

weather.msfc.nasa.gov/tempo/



Tropospheric Emissions:
Monitoring of Pollution
Hourly Measurement of Pollution



Smithsonian Astrophysical
Observatory



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



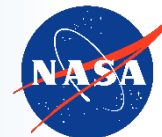
Tropospheric Emissions: Monitoring of Pollution (TEMPO) Mission

ARSET EPA Training
March 21 - 23, 2023

Aaron Naeger

TEMPO Deputy Program Applications Lead
NASA / University of Alabama in Huntsville

U.S. Government sponsorship acknowledged.





TEMPO Mission Status, Products, & Operations



TEMPO Quick Facts



Launch 2023

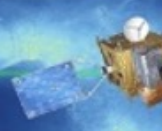
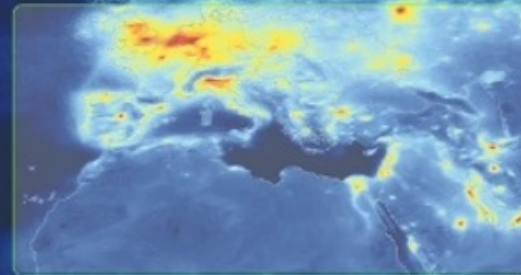
TEMPO (hourly)
Tropospheric Emissions:
Monitoring of Pollution



Sentinel-5P (once per day)

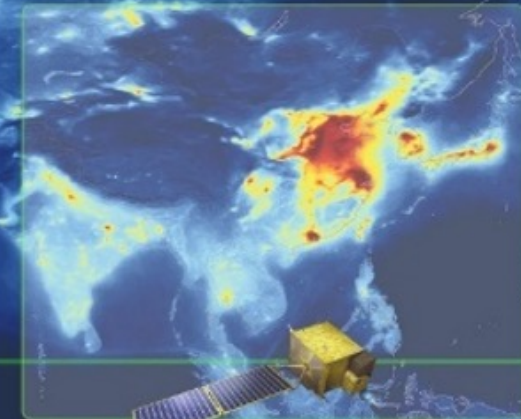
Launch 2024

Sentinel-4 (hourly)



Launched Feb 2020

GEMS (hourly)
Geostationary Environmental
Monitoring Spectrometer



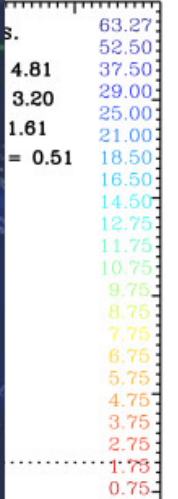
GaoFen-5 (once per day)

Image Credit: NASA LaRC

(EVI)

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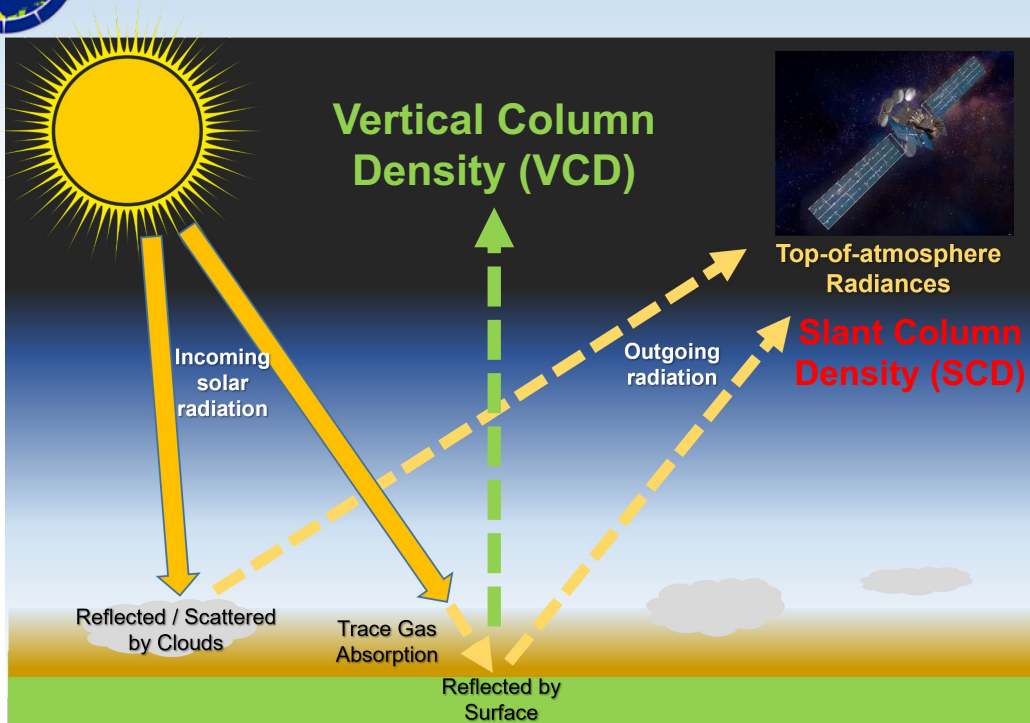
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Averaging kernels (norm. to 1 km) Averaging kernels (norm. to 1 km)

- UV/rel
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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

- ❑ 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

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

TEMPO products will be of high accuracy and precision, particularly NO₂

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



TEMPO Data Products



Level	Product	Key Variables	Resolution ** (km ²)	Frequency/ Size
L1b	Radiance	Geolocated, calibrated, geolocation & quality flags	2.0 x 4.75	Hourly, granule
L2	★ Cloud	Cloud fraction, cloud pressure	2.0 x 4.75	Hourly, granule
	O ₃ (Ozone) profile	O ₃ profile, Tropospheric O ₃ column, 0-2 km O ₃ column, Errors	8.0 x 4.75 OR 8.0 x 9.5	Hourly, granule
	Total O ₃	Total column O ₃	2.0 x 4.75	Hourly, granule
	★ NO ₂ (Nitrogen Dioxide)	Slant Column Density (SCD) Tropospheric Vertical Column Density (VCD) Errors	2.0 x 4.75	Hourly, granule
	★ HCHO (Formaldehyde)	SCD	2.0 x 4.75	Hourly, granule
	C ₂ H ₂ O ₂ (Glyoxal)	Total VCD	2.0 x 4.75	
	H ₂ O (Water Vapor)	Errors	2.0 x 4.75	
	BrO (Bromine)		2.0 x 4.75	
	★ SO ₂ (Sulfur Dioxide)	SCD VCD (Total, Planetary Boundary Layer, & Lower / Middle / Upper Tropospheric, Lower Stratospheric)	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	Hourly, granule
	TEMPO/GOES-R Synergistic	Aerosol (see above), Fire / Hotspot, Lightning, snow/ice, etc.	2.0 x 4.75	Hourly, granule
L3	Gridded L2	Same as L2	~5 x 5 (TBD)	Hourly, scan
L4	UVB	UV irradiance, erythemal irradiance, UVI	TBD	Hourly, scan

**** Center of Field of Regard**

★ Proposed Near Real-Time products (latency 2-3 hours)

Black text: Baseline products

Orange text: Additional / proposed products

Level 3 product composed of 10 granules of Level 2 files for complete TEMPO FoR scans

