

weather.msfc.nasa.gov/tempo/



Tropospheric Emissions:  
Monitoring of Pollution  
*Hourly Measurement of Pollution*



Smithsonian Astrophysical  
Observatory



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



# Upping the TEMPO on Air Pollution Observations from Space for Enhanced Science Applications

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**& TEMPO Team**

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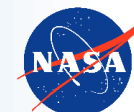
AMERICAN METEOROLOGICAL SOCIETY

**104TH ANNUAL MEETING**

**28 JANUARY-1 FEBRUARY 2024**

**BALTIMORE, MD & ONLINE**

U.S. Government sponsorship acknowledged.



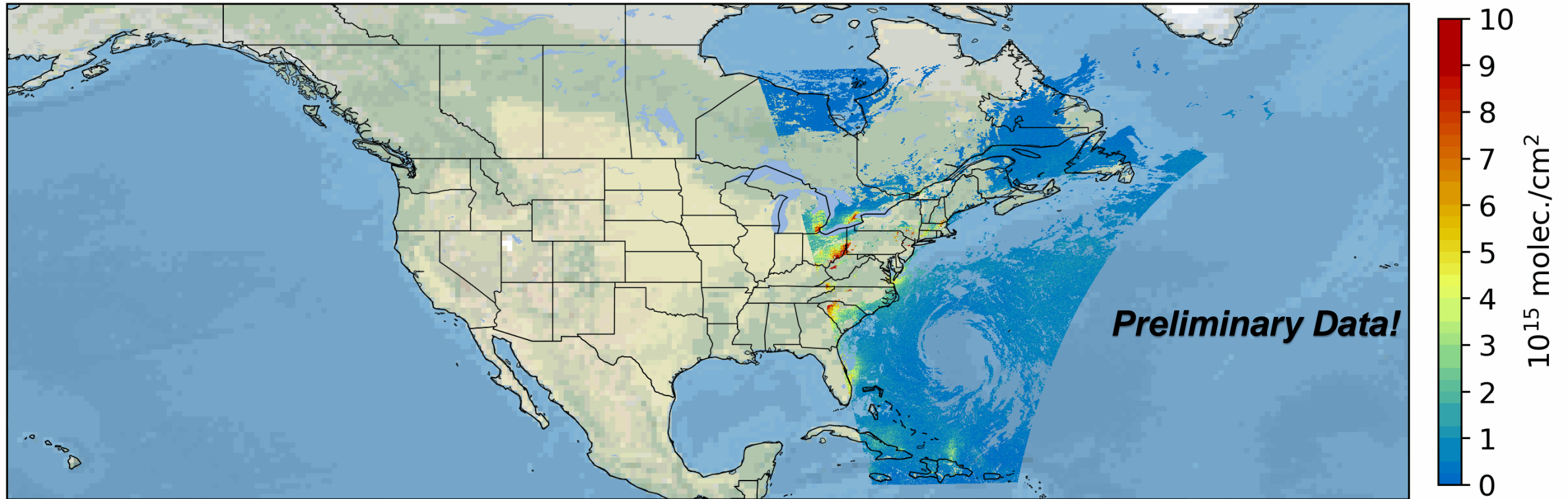


# TEMPO Scan Operations – August 29, 2023



- The NASA TEMPO mission will monitor air pollutants at high temporal (hourly during the daytime) and spatial ( $\sim 2 \times 4.8 \text{ km}^2$ ) resolution from geostationary orbit  $\sim 22,000$  miles above the equator at  $91^\circ \text{W}$ .

TEMPO Tropospheric  $\text{NO}_2$  20230829 1107 UTC



TEMPO performs **standard (nominal)** East-West hourly daytime scans across the Field of Regard (FoR) over North America and **optimized (sub-hourly)** scans over daylight portions of the FoR during the early morning and late afternoon.



# TEMPO L2+ Products: Baseline + SNWG TEMPO NRT



Level	Product	Key Variables	Resolution (km <sup>2</sup> ) **	Frequency/ Size
L2	Cloud	Cloud Fraction, Cloud Pressure	2.0 x 4.75	Per granule, ~ 6 min 40 sec  9 granules makeup the hourly TEMPO FoR
	O <sub>3</sub> (Ozone) profile	<b>O<sub>3</sub> profile, Tropospheric O<sub>3</sub> column, Total O<sub>3</sub> column, Stratosphere O<sub>3</sub> column, Cloud Fraction, O<sub>3</sub> a priori, O<sub>3</sub> Averaging Kernel</b>	>= 8.0 x 4.75	
	Total O <sub>3</sub>	<b>Total column O<sub>3</sub>, Cloud Fraction, Aerosol Index</b>	2.0 x 4.75	
	<b>NO<sub>2</sub> (Nitrogen Dioxide) NRT</b>	<b>Tropospheric Vertical Column Density (VCD), Total VCD, Slant Column Density (SCD), Cloud Fraction, Air Mass Factor (AMF), Data Quality Flag</b>	2.0 x 4.75	
	<b>HCHO NRT (Formaldehyde)</b>	<b>Total VCD, SCD, Cloud Fraction, AMF, Data Quality Flag</b>	2.0 x 4.75	
	<b>Aerosol NRT</b>	<b>UV &amp; VIS Aerosol Optical Depth (AOD), Aerosol Optical Centroid Height (AOCH), Aerosol Absorption Index (AAI)</b>	8.0 x 4.75 (TBD)	
L3	Same as L2 (Gridded)	Same as L2	0.02° x 0.02°	Per scan, hourly & sub-hourly

**\*\* Center of Field of Regard**

33.7°N  
91.7°W

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

**Baseline (Offline) products: Latency 3 - 6 hours (except O<sub>3</sub> profile ~24 hours)**

SNWG: Satellite

Needs Working Group 





# TEMPO L2+ Products: **SNWG NRT / Enhanced**



Level	Product	Key Variables	Resolution (km <sup>2</sup> ) **	Frequency/ Size
L2	C <sub>2</sub> H <sub>2</sub> O <sub>2</sub> (Glyoxal)	<b>Total VCD</b> , SCD, Cloud Fraction, AMF, Data Quality Flag	2.0 x 4.75	Hourly, granule
	H <sub>2</sub> O (Water Vapor)		2.0 x 4.75	
	BrO (Bromine)		2.0 x 4.75	
	<b>SO<sub>2</sub> (Sulfur Dioxide)</b> <b>NRT</b>	<b>VCD</b> (Total, Planetary Boundary Layer, & Lower / Middle / Upper Tropospheric, Lower Stratospheric), SCD	2.0 x 4.75	Hourly, granule
	TEMPO/GOES-R Synergistic	<b>Aerosol</b> , Fire / Hotspot, Cloud & Mask, Lightning, Snow / Ice, Precipitable Water, etc.	2.0 x 4.75	Hourly, granule
	UVB	UV irradiance, erythemal irradiance, UVI	2.0 x 4.75	Hourly, scan
L3	Same as L2 (Gridded)	Same as L2	0.02° x 0.02°	Hourly, scan

