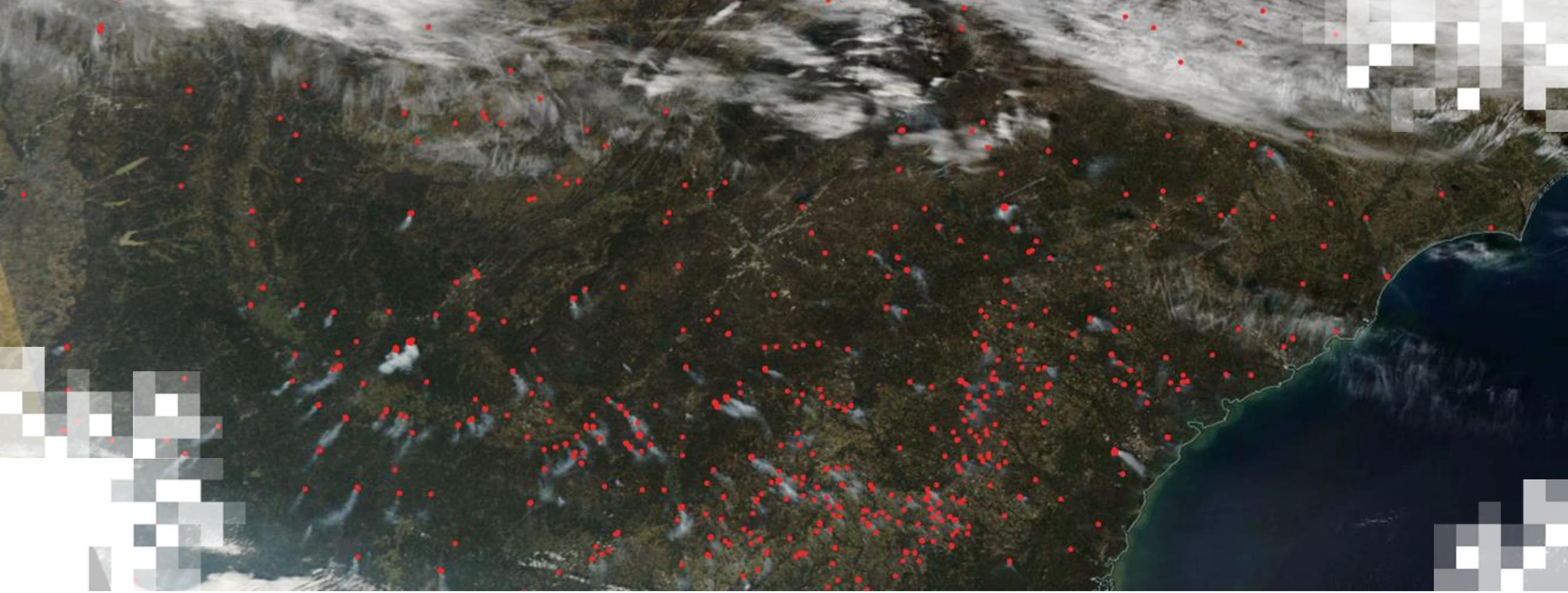


NASA Satellite Observations and Tools for Fire and Smoke Monitoring

Overview of Smoke Detection & Monitoring

Aaron Naeger (NASA MSFC)

