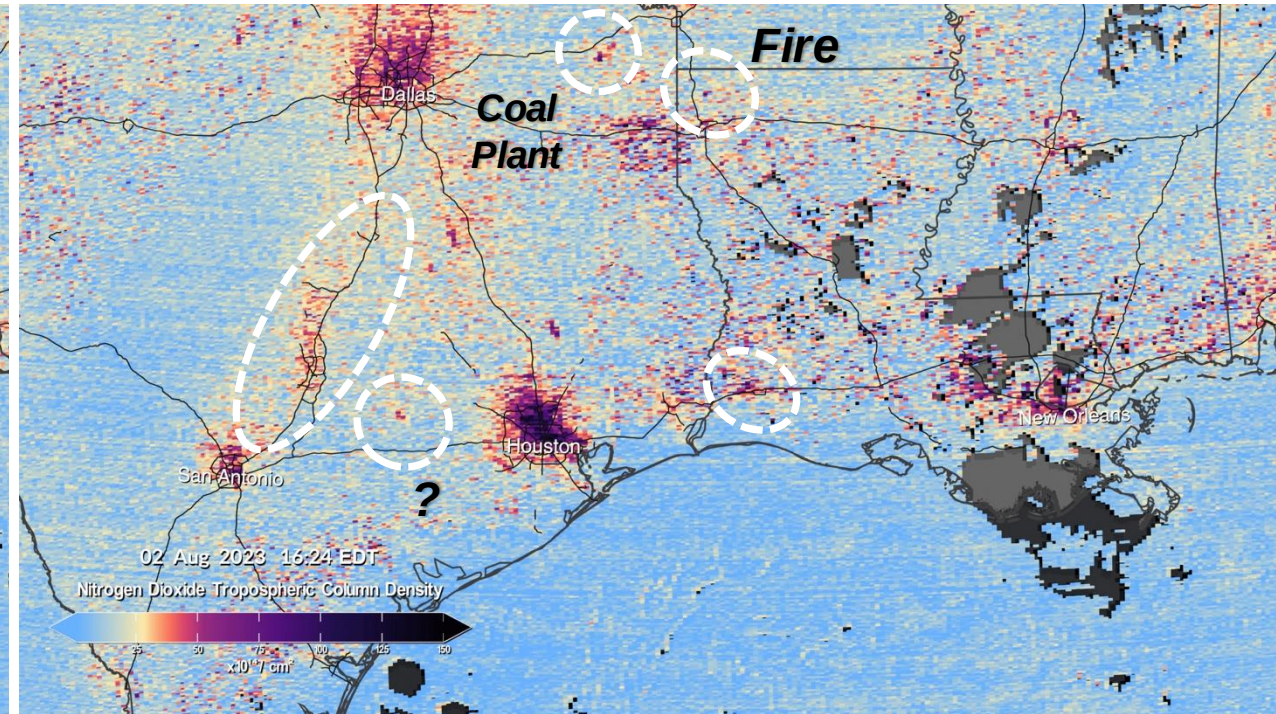
TEMPO First Light on Aug 2, 2023

Nitrogen Dioxide Tropospheric Columns

11:14 AM



3:24 PM



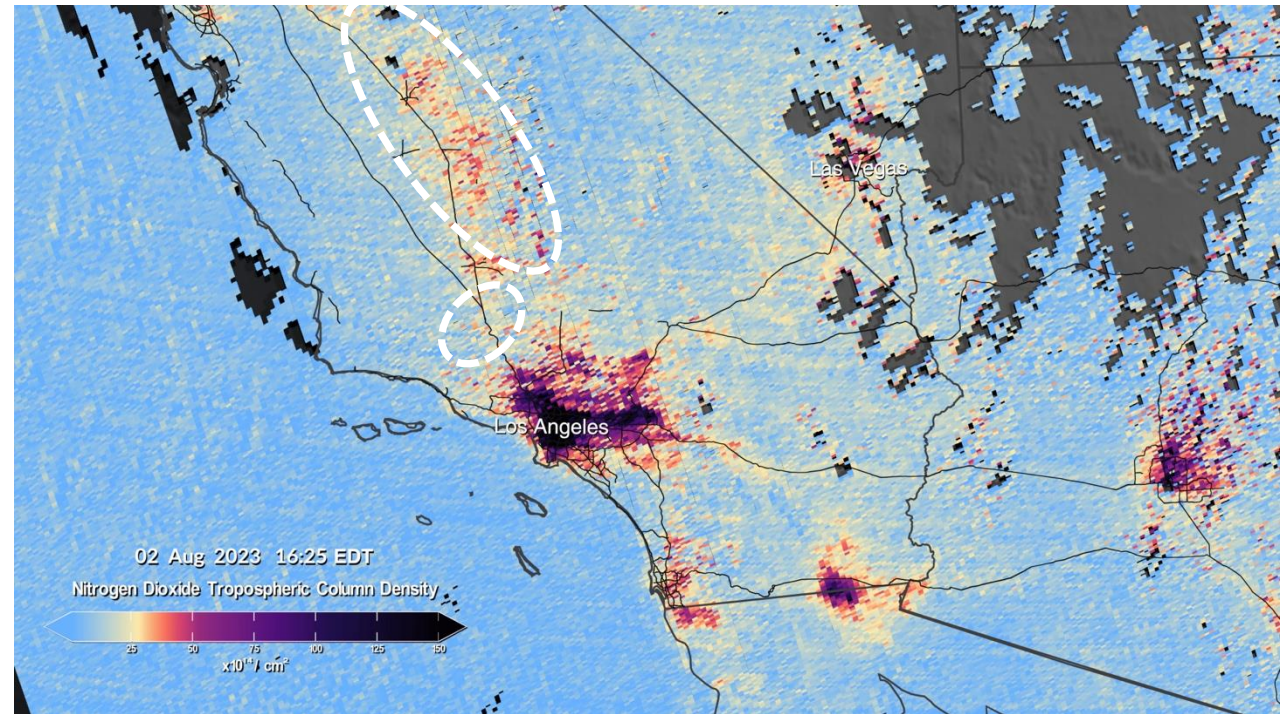
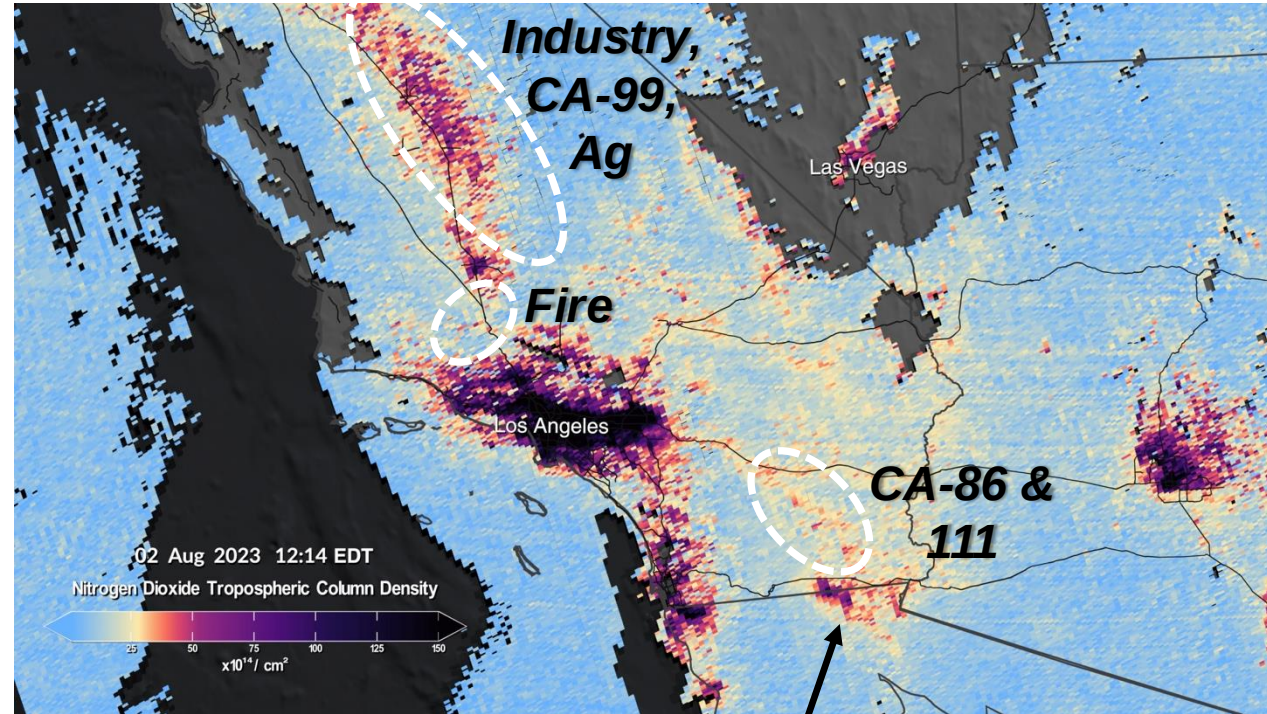
Credit: NASA Scientific Visualization Studio