**\*\* Center of Field of Regard**

33.7°N  
91.7°W

List of products **being considered** for TEMPO NRT/Enhanced Productions starting in 2025



# Mission Phases & Operational Timeline

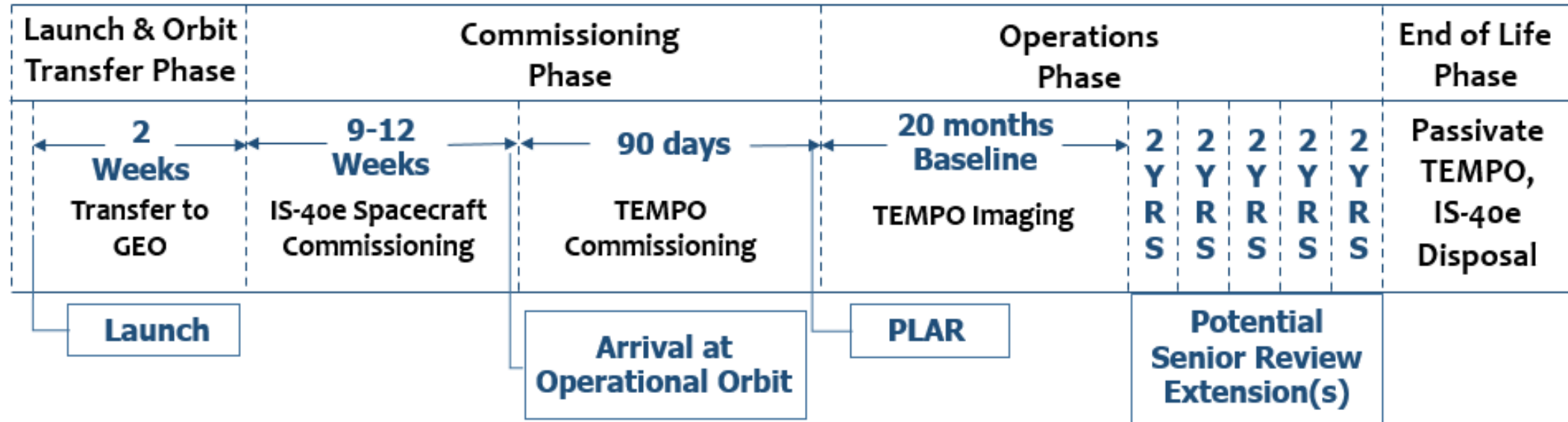


**Launched:**  
**April 7, 2023**

**Powered On:**  
**June 7**

**Commissioning:**  
**June 7 – Oct. 18**

**Nominal Operations:**  
**Oct. 19 – May 2025**



- **First light:** July 31 – August 2 with first Earth imaging on August 2
- Successfully passed Post Launch Acceptance Review (PLAR)
- **Started nominal operations on October 19**
- Baseline mission length: 20 months (Oct 2023 – May 2025) w/ **extension through NASA's Senior Review**
- Public release of Baseline products at ASDC: Level 1b data in Feb 2024, **Level 2 & 3 data in 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

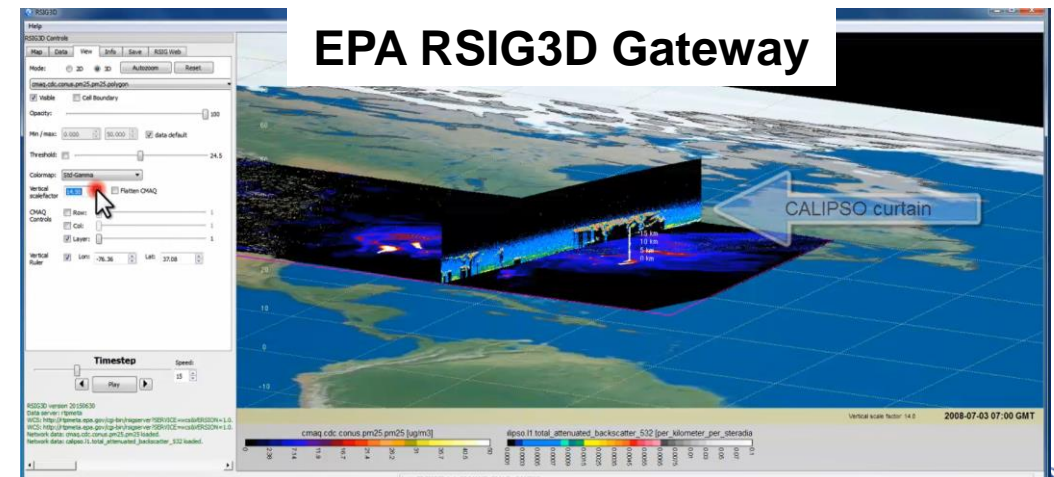
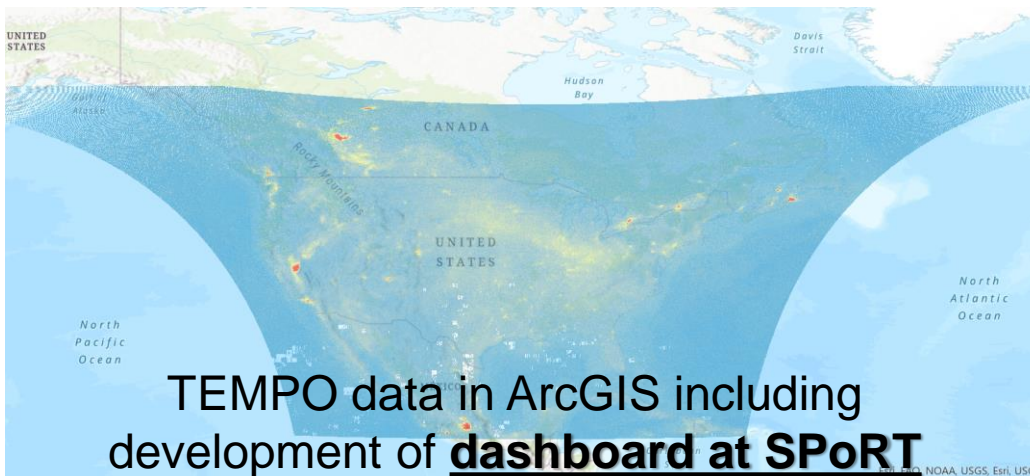
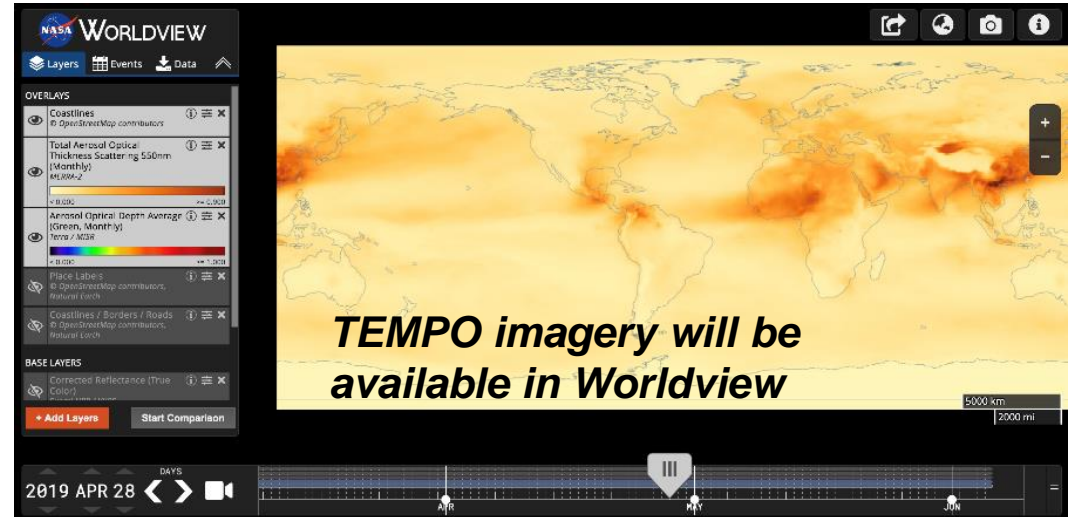
Baseline TEMPO data format: **NetCDF**