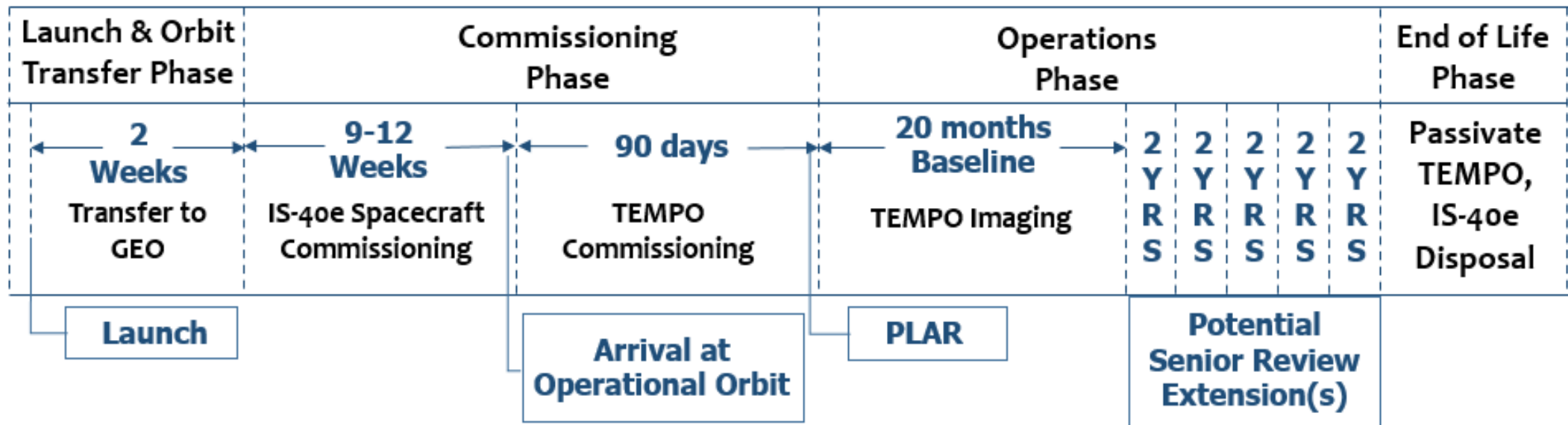


Mission Phases & Operational Timeline



Launch:
April 2023

Commissioning:
July – Sept 2023



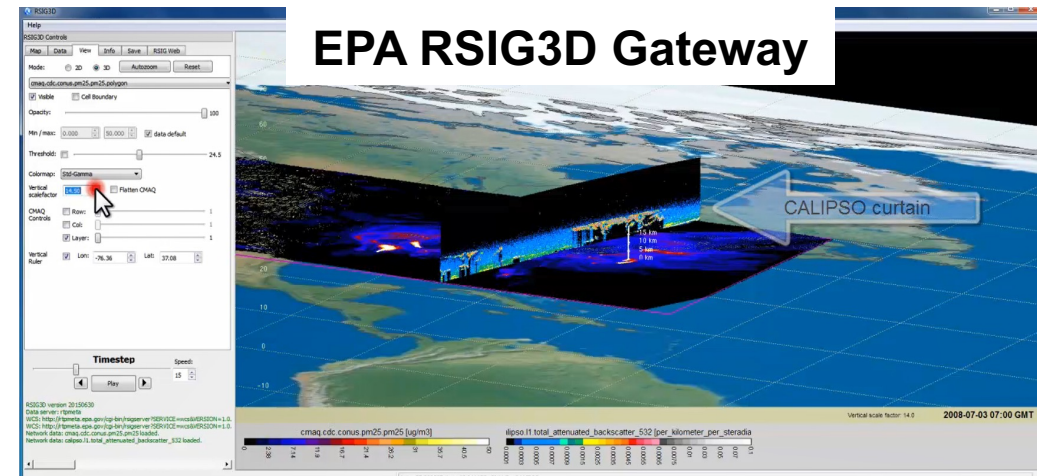
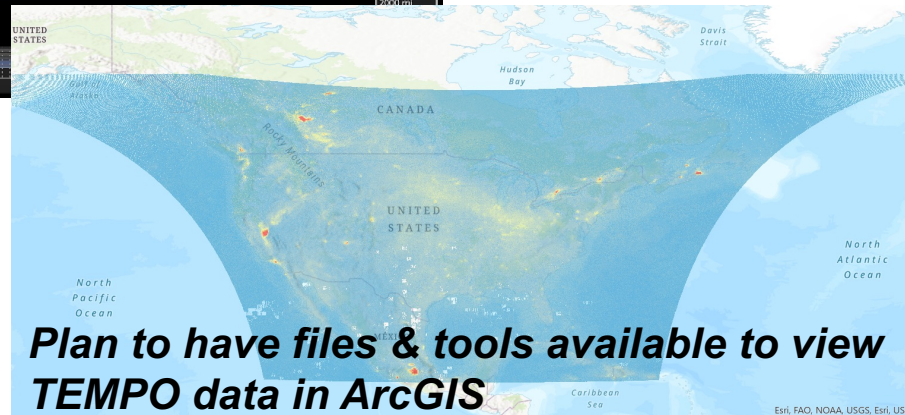
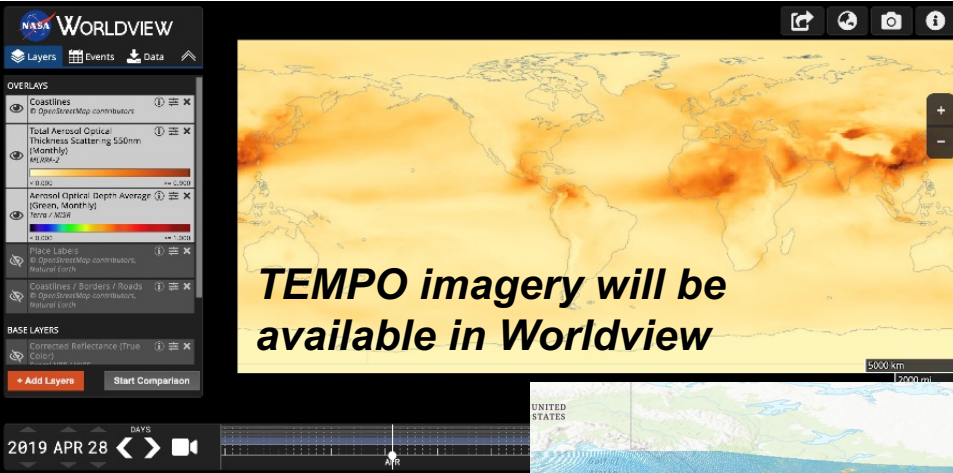
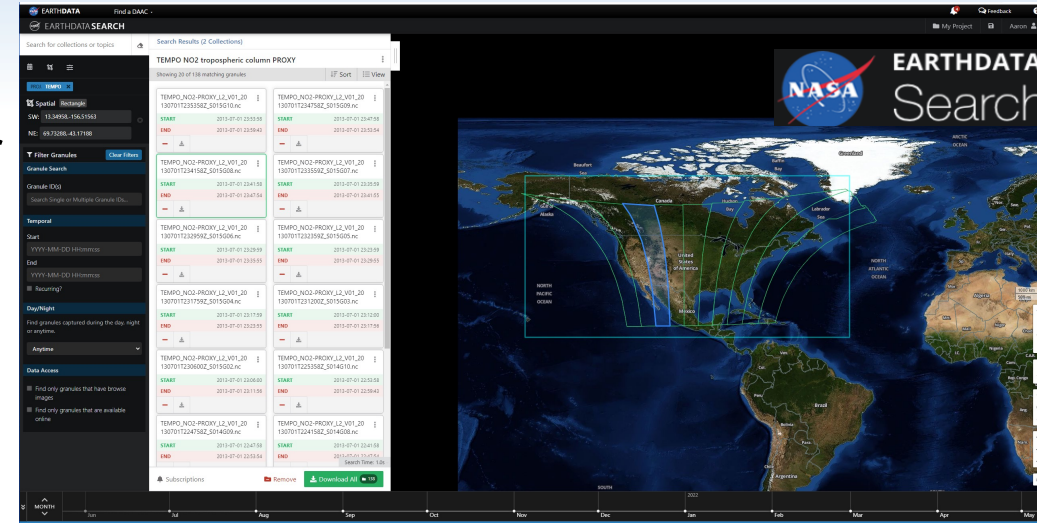
- ❑ TEMPO commissioning phase from July – Sept 2023
- ❑ Nominal operation: ~6 months after launch
- ❑ Baseline mission length is 20 months with possible 10+ year lifetime depending on senior review extensions
- ❑ Plan to release level 1b data ~4 months after commissioning phase (Feb 2024) and **level 2 and 3 data ~6 months after commissioning phase (April 2024)**