TEMPO First Light on Aug 2, 2023

Nitrogen Dioxide Tropospheric Columns

9:14 AM

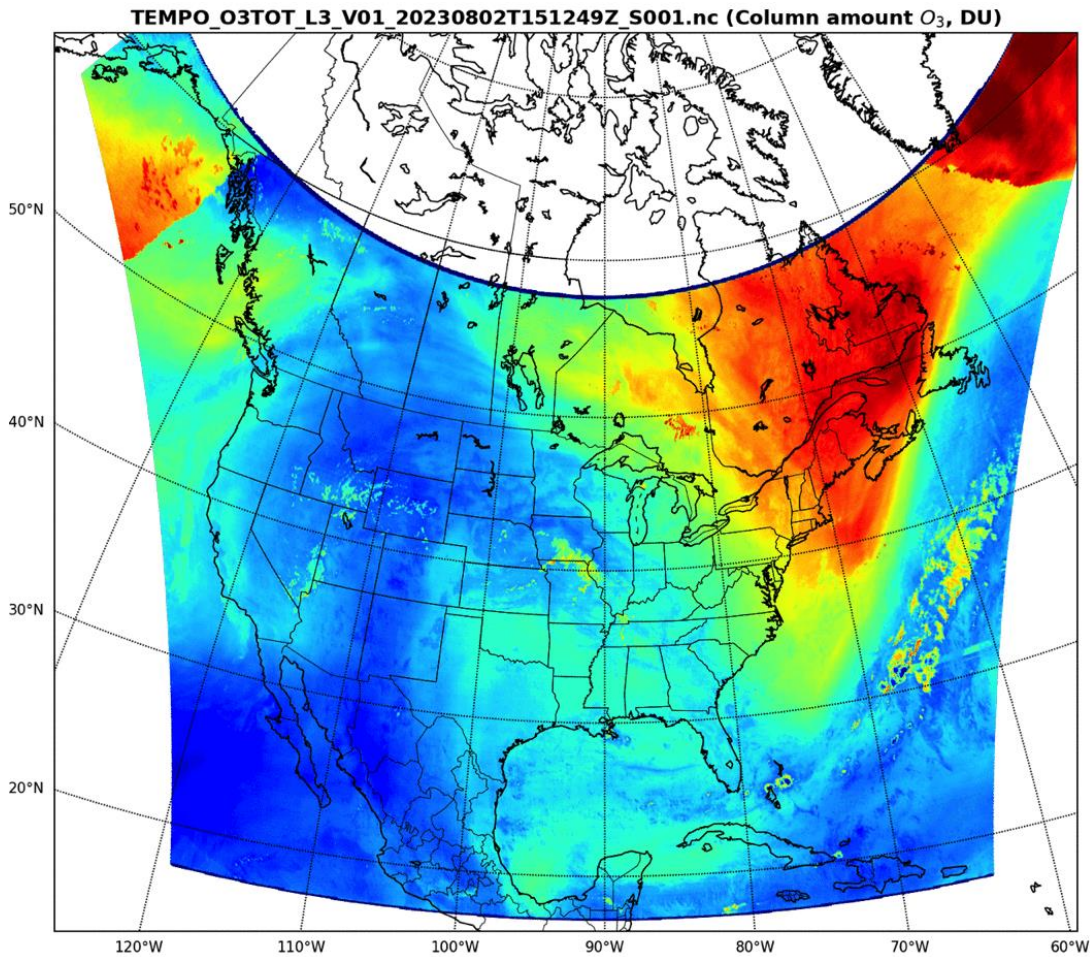
1:25 PM



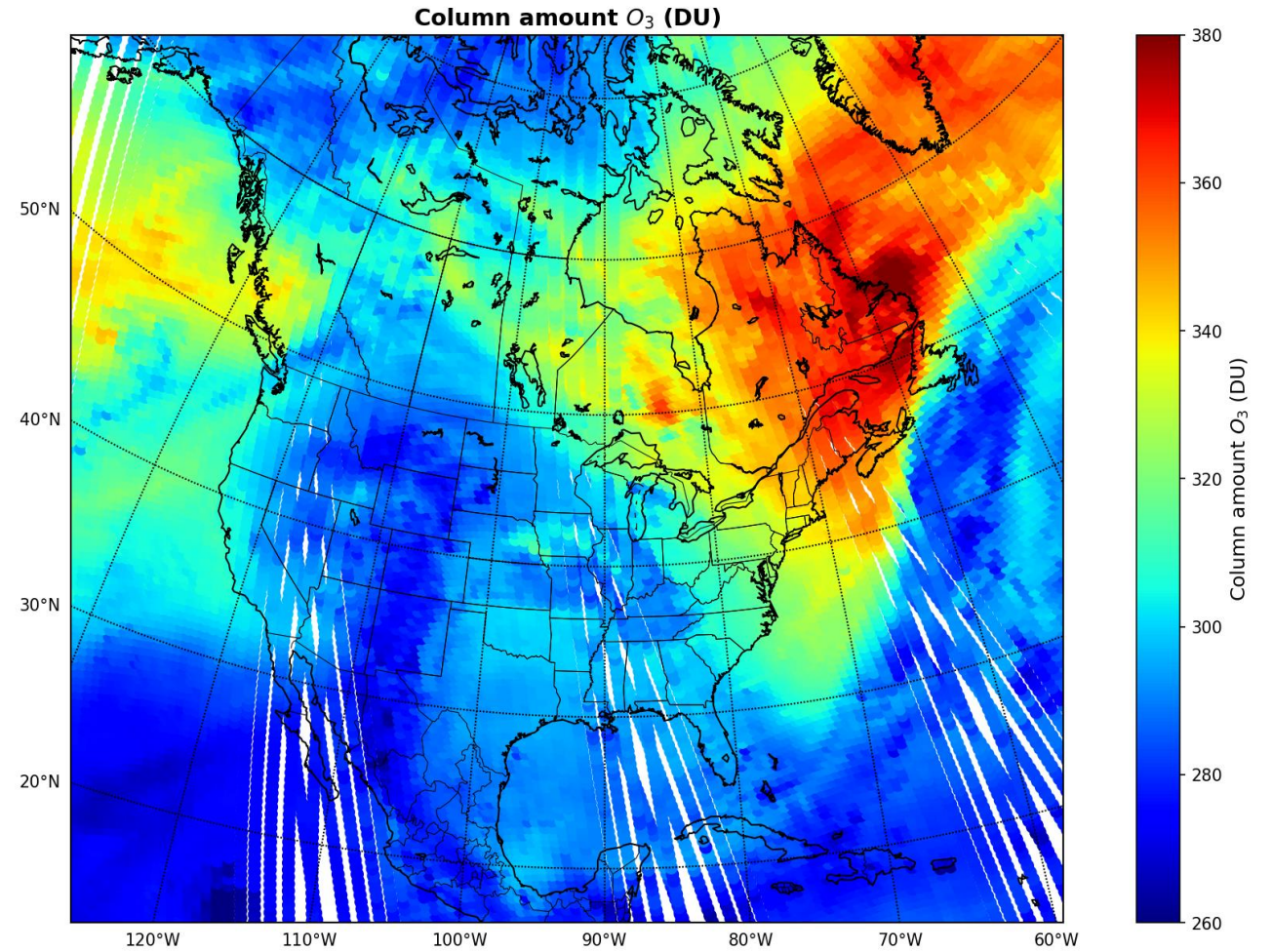
Mexicali Factories