# Data Access and Visualization Tools



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







# TEMPO Early Adopters Program & Applications



## 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

**TEMPO data will enable new and enhanced science applications**



~ **580 Early Adopters**, including 100+ federal (EPA), state, local, & tribal air agencies

### Major outcomes from program:

- (1) **Facilitated inclusion of TEMPO NRT products into pipeline**
- (2) **Expanded breadth of application concepts**

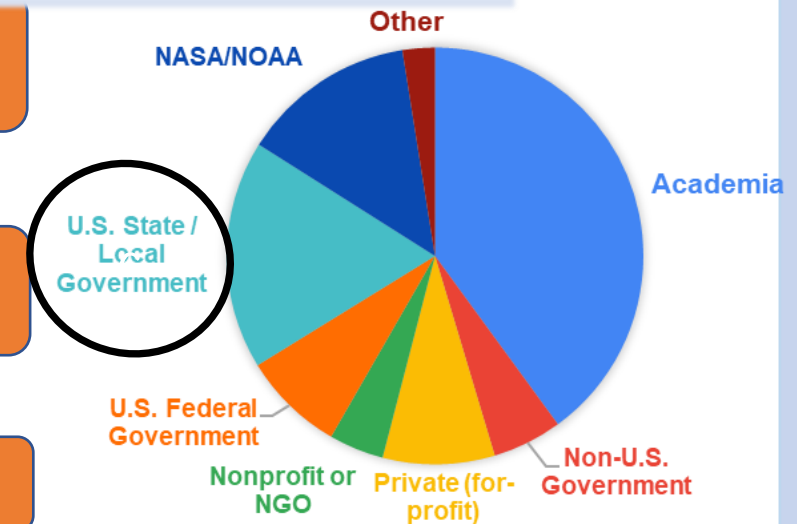
Enhance and accelerate applications of TEMPO data



Maximize the value of TEMPO data for societal benefit



Extend TEMPO mission lifetime





# TEMPO Application Focus Areas & Special Operations



- Up to 25% of TEMPO's observing time can be devoted to **special operations** over a slice of the FoR (e.g.,  $\leq 10$  min frequency)
- Focus areas include **air quality hazards** (e.g., wildfires, volcanoes), **chemistry studies** (e.g., lightning  $\text{NO}_x$ ), & field campaigns
- Involvement from Early Adopters including air quality agencies

## Subset of special experiments

- ❖ 2023 Coastal Texas Air Quality Observations
- ❖ Formation of ozone along the Colorado Front Range
- ❖ High Resolution Scanning over the New York City area
- ❖ Sub-city scale AQ forecasting system from data fusion
- ❖ Air Quality Impacts from Oil & Gas Activities in West U.S.
- ❖ Monitoring volcano emissions and plume transport
- ❖ Observing smoke from wildland fires and air quality impacts
- ❖ Lightning  $\text{NO}_x$



Green Paper!

SPORT

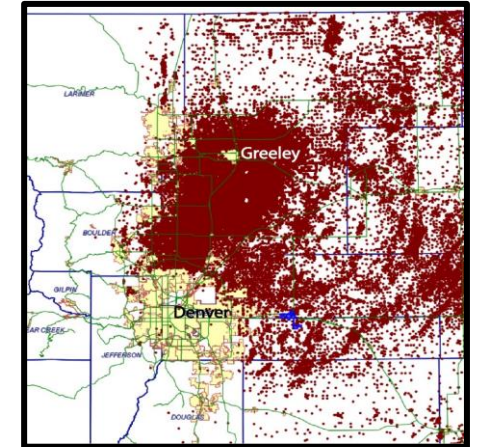




# Using TEMPO Data in Policy-Relevant Applications



**COLORADO**  
Department of Public  
Health & Environment

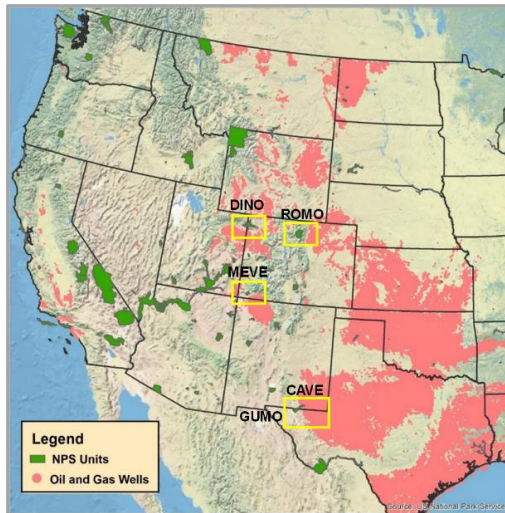


Oil & gas wells (red dots)