Data Distribution & Product Latency



- ❑ Data will be **publicly available** via [NASA Earthdata Search](#) in netCDF4/HDF5 format.
- ❑ Latency of standard (Offline) products ~3-6 hours, except for ozone profile (~24-hour latency).
- ❑ Latency of ~2-3 hours for proposed near real-time (NRT) products.



TEMPO data can be served directly through the EPA RSIG. <https://www.epa.gov/hesc/remote-sensing-information-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 (e.g., wildland fires, industrial accidents, dust storms) over a subset of mirror steps / time intervals (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 or monthly oversampling!

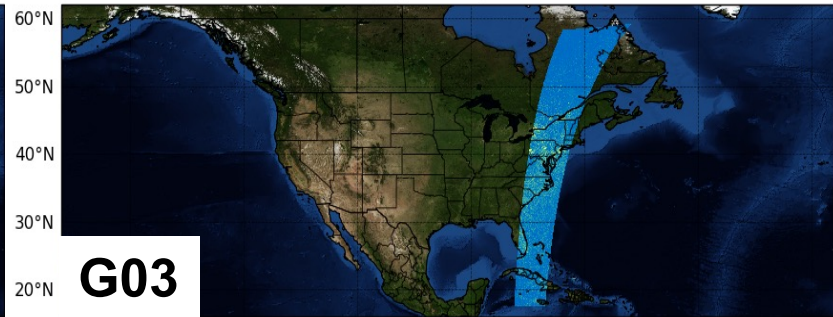
Proxy TEMPO Tropospheric NO₂ 20130829 1600 UTC



Proxy TEMPO Tropospheric NO₂ 20130829 1606 UTC



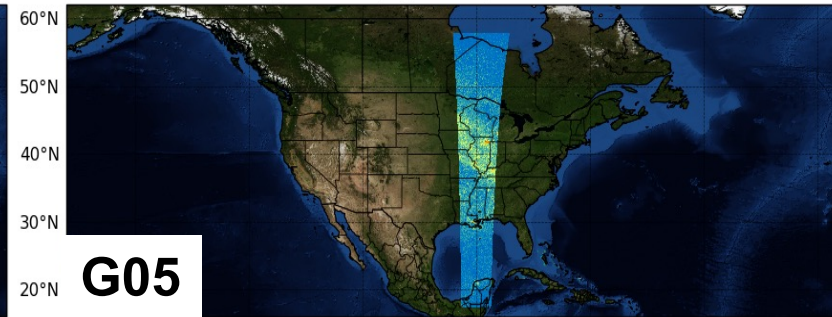
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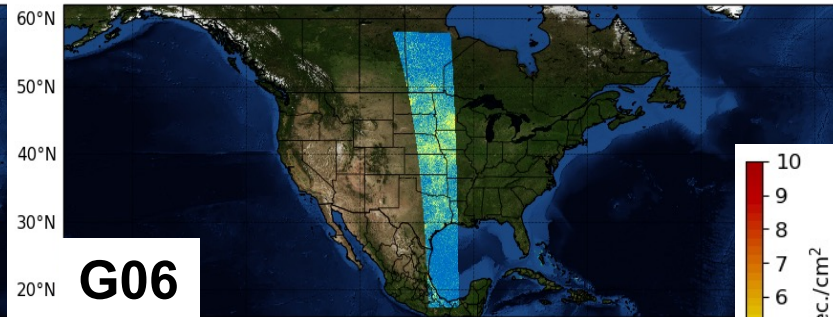
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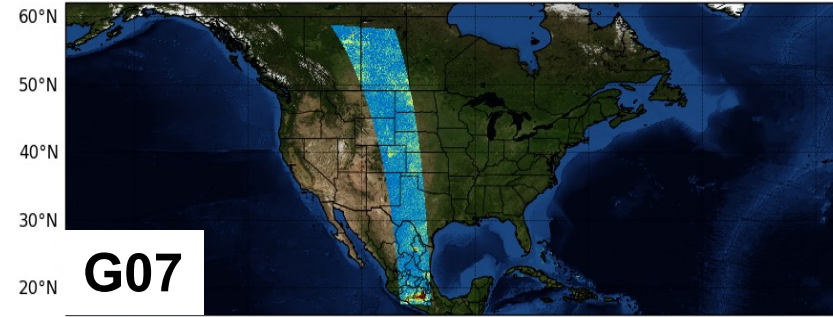
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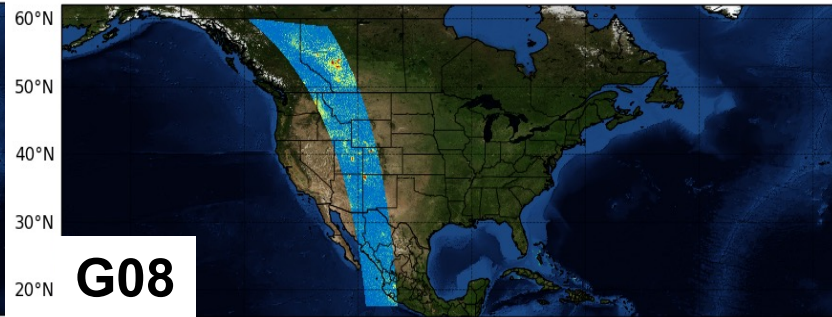
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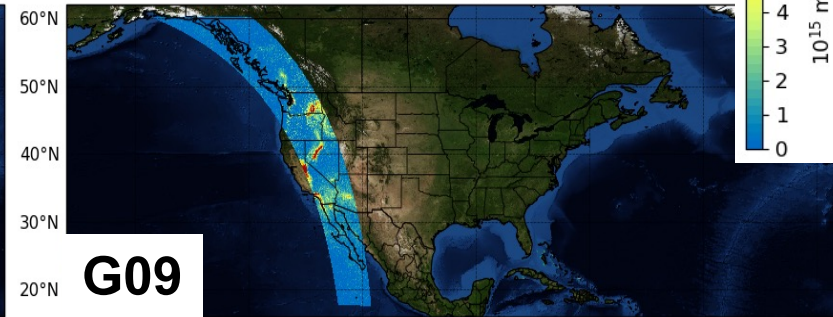
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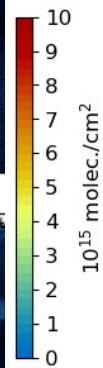
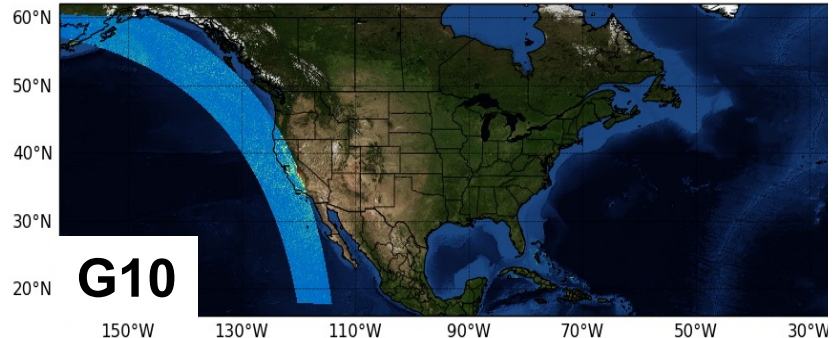
Proxy TEMPO Tropospheric NO₂ 20130829 1641 UTC