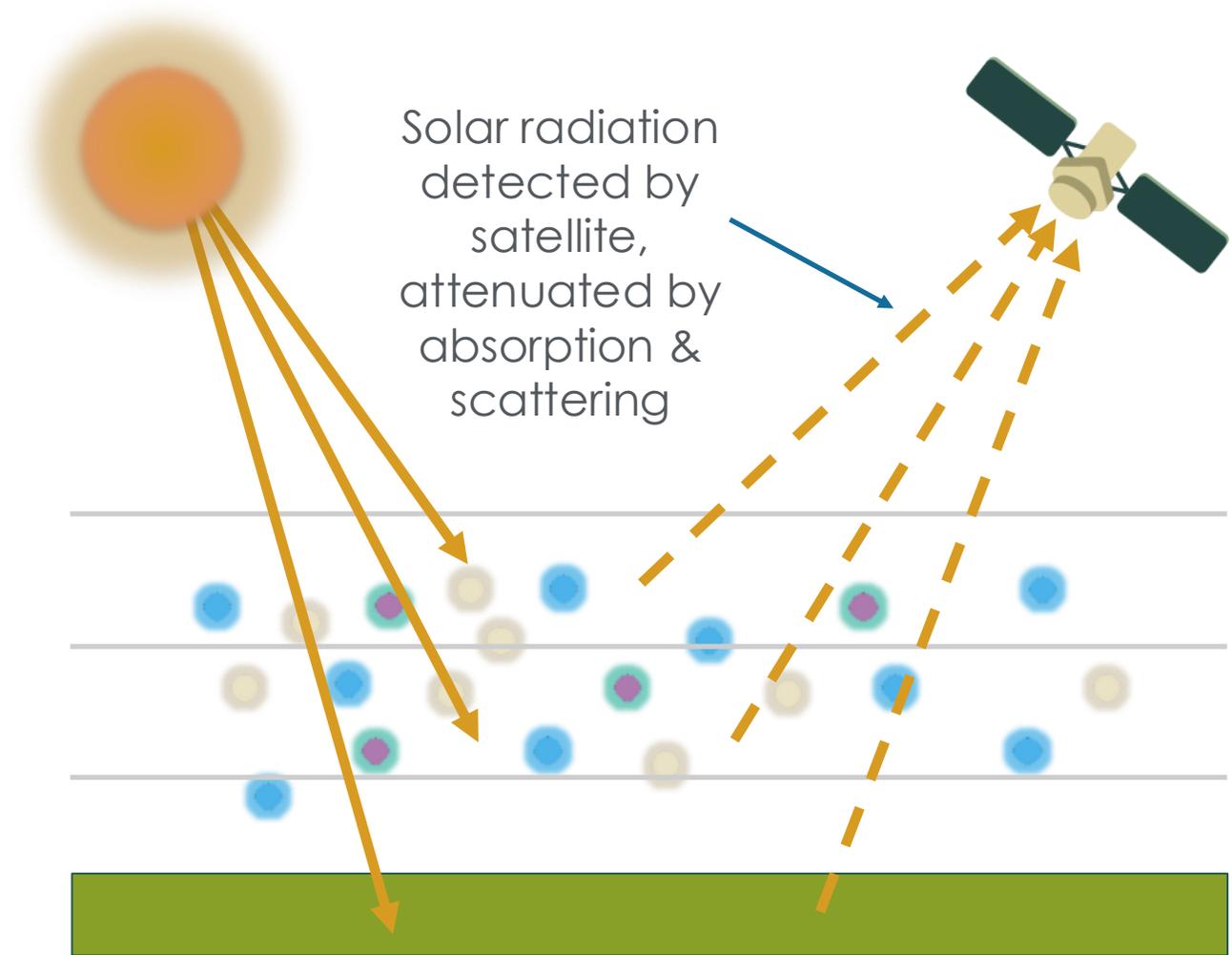
March 23, 2026



Overview of Smoke Detection & Monitoring

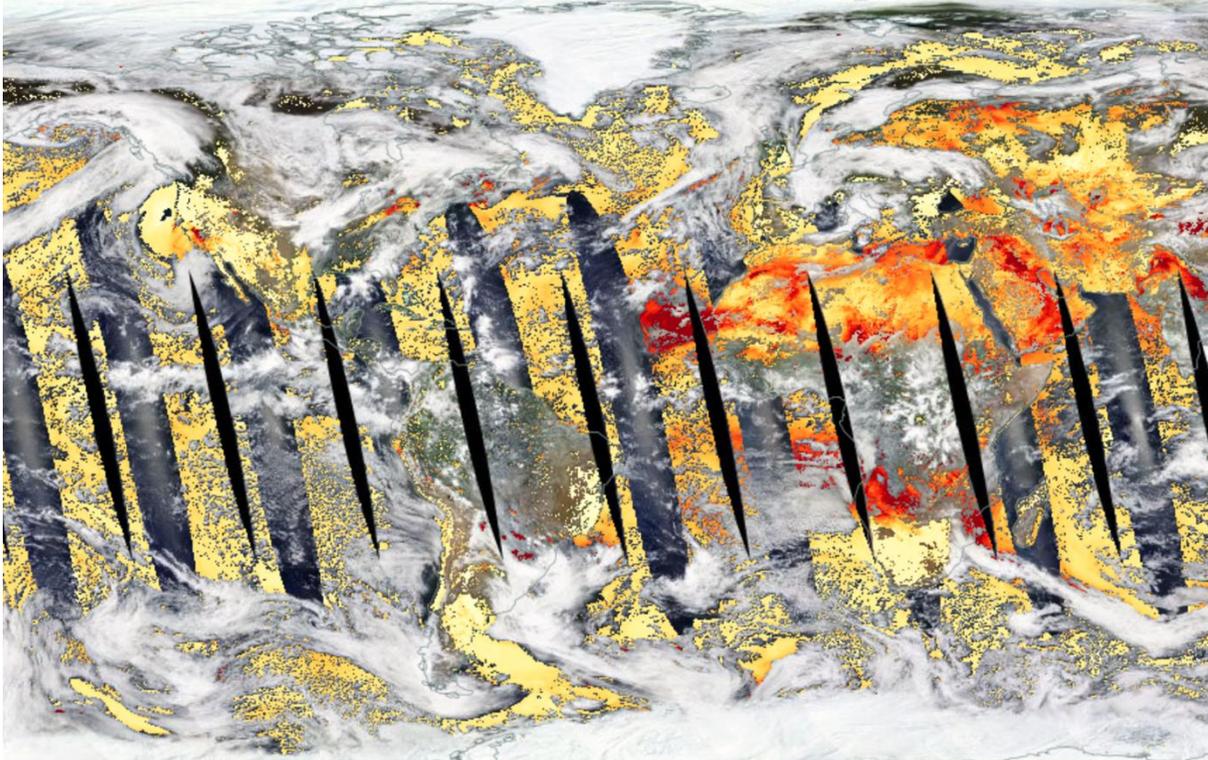
Remote Sensing of the Atmosphere

- Satellites measure backscattered **UV**, **visible**, and **IR** radiation (i.e., **radiances**) from the Earth's surface and atmosphere.
- Trace gases and particles in the atmosphere have **spectral signatures** relating to how they reflect, scatter, absorb, and re-emit radiation.
- **Retrieval algorithms** use radiation measurements and physics-informed models to infer **geophysical quantities** such as optical depth, particle number density, or partial pressure.