## • Focus Areas:

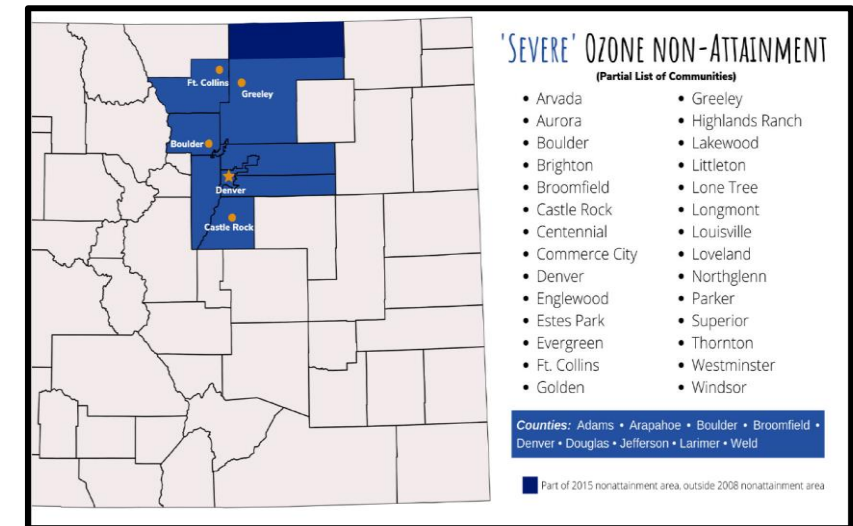
- **Colorado Front Range** -  $O_3$  nonattainment area is now classified as severe with repeated downgrades since 2008
- **National Park Service Units** – Emissions from oil & gas activities have been contributing to degraded air quality across National Parks
- **California** –  $O_3$  nonattainment areas continue to persist across much of the state

- **Goal:** Use TEMPO data for better characterizing emissions and  $O_3$  precursors and production in exceptional event analyses and reporting



8-hr $O_3$ DV Years	CAVE	Carlsbad, NM	DFW	Houston
2014-2016	67	67	80	79
<b>2015-2017</b>	<b>66</b>	<b>68</b>	<b>79</b>	<b>81</b>
2016-2018	71	74	76	78
<b>2017-2019</b>	<b>74</b>	<b>79</b>	<b>77</b>	<b>81</b>
2018-2020	73	78	76	79
<b>2019-2021</b>	<b>74</b>	<b>77</b>	<b>76</b>	<b>77</b>
2020-2022*	77	77	77	74

Location of NPS units (left) and  $O_3$  design values at NPS units and Dallas and Houston (above)

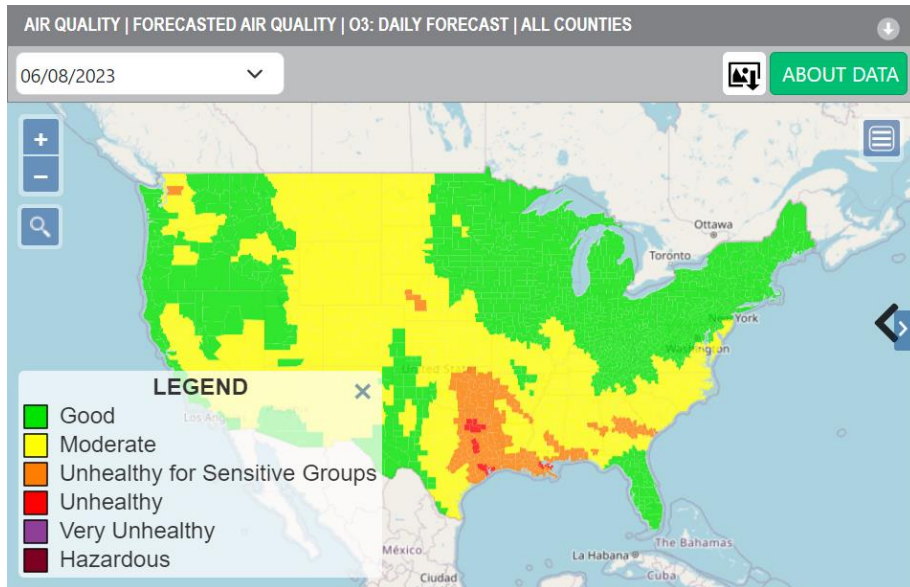




# Advancing Public Health Applications at CDC



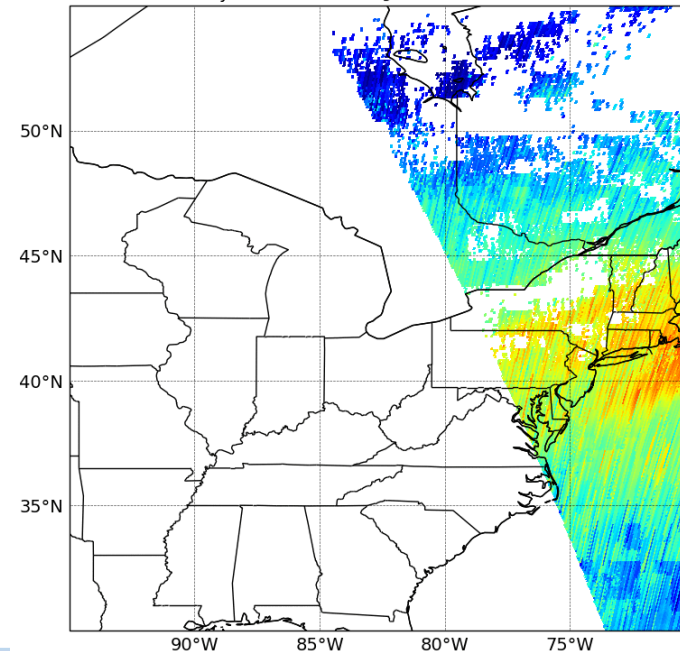
- **Objective:** Define and establish a routine process for transforming and transferring TEMPO data, particularly ozone, to CDC's National Environmental Public Health Tracking Program and its partners in an automated and near real-time fashion
  - Tracking Program identifies priority environmental health issues and evaluates the utility of existing data for answering questions and informing various issues.
- **Goal:** Enable health practitioners to access critical air quality data needed to understand and respond to health risks.