Credit: NASA Scientific Visualization Studio

Total Ozone: First Results Aug 2, 2023



TEMPO



OMPS

Data Courtesy of Xiong Liu (SAO)

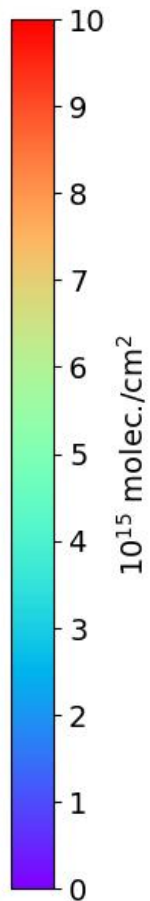
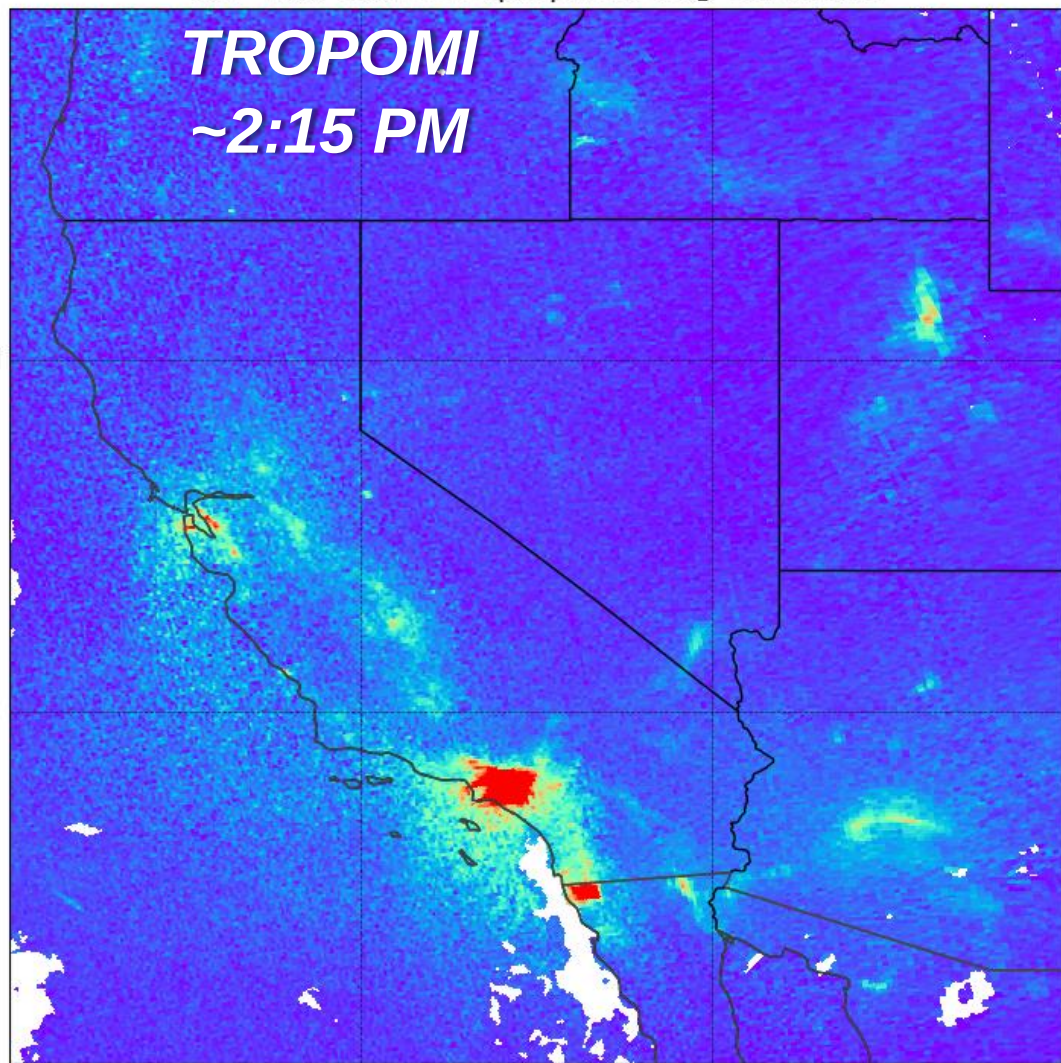