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 Early Adopters Program, Applications, & Proxy Data



Join EA Program here!

TEMPO Application Focus Areas



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

Early Adopters (EA) program focused on preparing end users and stakeholders for operational TEMPO data

TEMPO Early Adopter Studies

Observing NO₂ pollution inequality

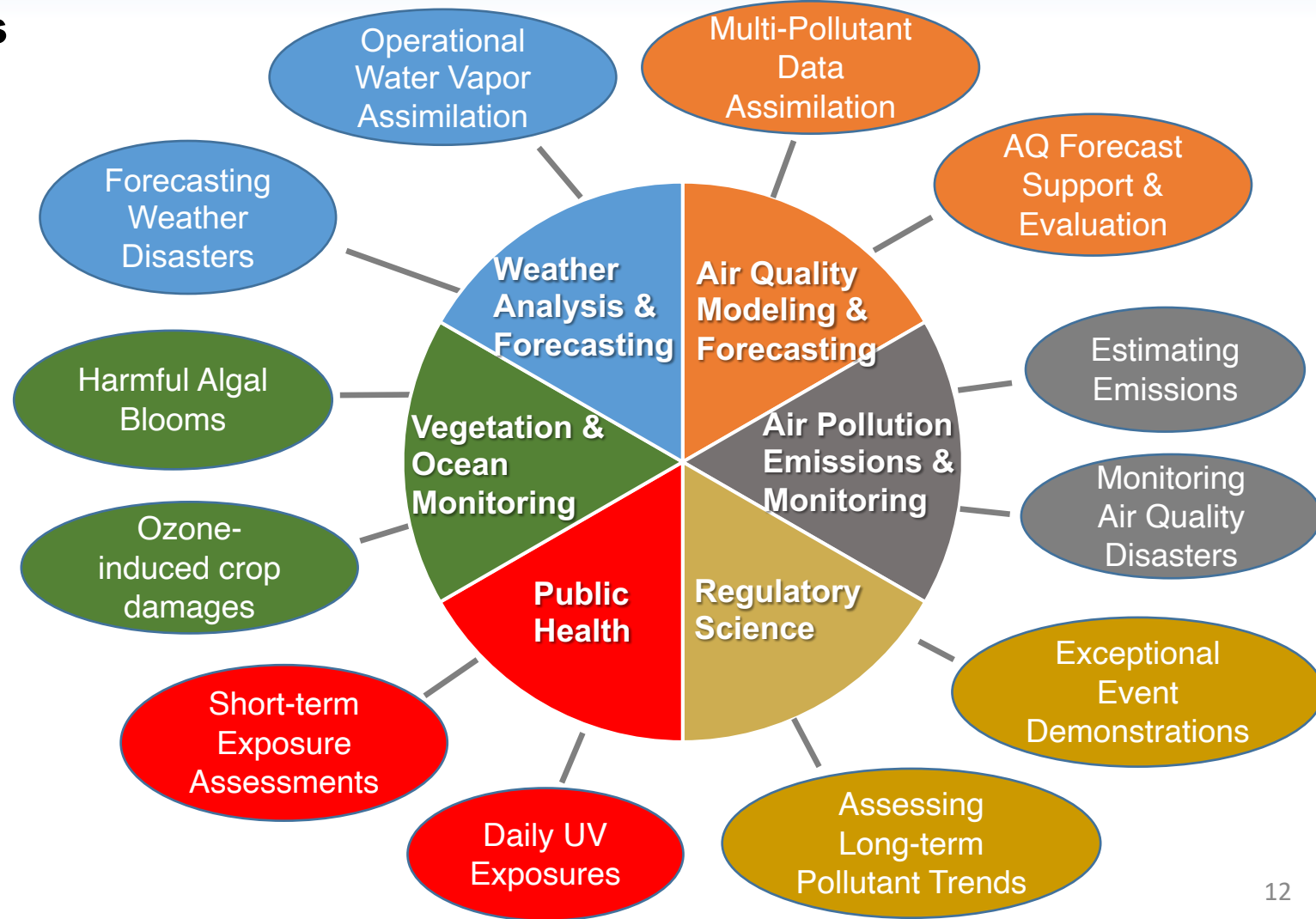
- TEMPO will provide new insight into emission sources and drivers of pollution inequality at intra-urban scales.

Dust storm monitoring

- Dust storms in U.S. are mostly short-lived, occurring a few hours before sunset. TEMPO will provide new monitoring capabilities of active dust storms.

Short-term public health outcomes

- Hourly gaseous pollutants from TEMPO will enable acute exposure assessments.