Air quality dashboard at CDC

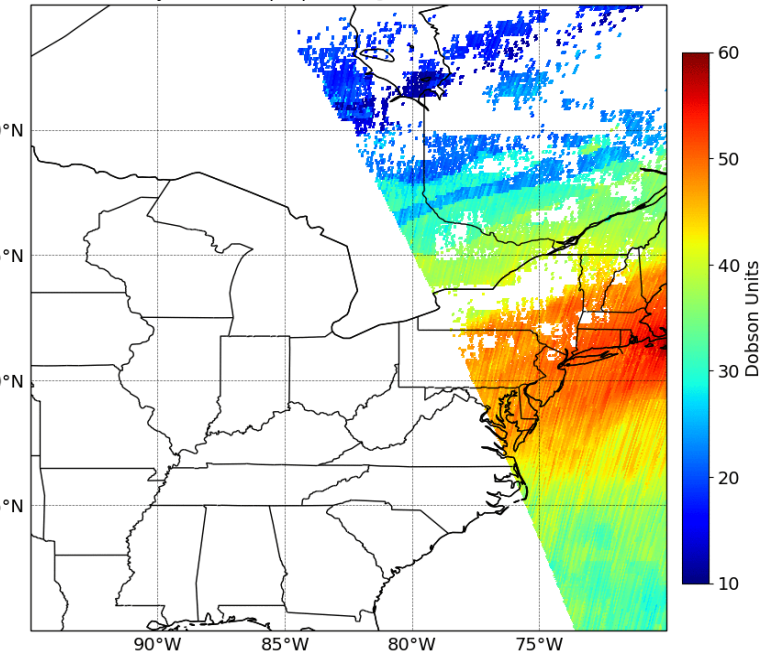
## 0-2 km (PBL) O<sub>3</sub>

Proxy TEMPO 0-2 km O<sub>3</sub> 20130720 1106 UTC



## Tropospheric O<sub>3</sub>

Proxy TEMPO Tropospheric O<sub>3</sub> 20130720 1106 UTC





# TEMPO First Light

*TEMPO data products are at beta level, meaning little is known on the data quality*

**First Light!**



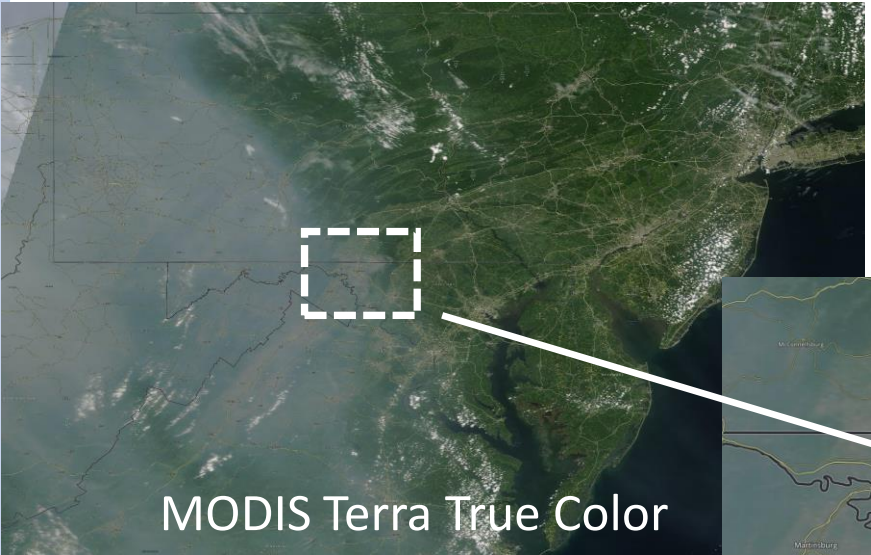
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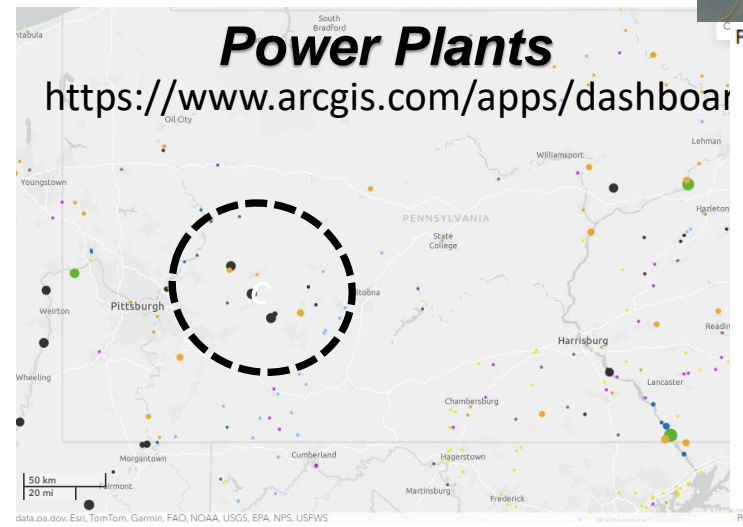
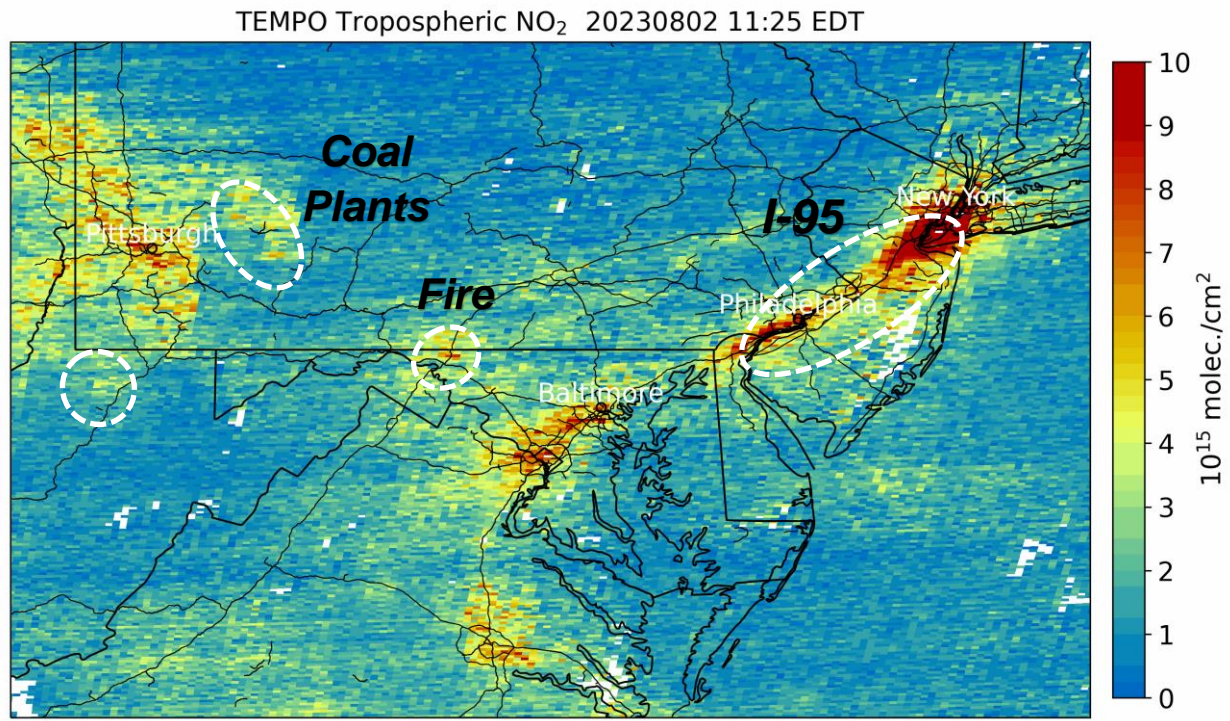