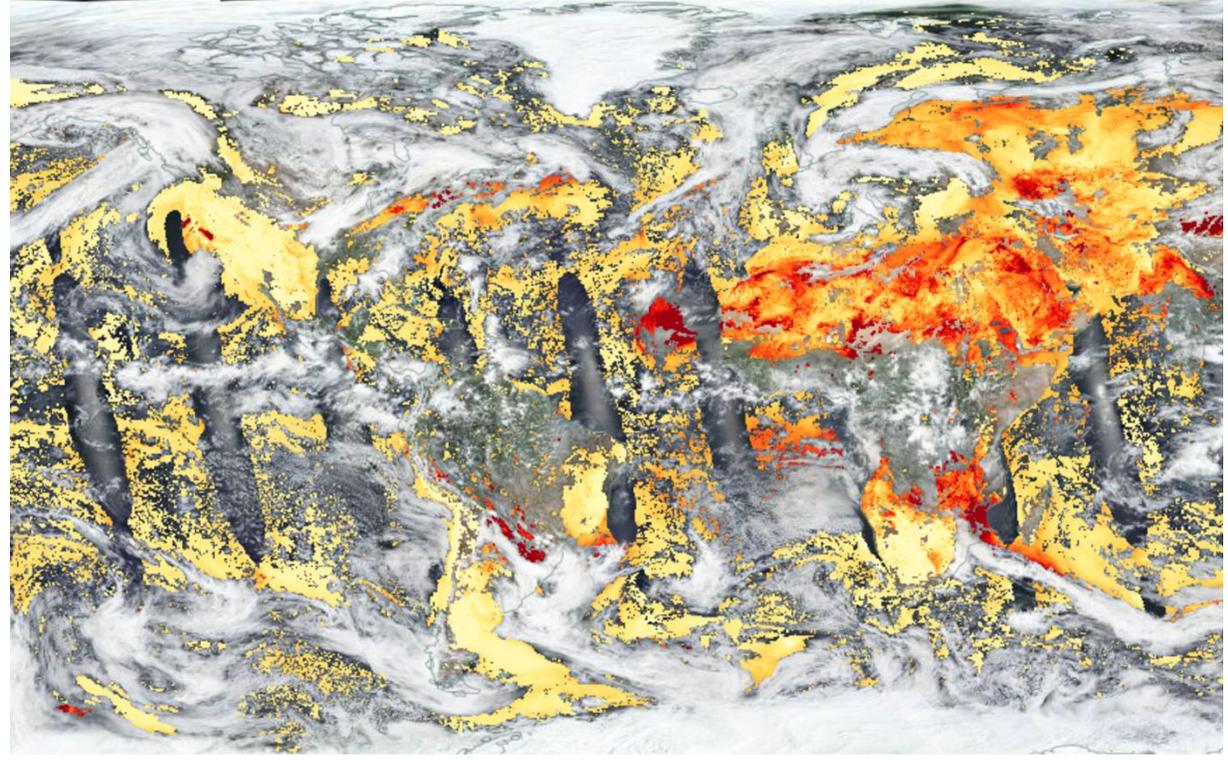
Radiometer Instruments - MODIS & VIIRS

MODIS-Aqua



2 Satellites: Terra, Aqua (1999-Present)
0.5 – 2.0 km Spatial Resolution
36 Spectral Channels
Sun-Synchronous LEO

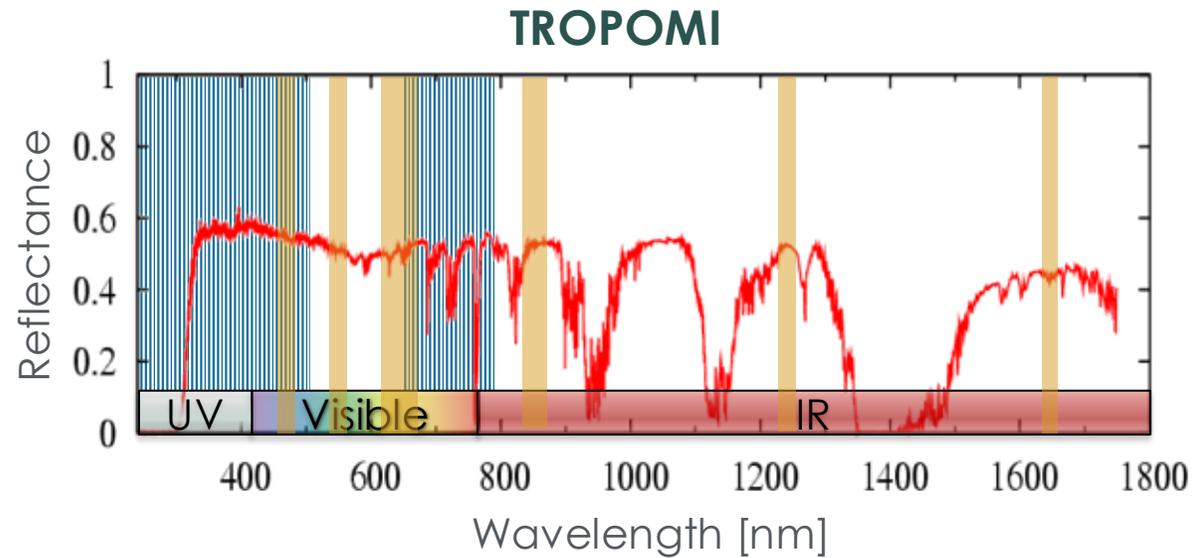
VIIRS-SNPP



3 Satellites: SNPP, NOAA-20, NOAA-21 (2011-Present)
0.75 – 1.5 km Spatial Resolution
22 Spectral Channels
Sun-Synchronous LEO