TEMPO Commissioning Phase Oct 6, 2023

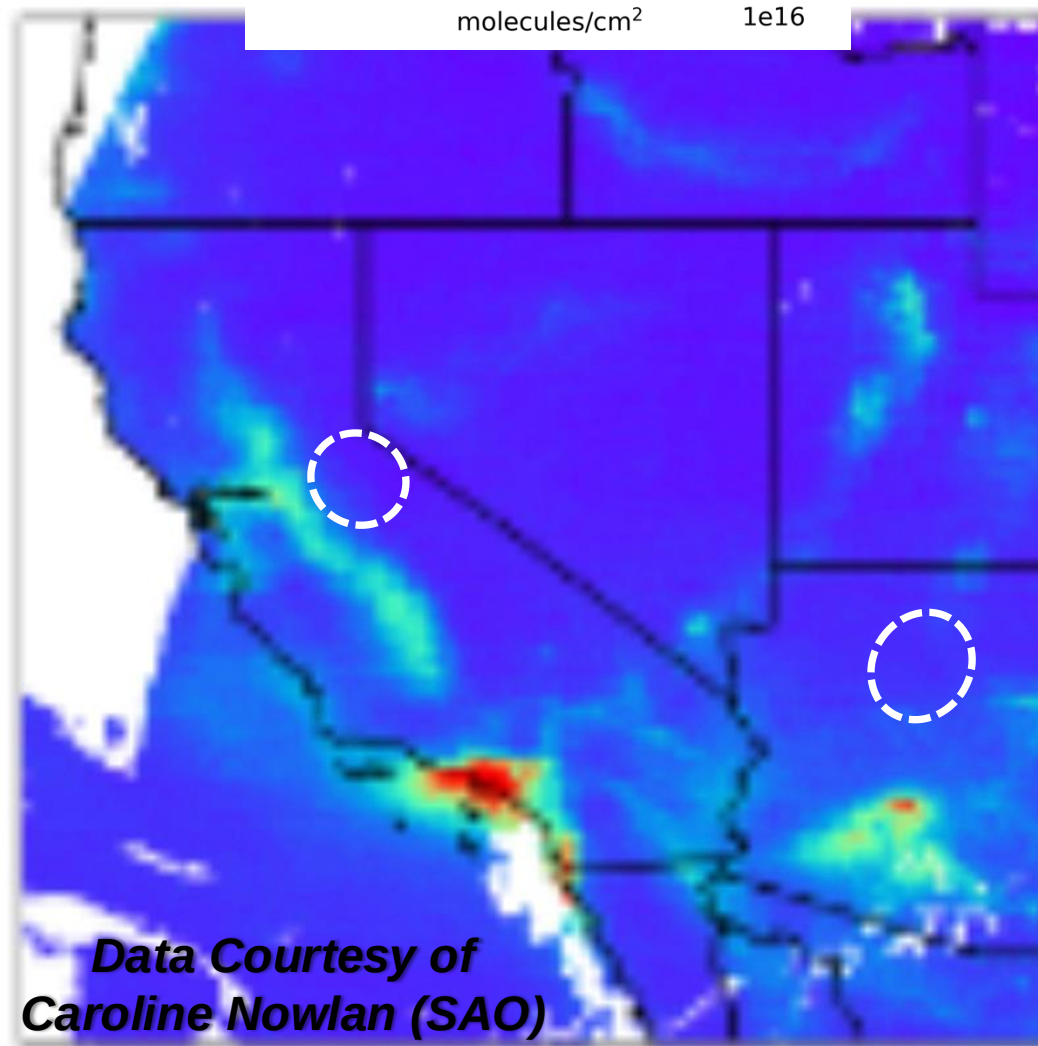
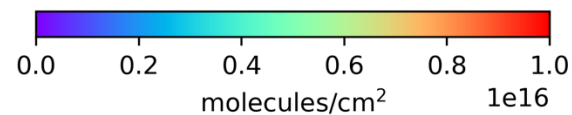