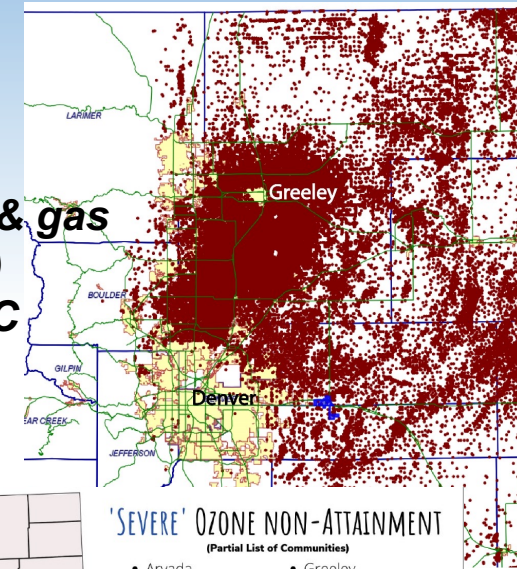
TEMPO Special Experiments

- ❑ Up to 25% of TEMPO's observing time will be devoted to special operations with sub-hourly frequency (e.g, <= 10 min) over subset of TEMPO steps (reduced E/W spatial coverage)
- ❑ **Air quality disasters** (e.g., wildfires, dust storms, industrial accidents), episodic events, and **research studies** (e.g, agriculture, lightning NO_x) can be conducted using the operations
- ❑ Pre-loaded scan patterns can be easily initiated with a couple days notice, possibility a couple hours after notice of an event
- ❑ Special operations can be commenced as early as the commissioning phase from July – Sept 2023

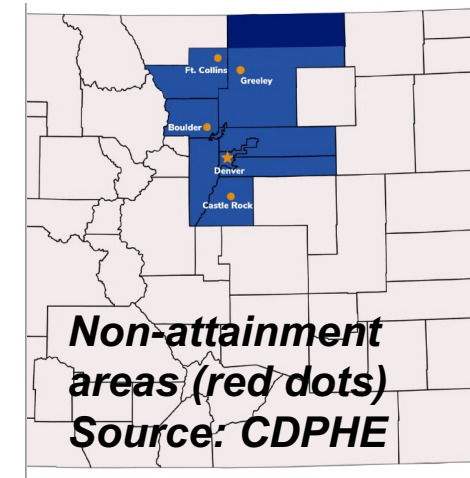
Special Experiments with regulatory implications

- ❑ Formation of ozone along the Colorado Front Range
- ❑ High Resolution Scanning over the New York City area
- ❑ Study of Winter Air Pollution in Toronto
- ❑ Air Quality Impacts from Oil and Gas Activities Across Multiple Basins in the Western U.S.
- ❑ TEMPO Validation during Satellite Coastal and Oceanic Atmospheric Pollution Experiment 2 (SCOAPE-II) Gulf of Mexico Cruise

Location of oil & gas wells (red dots)
Source: COGCC



Credit: CDPHE



Non-attainment areas (red dots)
Source: CDPHE

'SEVERE' OZONE NON-ATTAINMENT (Partial List of Communities)

- Arvada
- Aurora
- Boulder
- Brighton
- Broomfield
- Castle Rock
- Centennial
- Commerce City
- Denver
- Englewood
- Estes Park
- Evergreen
- Ft. Collins
- Golden
- Greeley
- Highlands Ranch
- Lakewood
- Littleton
- Lone Tree
- Longmont
- Louisville
- Loveland
- Northglenn
- Parker
- Superior
- Thornton
- Westminster
- Windsor

Counties: Adams • Arapahoe • Boulder • Broomfield • Denver • Douglas • Jefferson • Larimer • Weld

■ Part of 2015 nonattainment area, outside 2008 nonattainment area

Green Paper here!



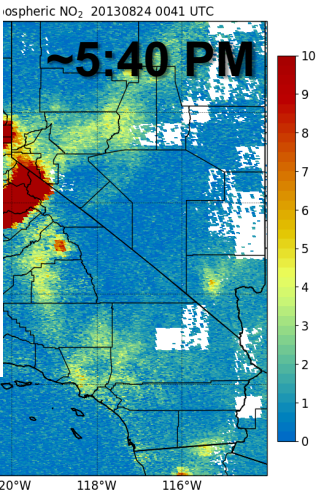
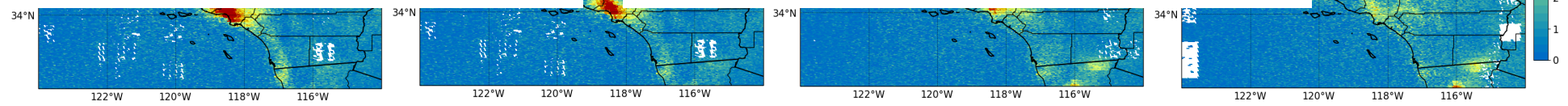
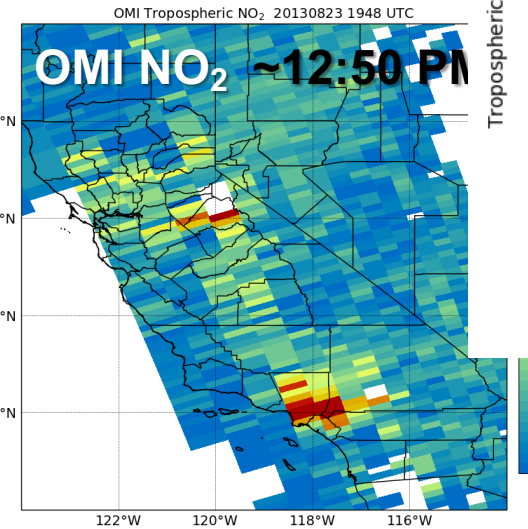
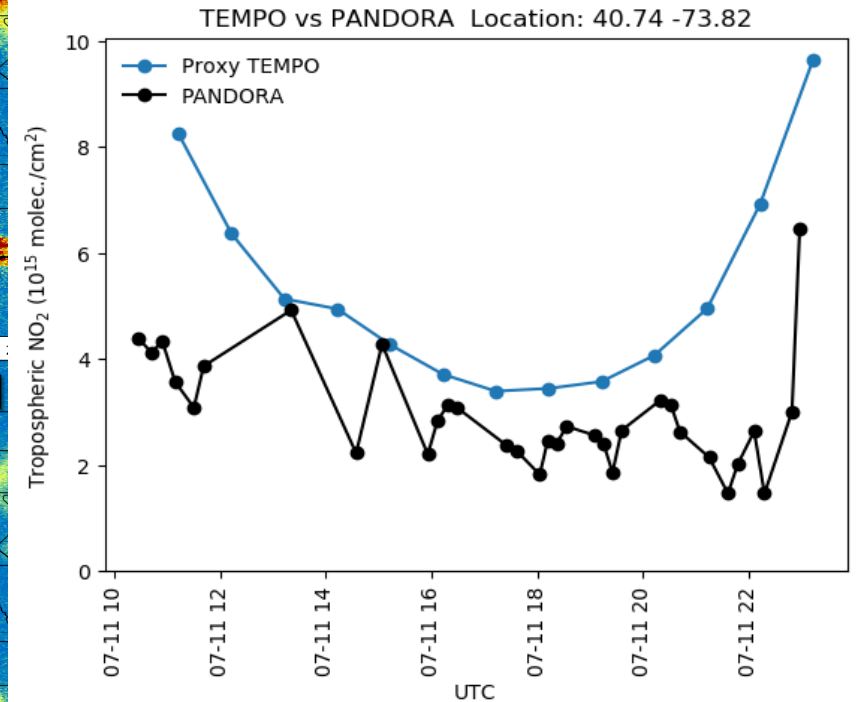
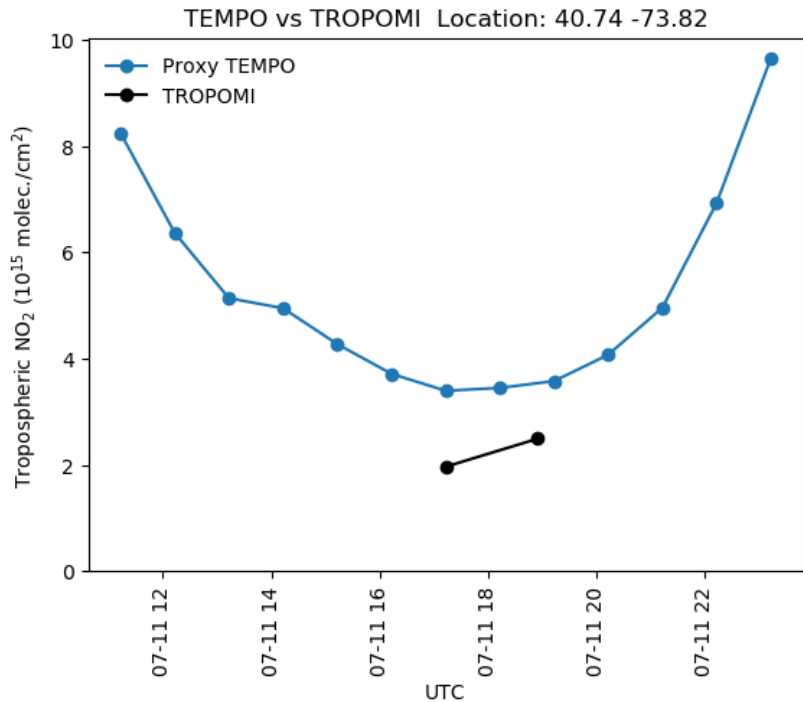
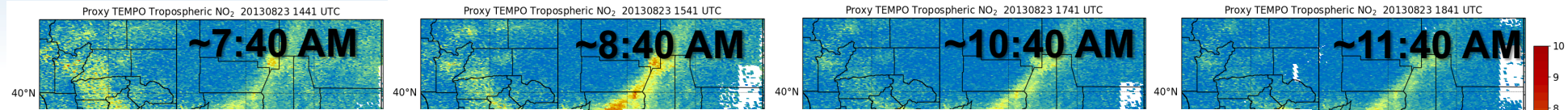
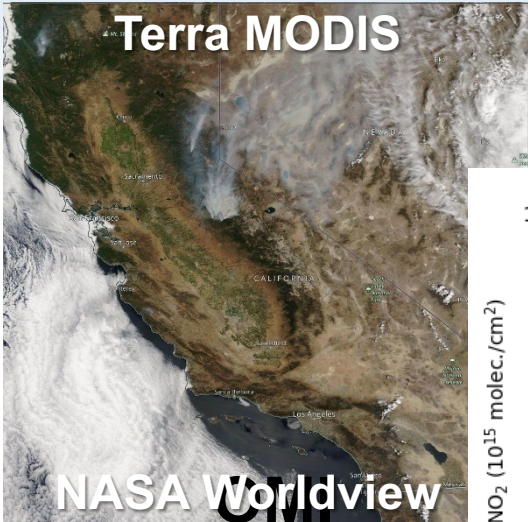