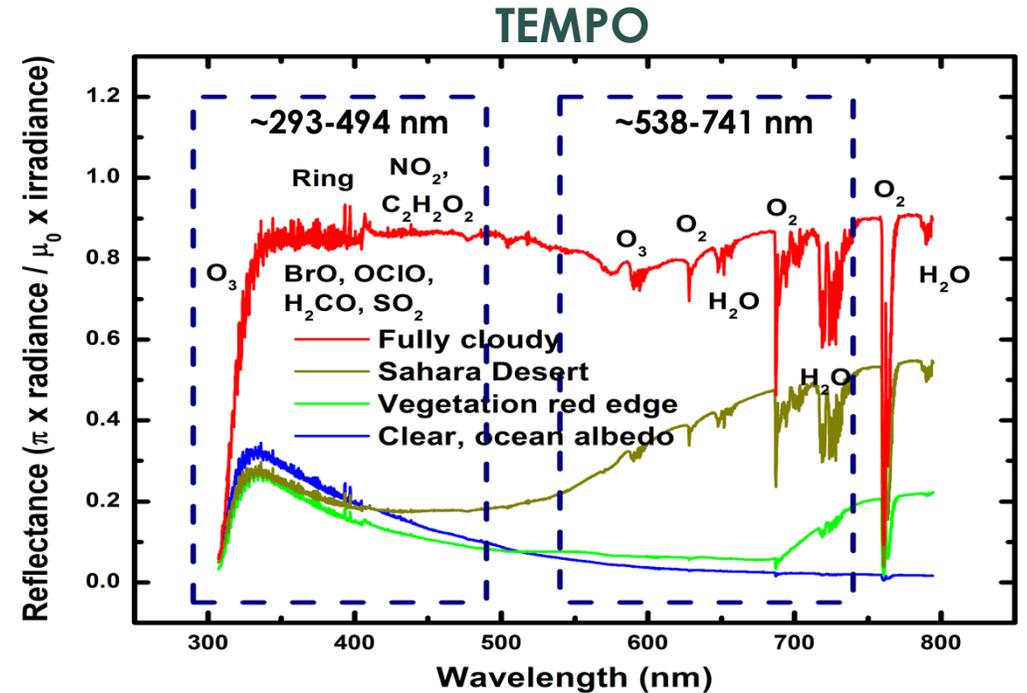


Spectrometer “Hyperspectral” Instruments - TROPOMI & TEMPO



- Band width: 0.55 nm for UV/visible (270-775 nm) & 0.25 nm for shortwave infrared (2305-2385 nm)
- Number of channels: 2600 channels
- Spatial resolution: 5.5 km x 3.5 km (nadir)
- Polar Orbit (LEO), launched October 2017
- Data collection: Nov. 11, 2017 - Present

MODIS Multispectral Band Width:
10-50 nm (19 channels)



- Band width: 0.6 nm for UV (293-494 nm) & visible (538-741 nm)
- Number of channels: ~2056 channels
- Spatial resolution: 2.0 km x 4.75 km (center of Field of Regard)
- Geostationary Orbit (GEO)
- Data collection: Aug. 2, 2023 - Present



Summary of Satellite Instruments

Satellite	Instrument	Orbit	Launch	Relevant Observations
Terra	Moderate Resolution Imaging Spectroradiometer (MODIS)	LEO	1999	Aerosols
Aqua	MODIS	LEO	2002	Aerosols
Suomi National Polar-Orbiting Partnership (Suomi NPP [SNPP])	Visible Infrared Imaging Radiometer Suite (VIIRS)	LEO	2011	Aerosols
National Oceanic and Atmospheric Administration – 20 (NOAA-20)	VIIRS	LEO	2017	Aerosols
NOAA-21	VIIRS	LEO	2022	Aerosols
Sentinel-5 Precursor (S5P)	TROPOspheric Monitoring Instrument (TROPOMI)	LEO	2017	Trace gases (primary) & aerosols (secondary)
Intelsat 40e (IS-40e)	Tropospheric Emissions: Monitoring of Pollution (TEMPO)	GEO	2023	Trace gases (primary) & aerosols (secondary)

Low Earth Orbit (LEO)

Geostationary Earth Orbit (GEO)