S5P TROPOMI L3 Tropospheric NO₂ 20231006

TROPOMI
~2:15 PM



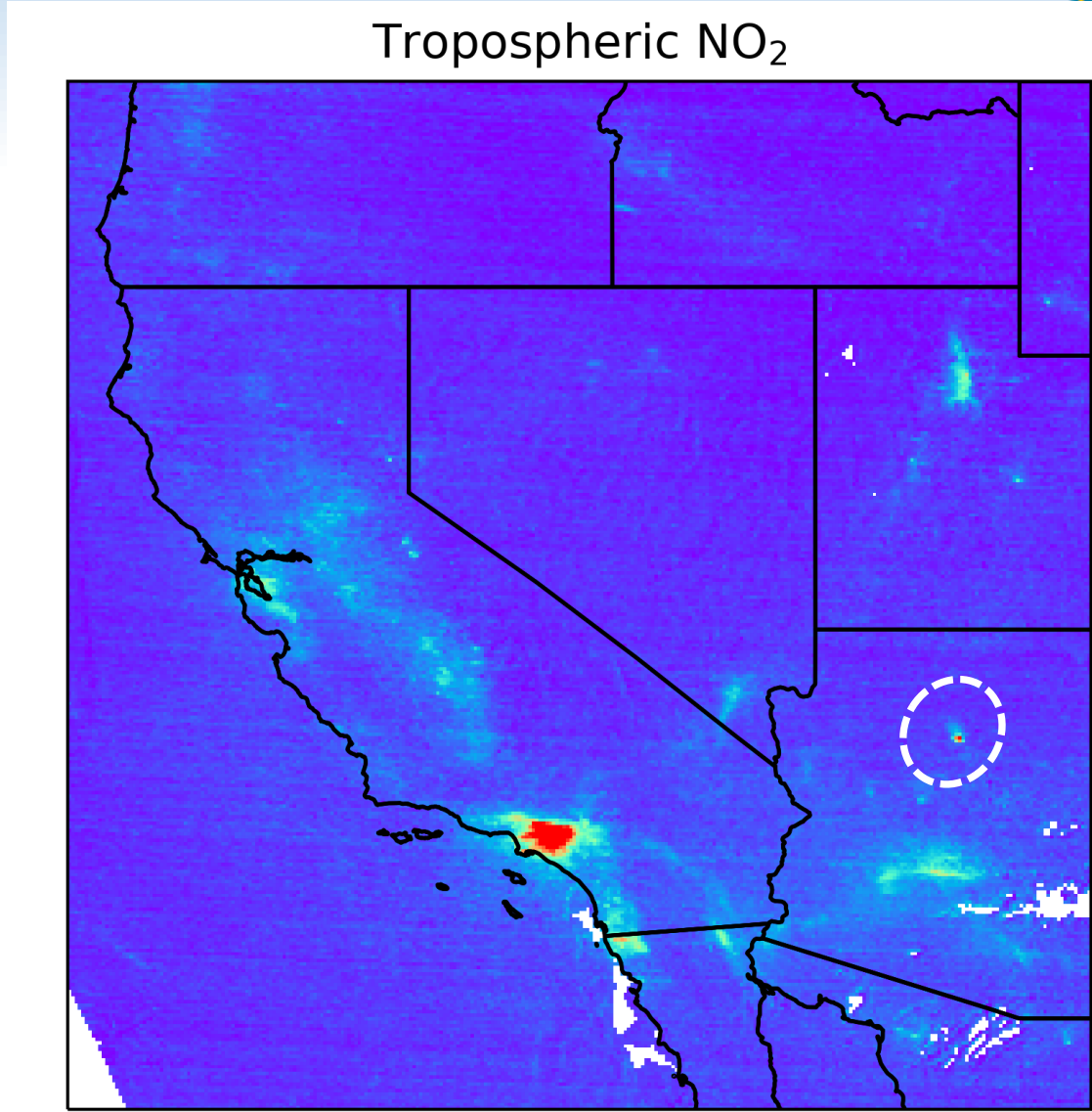
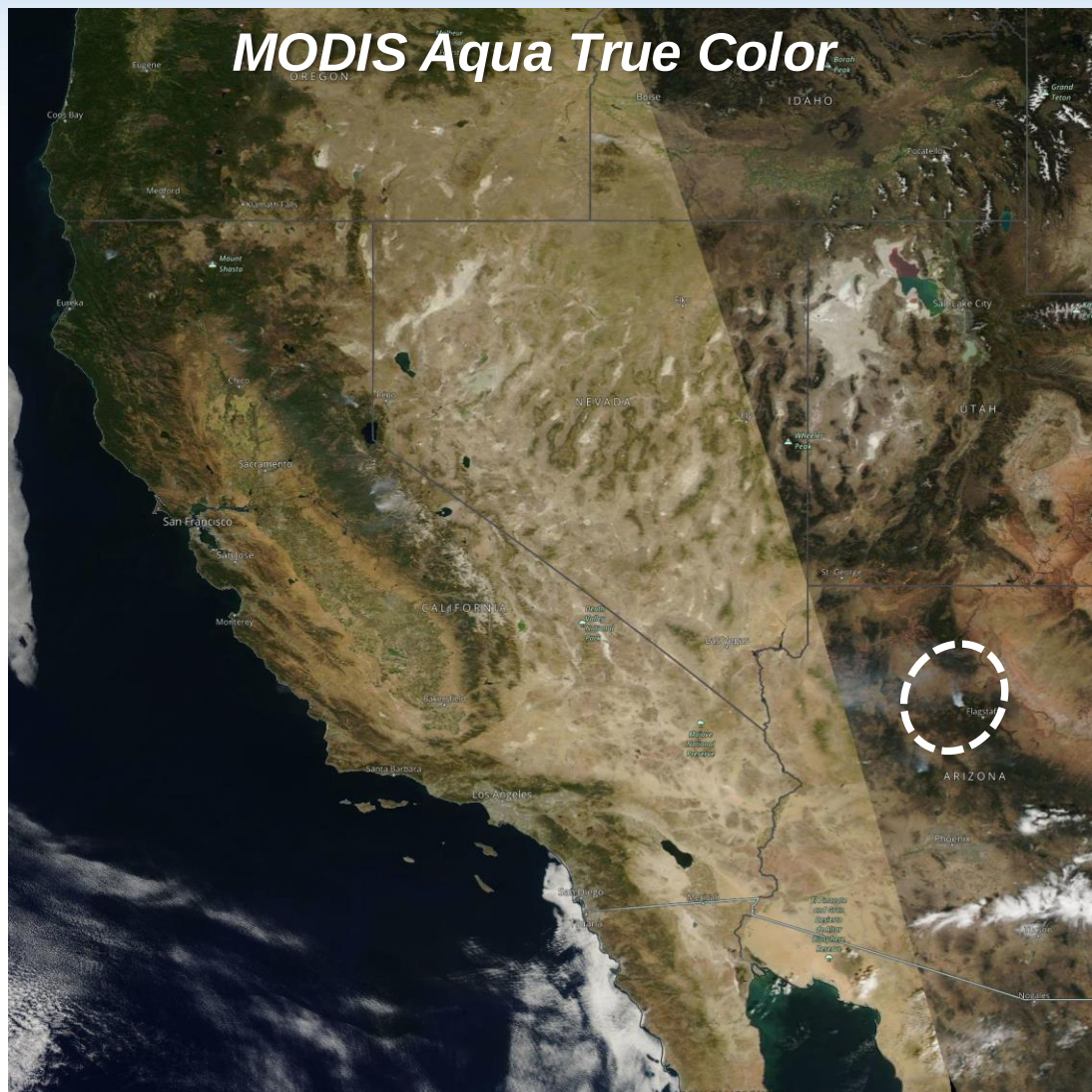
TEMPO_NO2_L3_V01_20231006T1356422_5006