# First Light – Mid Atlantic Zoom

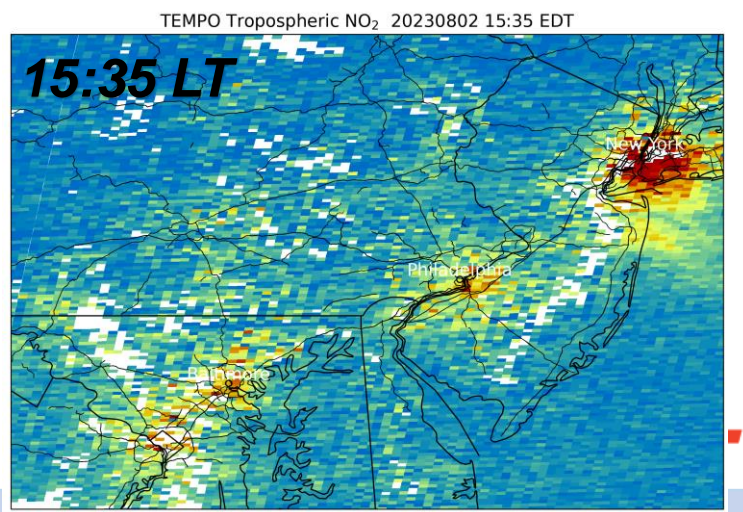
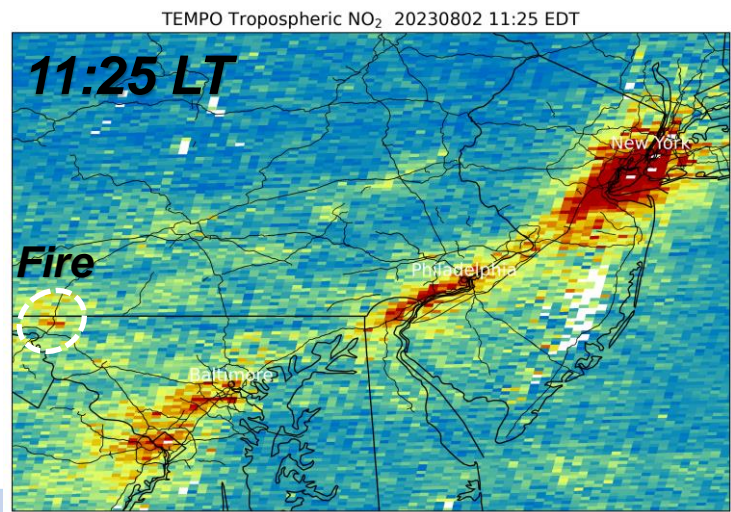
## Preliminary NO<sub>2</sub> Data!



MODIS Terra True Color



- Power Plants
- Coal
  - Biomass
  - Geothermal
  - Hydro
  - Natural Gas
  - Nuclear
  - Oil
  - Other
  - Solar
  - Wind