Monitoring Precursor Gases with TEMPO



Aug. 23, 2013

TEMPO Proxy Level 2 NO₂ data



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

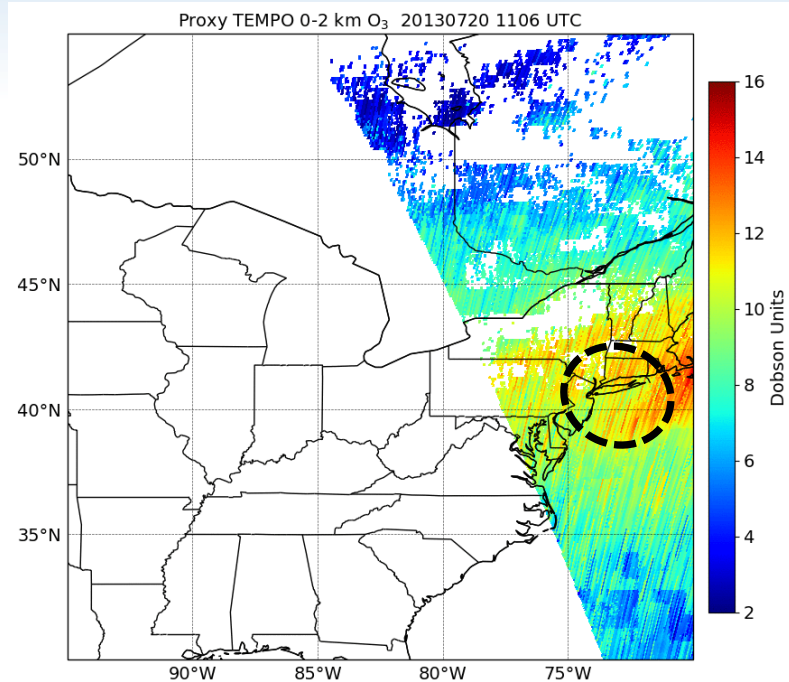
***Proxy data not intended to support operational decisions or scientific research studies**