Data Courtesy of
Caroline Nowlan (SAO)



TEMPO Commissioning Phase Oct 6, 2023



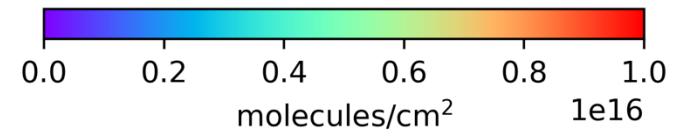
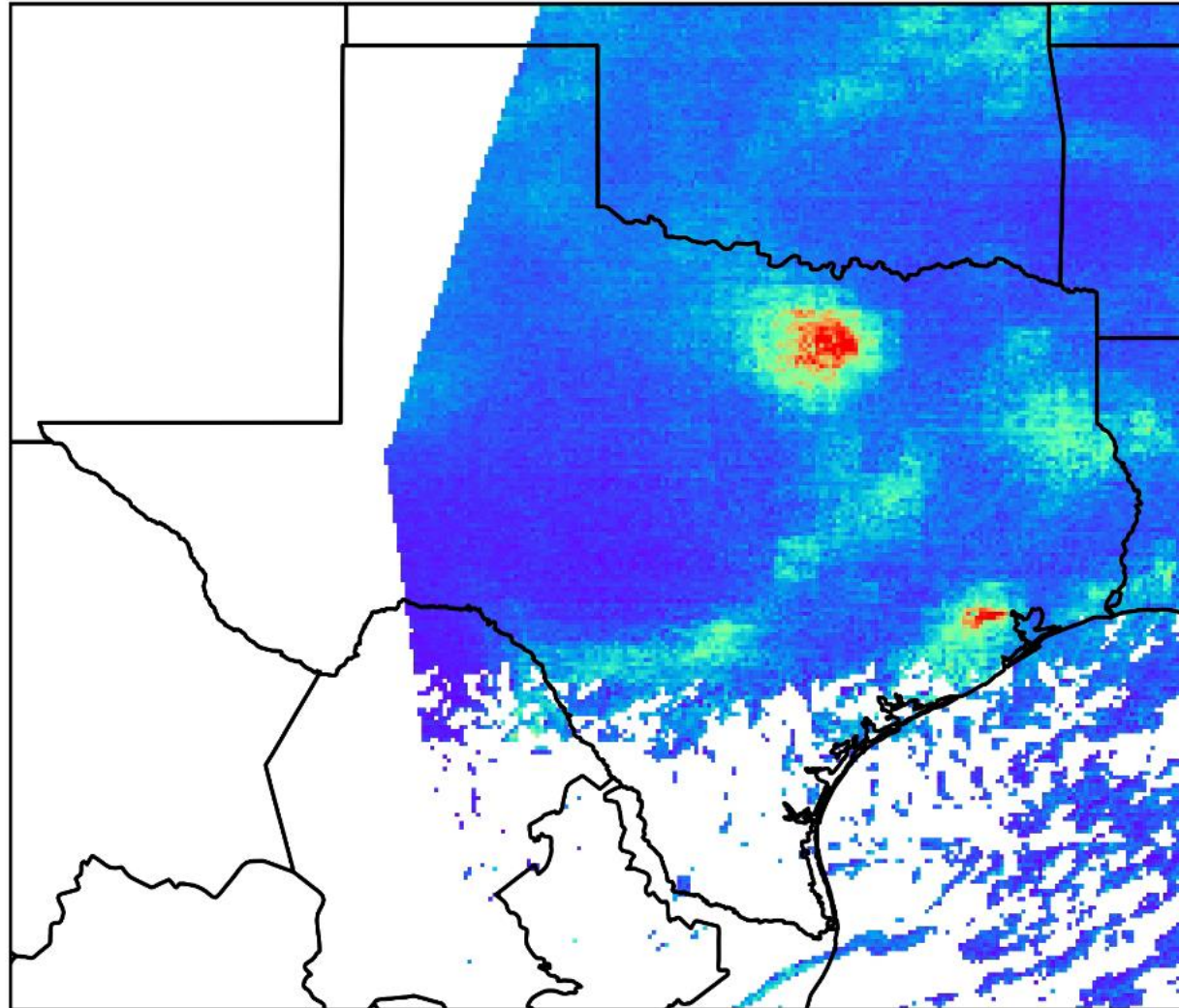