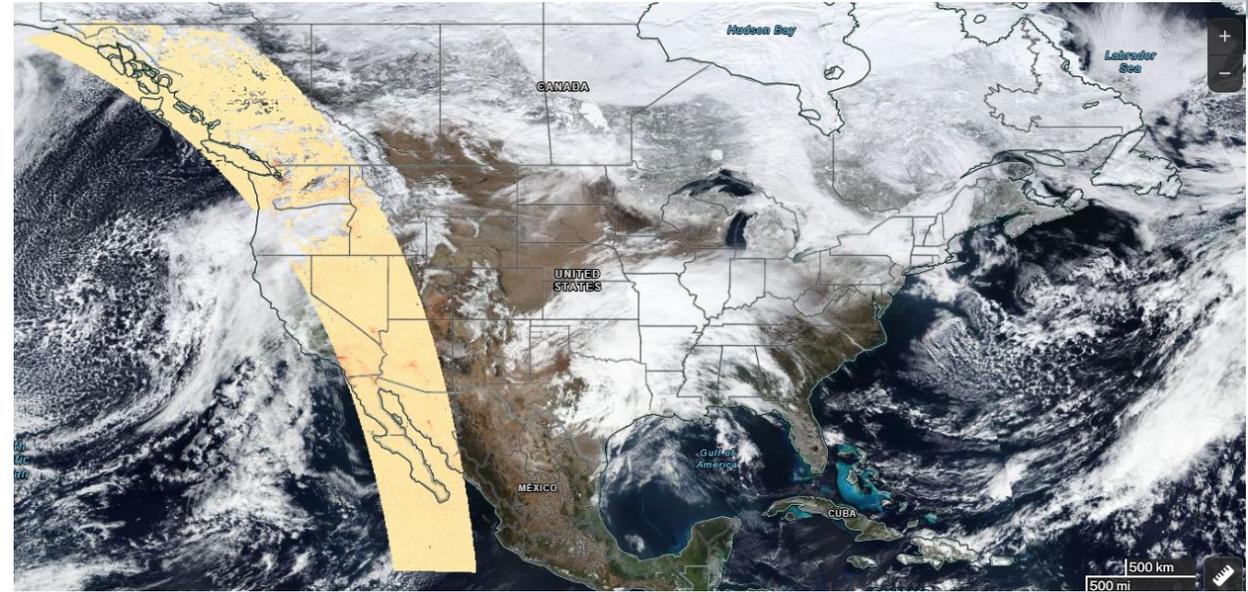


Satellite Data Processing Levels

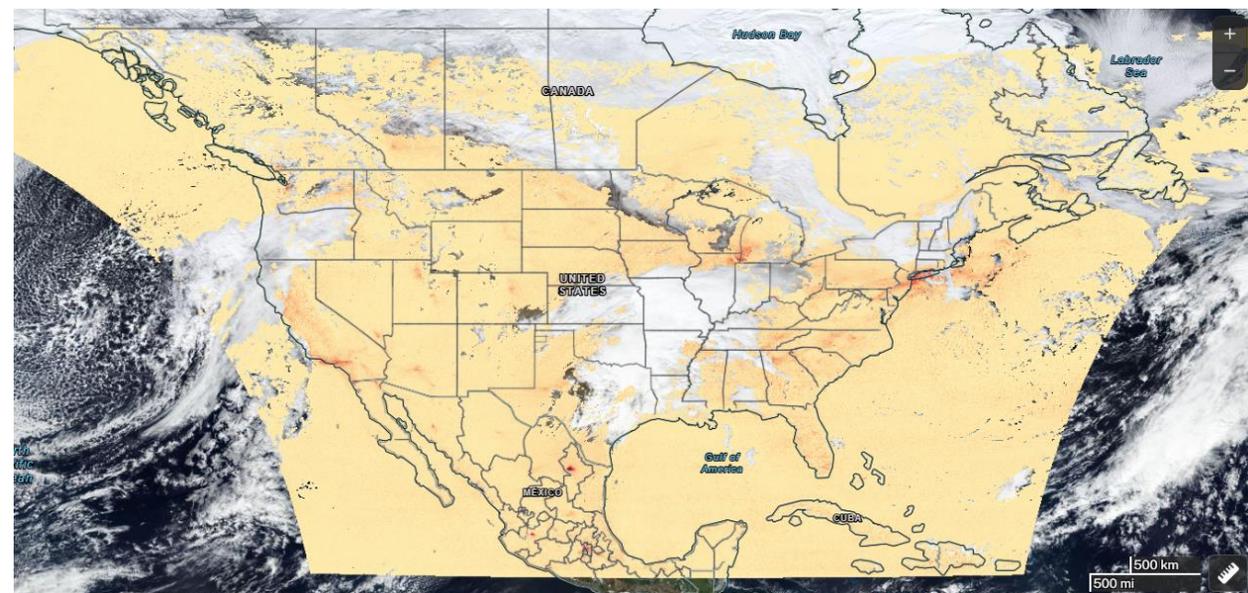
- **Level 0:** Raw data
- **Level 1:** Geo-referenced raw (e.g., radiance) data
- **Level 2:** Derived geophysical variables (e.g., column concentrations)
- **Level 3:** Data re-mapped to uniform space & time grids (usually with recommended quality controls)