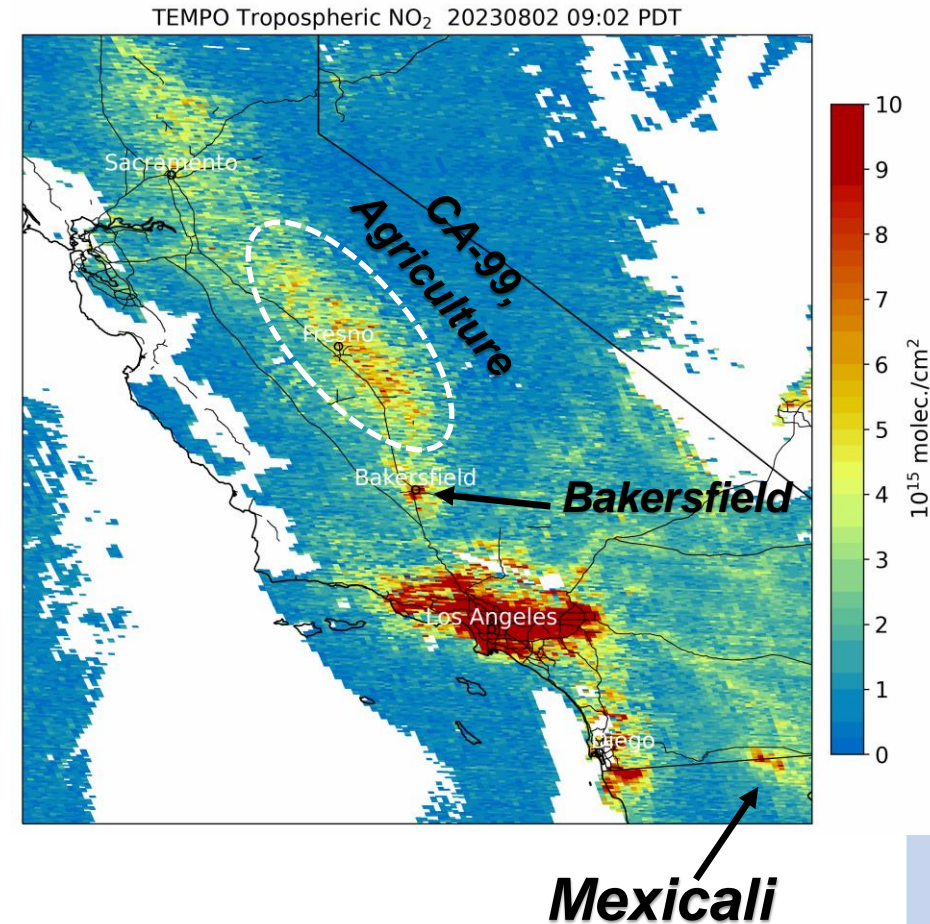


# Summary of TEMPO strengths (non exhaustive)



- O<sub>3</sub> profile for new capabilities to monitor tropospheric ozone
- Understanding small-scale emission sources that have not been adequately resolved by current satellites
- Capability to observe sharp pollutant gradients and transport
- Monitor rapidly evolving pollutants from episodic events such as wildland fires
- **Robust monitoring of industrial operations, regulatory monitors may miss peak emissions!**
- Hourly scans for observing gaps in clouds, mitigate impact of clouds on air quality monitoring from space
- Aerosol optical depth and aerosol layer height for aerosol plume monitoring and PM<sub>2.5</sub> estimates
- **Near real-time NO<sub>2</sub>, HCHO, and aerosol products for air quality monitoring & forecasting!**

## *First Light Zoom over California*



*Preliminary data has provided early insight into advanced TEMPO capabilities*





# Geostationary Air Quality Constellation!



**Launched April 2023**

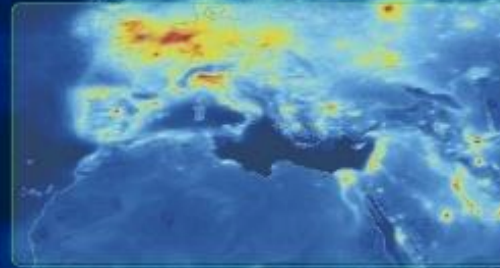
**TEMPO** (hourly)  
Tropospheric Emissions:  
Monitoring of Pollution



**Sentinel-5P** (once per day)

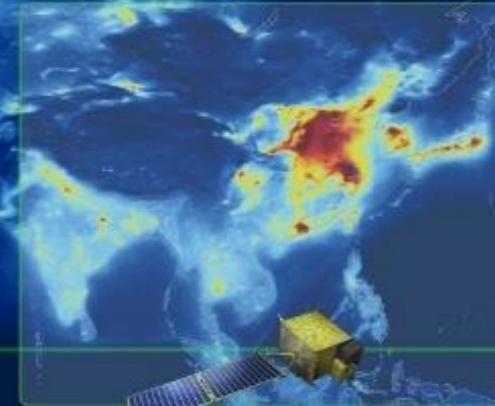
**Launch 2025**

**Sentinel-4** (hourly)



**Launched Feb 2020**

**GEMS** (hourly)  
Geostationary Environmental  
Monitoring Spectrometer



**GaoFen-5** (once per day)



Equator

Image Credit: NASA LaRC







# Current & Upcoming Work on TEMPO



- **Article on TEMPO to be published this month in A&WMA EM Plus magazine**
- Continue to engage users and stakeholders on TEMPO products and applications
  - Identify and produce value-added products and tools tailored to stakeholder needs
  - Development of codes, user guides, and training items to enable effective use of TEMPO data
- Early evaluation / validation of TEMPO data
  - Coordinate between different projects and initiatives to most effectively evaluate TEMPO data in areas throughout the Field of Regard
  - Provide feedback to TEMPO retrieval team to improve future versions of data products
- Coordination of TEMPO special operations
  - Align TEMPO special operations with important initiatives between projects