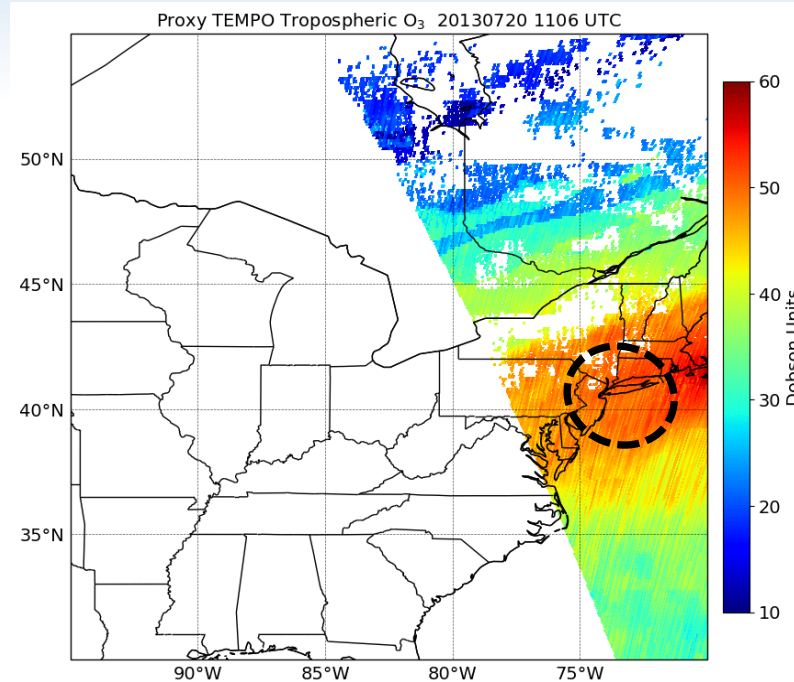
Monitoring Ozone Pollution with TEMPO



0-2 km (PBL) O₃

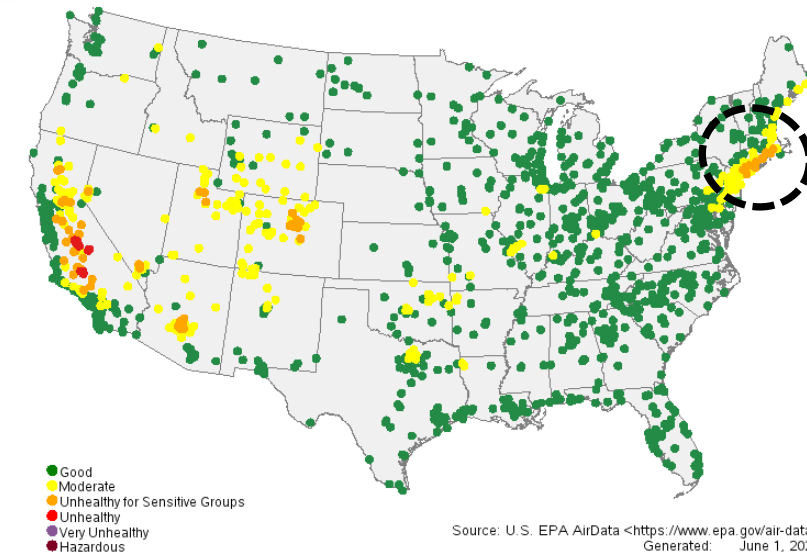


Tropospheric O₃



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



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)**
- ❑ **High-resolution tracking of air pollutants during interstate and international transport**, which will provide valuable information and support for exceptional event analyses
- ❑ 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**
- ❑ **Diurnal information on HCHO / NO₂ ratios for new understanding of sensitivity of local O₃ production and assessments of O₃ production regimes**
- ❑ Data will be valuable for surface monitor site analysis (selecting 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 satellite monitoring
- ❑ Aerosol optical depth and aerosol layer height for aerosol plume monitoring and PM_{2.5} estimates
- ❑ **Low latent NO₂, SO₂, HCHO, and aerosol products for real-time monitoring & forecasting!**



Challenges Remain!

- ❑ Space-borne spectrometers like TEMPO provide vertical column measurements, not nose-level concentration measurements
 - Periods of persistent cloud cover will still cause gaps in TEMPO
- ❑ 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 changes in O₃ in the PBL will require detailed assessments



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.

A&WMA EM article on TEMPO!

<https://online.1stflip.com/dsup/3fv8/>

TEMPO Meeting Registration!



@NaegerAaron

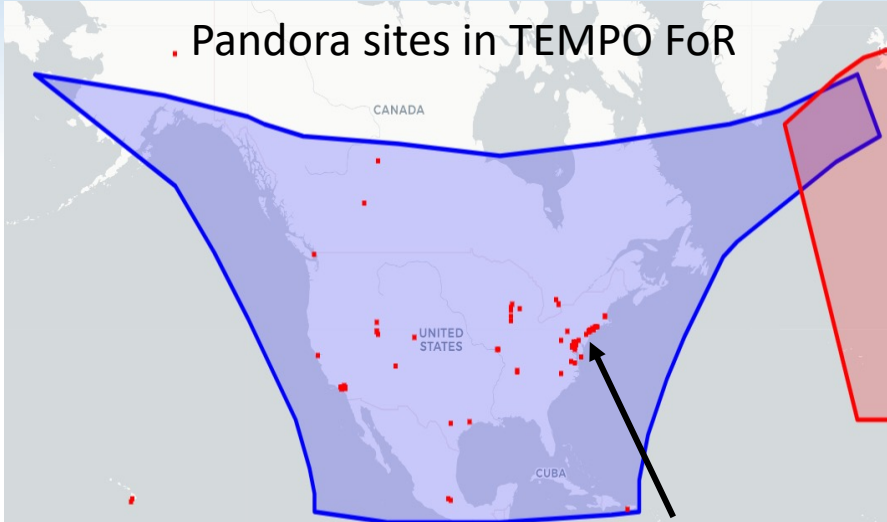
aaron.naeger@nasa.gov



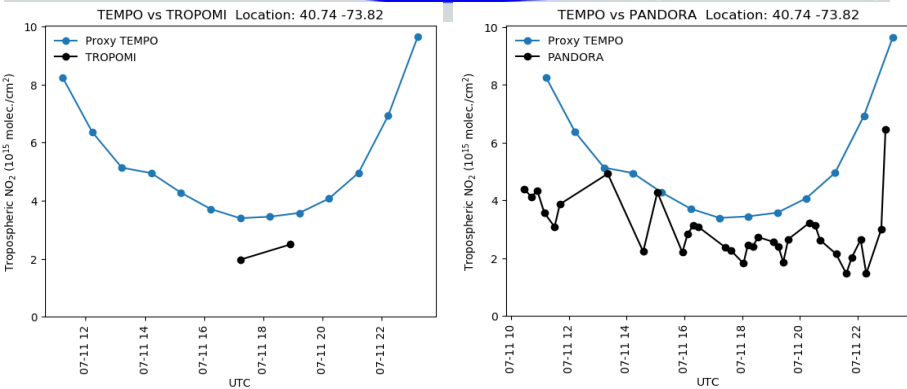
Backup Slides



TEMPO Validation and Supplementary Data

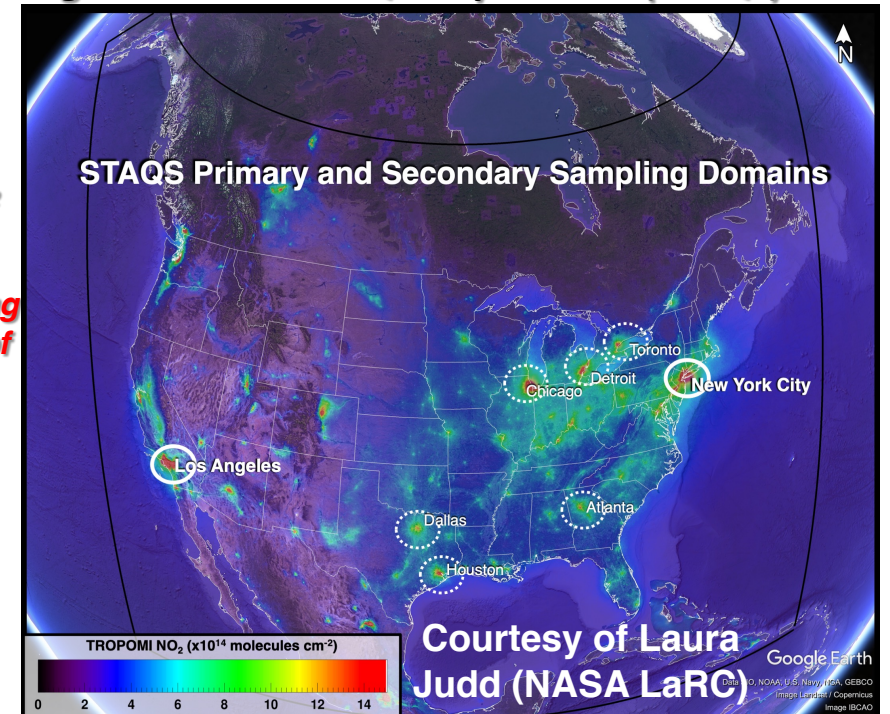


- ❑ Network of ground-based NASA Pandora spectrometers will be used to validate and characterize TEMPO products of O₃, NO₂, HCHO, and SO₂ (experimental)
- ❑ EPA's AirNow network will supplement TEMPO's observations by connecting space to ground observations and develop top-down approaches for estimating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



Annual average of TROPOMI NO₂ overlaid with currently planned primary (solid circles) and secondary (dotted circles) sampling domains within the TEMPO field of regard (black outline).