TEMPO Commissioning Phase Oct 8, 2023



TEMPO_NO2_L3_V01_20231008T123558Z_S004

Tropospheric NO₂



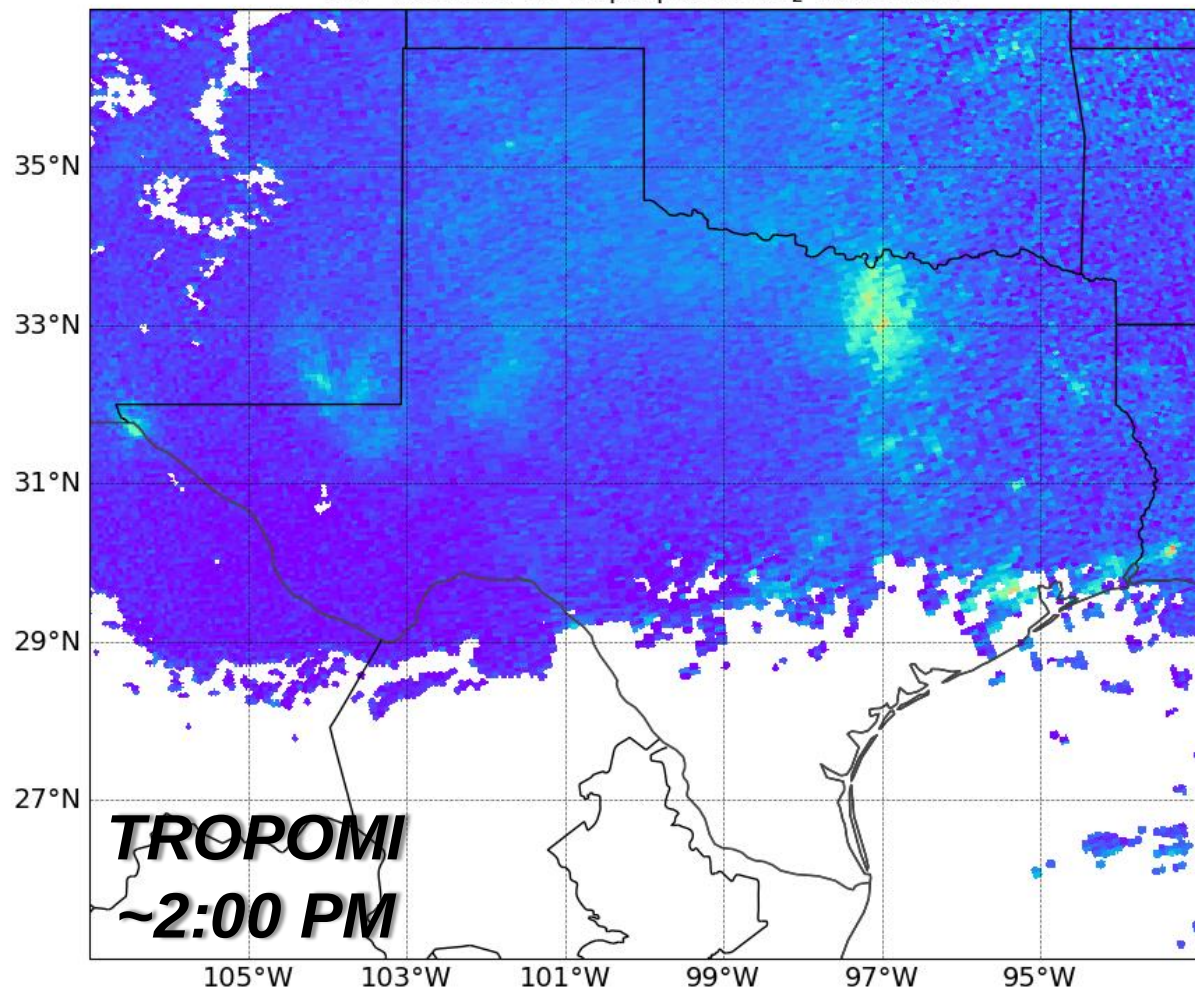


TEMPO Commissioning Phase Oct 8, 2023

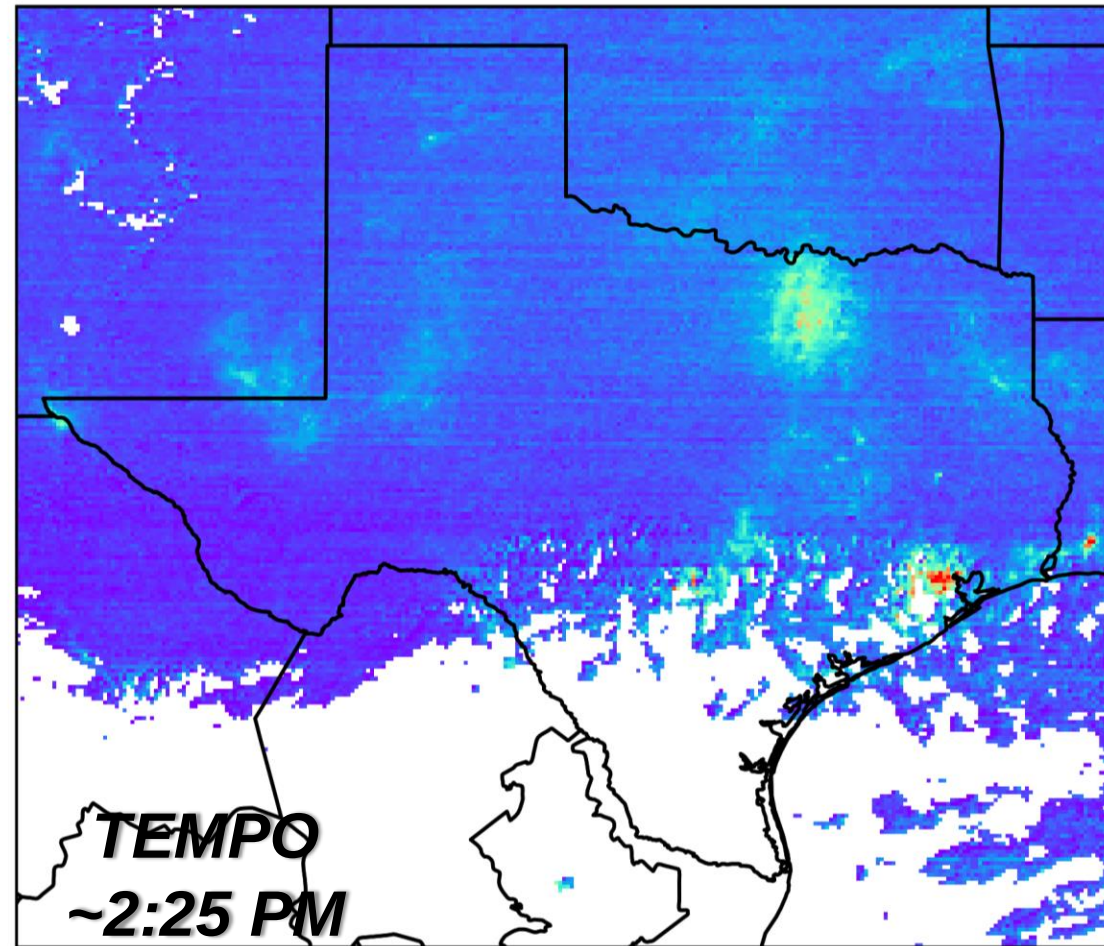


in

S5P TROPOMI L3 Tropospheric NO₂ 20231008



Tropospheric NO₂





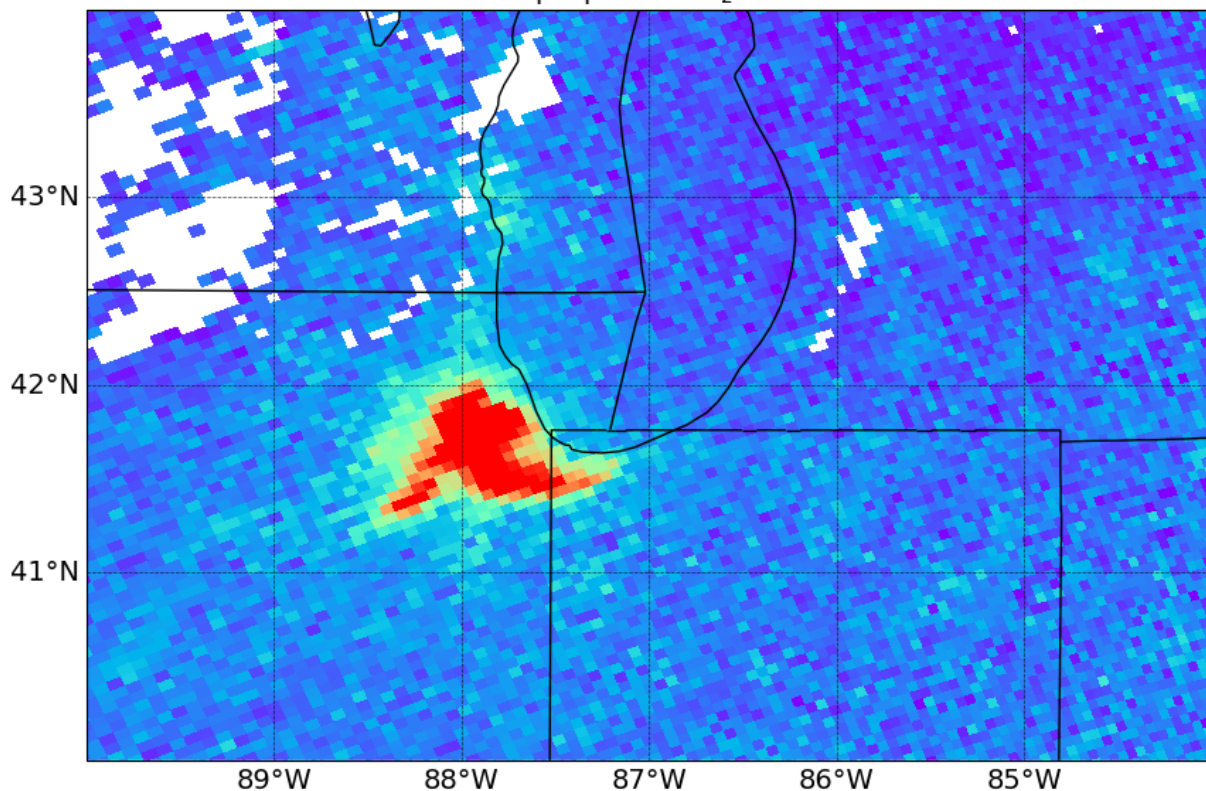
TEMPO Commissioning Phase Aug 28, 2023



**Data Courtesy
of Caroline
Nowlan (SAO)**

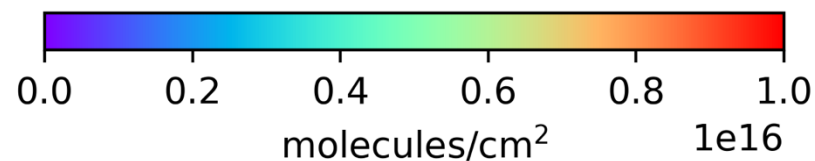
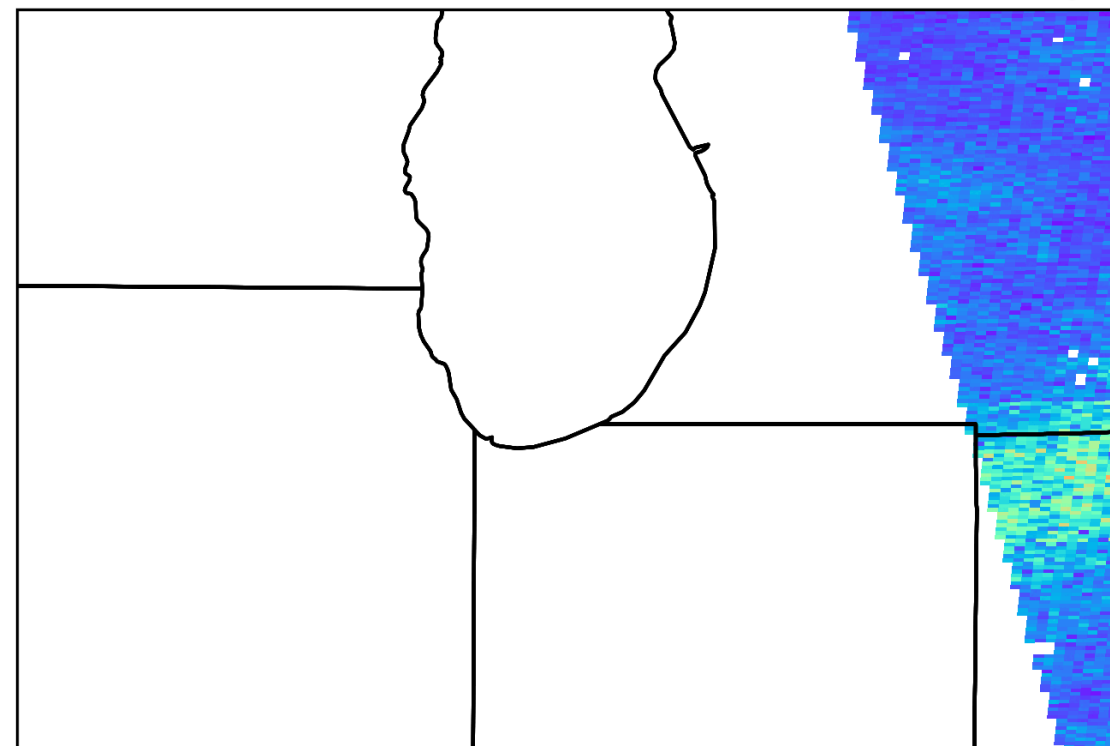
TROPOMI 12:25 PM

S5P TROPOMI L2 Tropospheric NO₂ 20230828 12:26 CDT



TEMPO

28 August 2023 S001
06:32 LT





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!**



Limitations!

- ❑ **Space-borne spectrometers like TEMPO provide vertical column measurements, not nose-level concentration measurements**
 - Ancillary data and methods required to estimate nose-level concentrations
 - Cloud cover can limit the use of satellite data
- ❑ **Uncertainties associated with satellite data products, especially more difficult retrievals (HCHO, O₃ profile)**
 - Solar geometry, surface reflectivity (snow covered surfaces), water-land boundaries, a priori
- ❑ **Across northern portions of TEMPO FoR (Canada!) larger solar and viewing angles will lead to reduced sensitivity of some gases (i.e., NO₂, O₃) to the boundary layer.**
- ❑ **Areas of high aerosol loading such as wildfire smoke plumes complicate trace gas retrievals**

**Join EA
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**TEMPO
Green Paper!**