**Join EA  
Program  
here!**

**TEMPO Mission  
Applications Lead  
[aaron.naeger@nasa.gov](mailto:aaron.naeger@nasa.gov)**

**X @NaegerAaron**

**TEMPO  
Green Paper!**





# Additional Slides

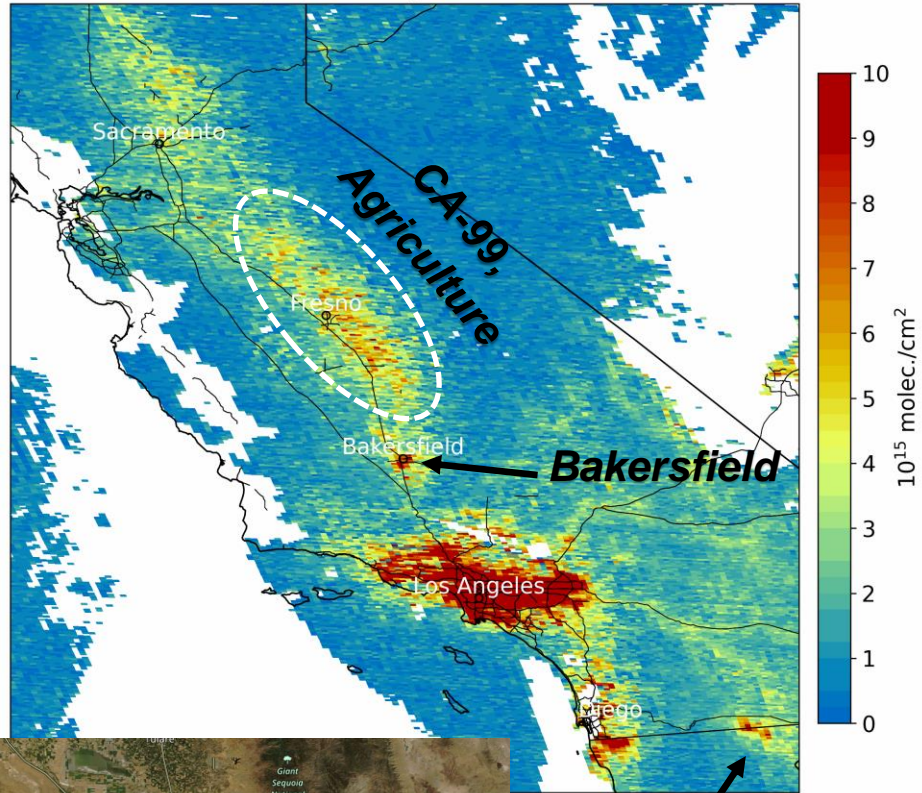




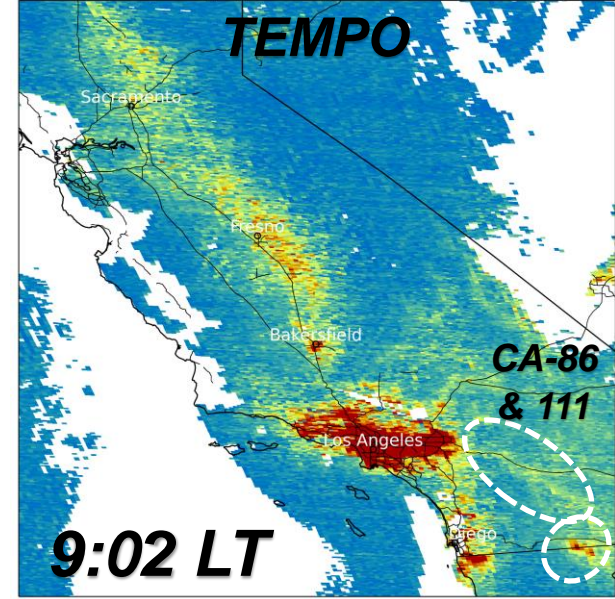
# First Light – California Zoom

**Preliminary NO<sub>2</sub> Data!**

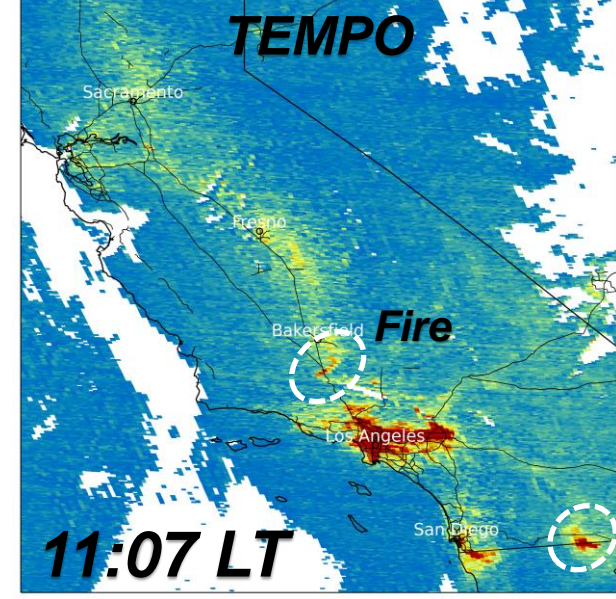
TEMPO Tropospheric NO<sub>2</sub> 20230802 09:02 PDT



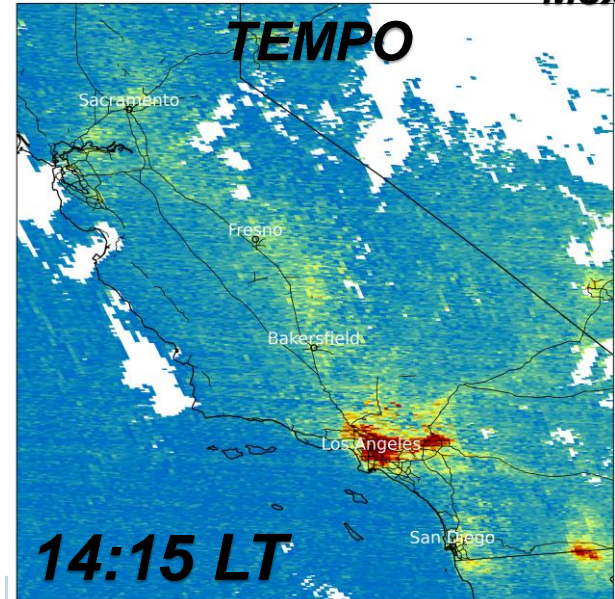
TEMPO Tropospheric NO<sub>2</sub> 20230802 09:02 PDT



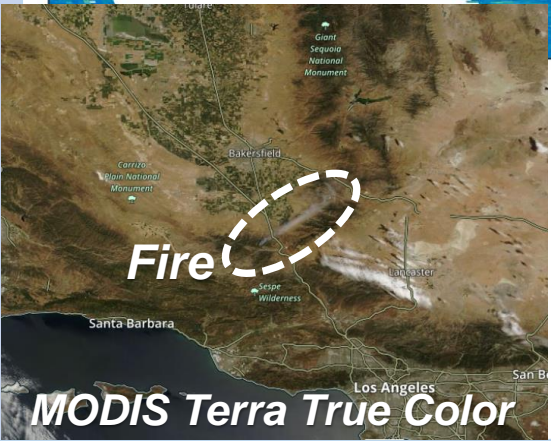
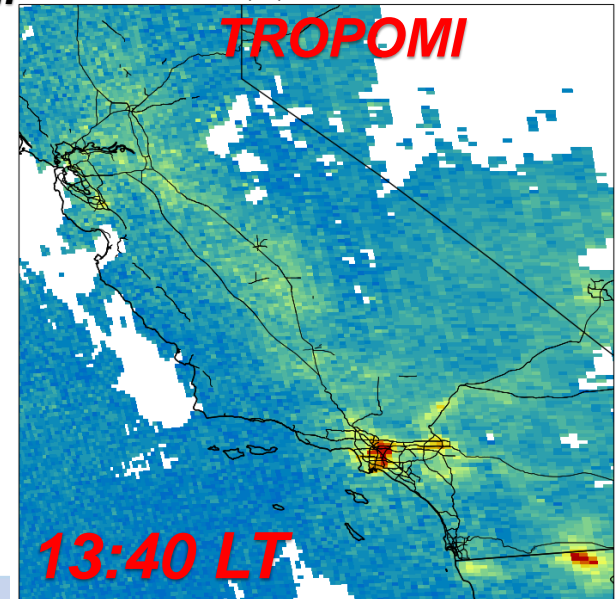
TEMPO Tropospheric NO<sub>2</sub> 20230802 11:07 PDT



TEMPO Tropospheric NO<sub>2</sub> 20230802 14:15 PDT



S5P TROPOMI L2 Tropospheric NO<sub>2</sub> 20230802 13:39 PDT



**Mexicali**



**RT**





# Monitoring Air Pollution Transport over East Coast



- **Problem:** Connecticut coastal sites continue to record the highest ozone design values on the east coast.
  - O<sub>3</sub> precursors from NYC are funneled into the Long Island Sound, trapped in marine boundary layer, then transported into Connecticut.
  - To develop better NO<sub>x</sub> 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 NO<sub>2</sub> plumes across land/sea interface



Connecticut  
Department of Energy &  
Environmental Protection

Credit: Michael Geigert