Synergistic TEMPO Air Quality Science (STAQS) Mission



- ❑ 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

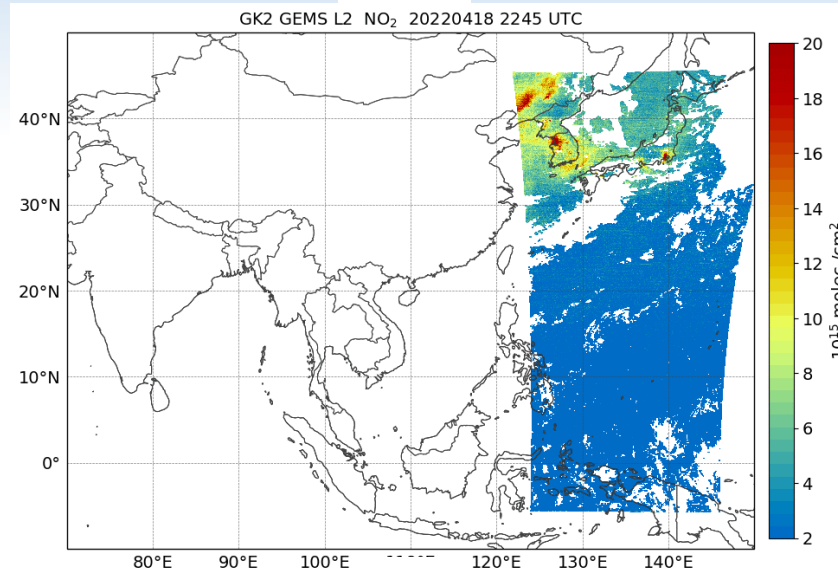
Interested in connecting with the STAQS team?
laura.m.judd@nasa.gov and john.t.sullivan@nasa.gov



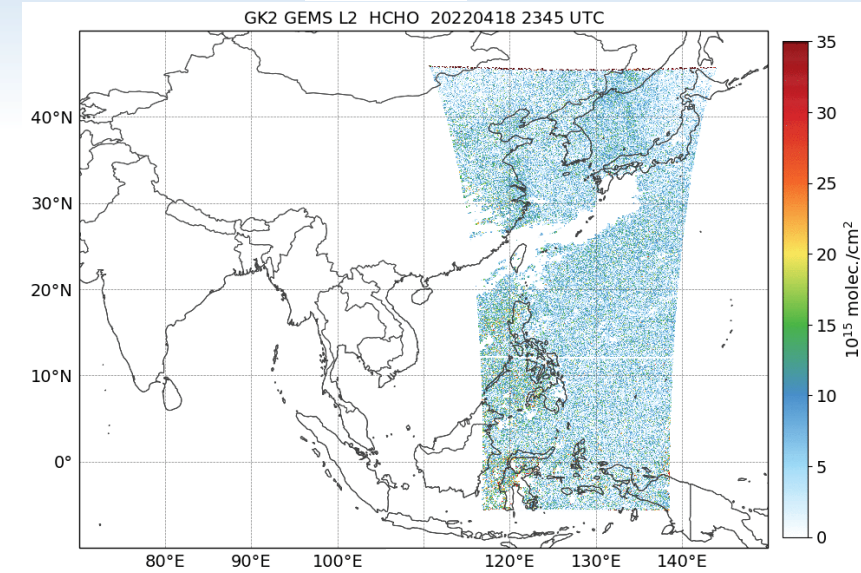
GEMS Over Asia



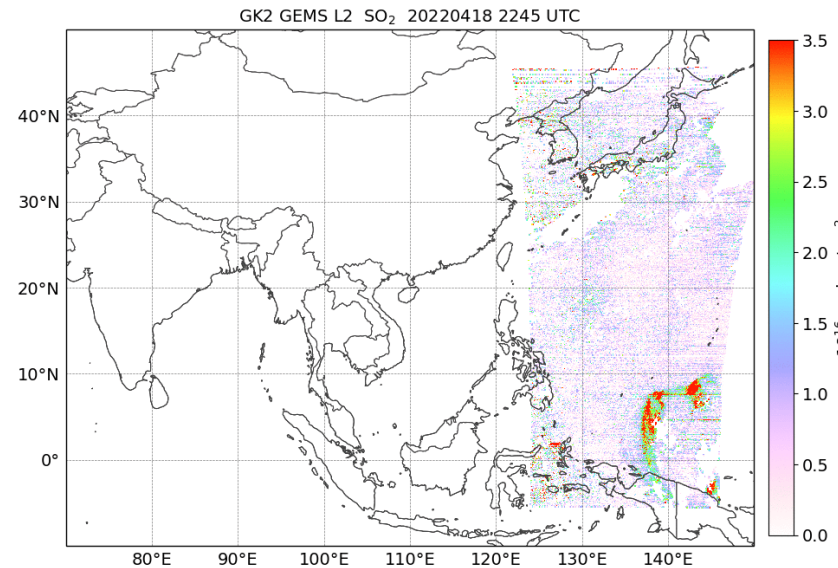
NO₂



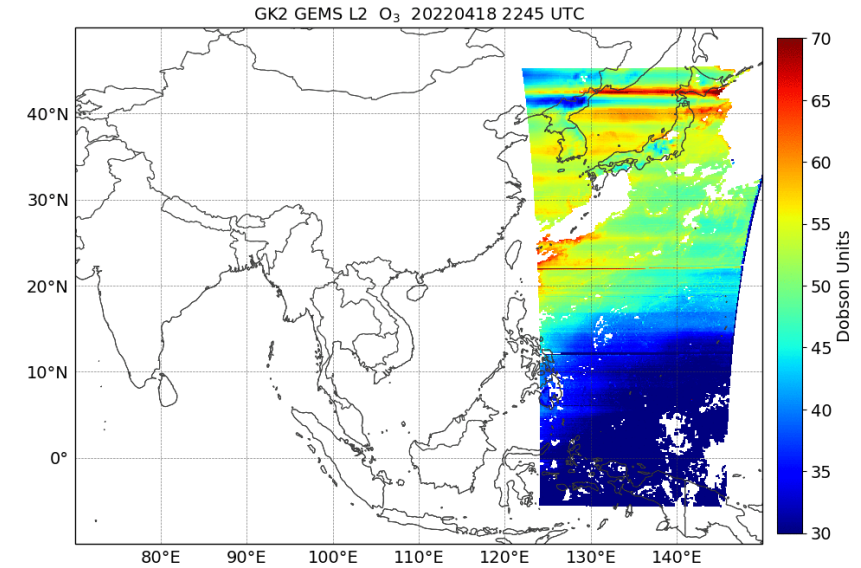
HCHO



SO₂



O₃



- ❑ GEMS is breaking ground on GEO air quality observations, providing early insight into benefits & challenges of TEMPO
- ❑ GEMS scan operations cover a larger domain than TEMPO at cost of lower spatial resolution (nominal resolution 7 km x 8 km)
- ❑ Intensive validation currently being done to ensure high-quality GEMS products
- ❑ Ongoing work incorporating GEMS data into an air quality monitoring & forecasting tools
- ❑ Early development using GEMS data will build framework for TEMPO over North America