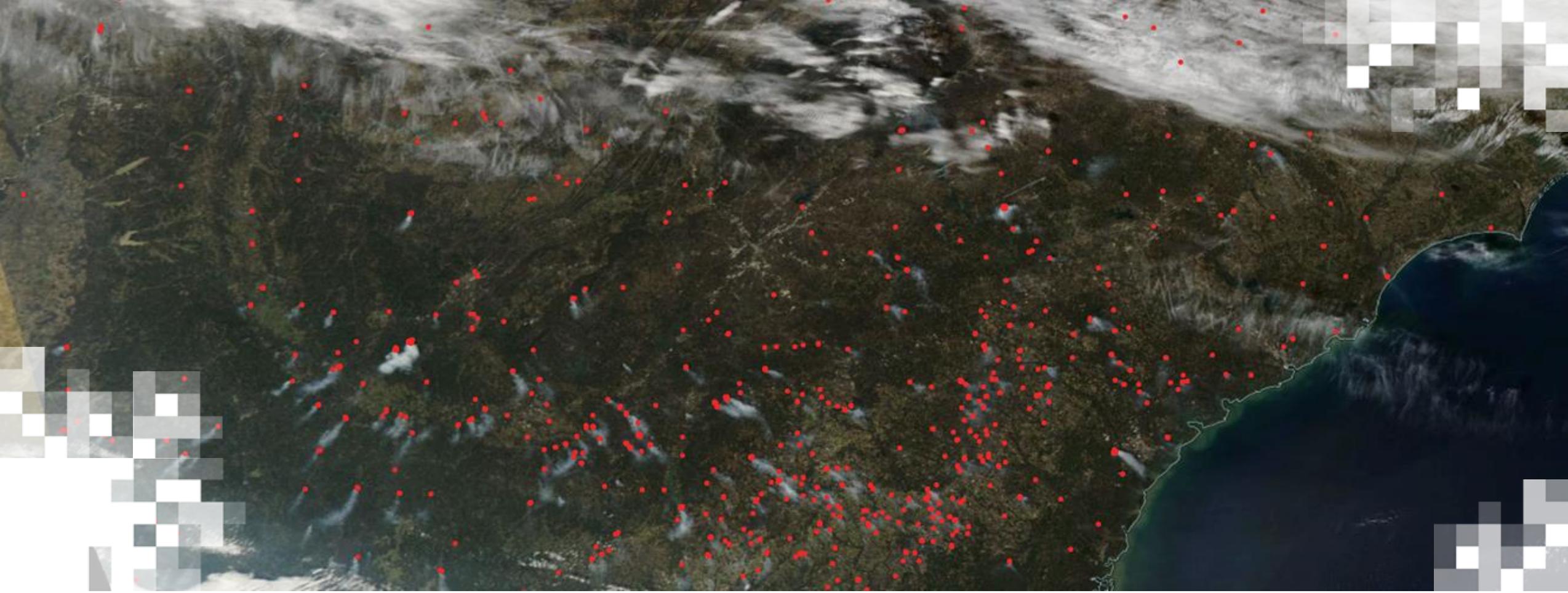
Source: [Data Processing Levels](#). NASA EarthData.

TEMPO Level 2 Data



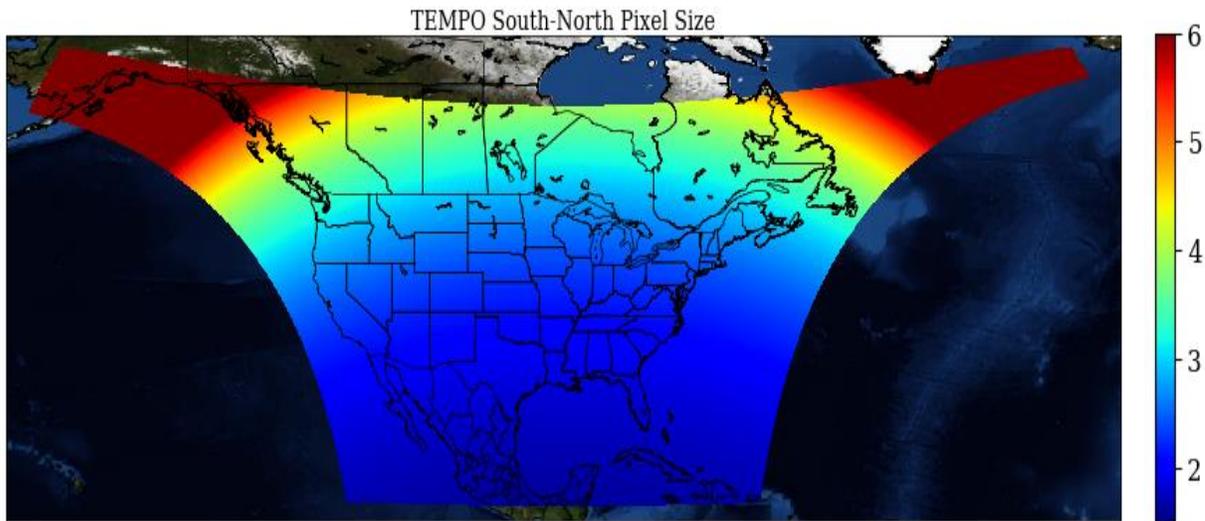
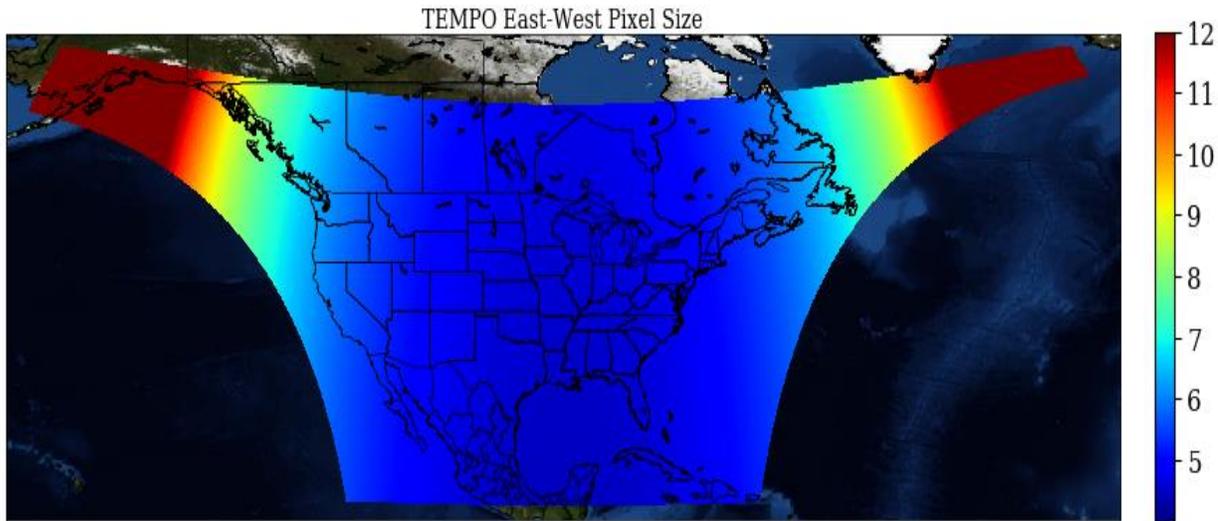
TEMPO Level 3 Data





TEMPO Introduction & Data Products

TEMPO's Footprint Size Across the Field of Regard



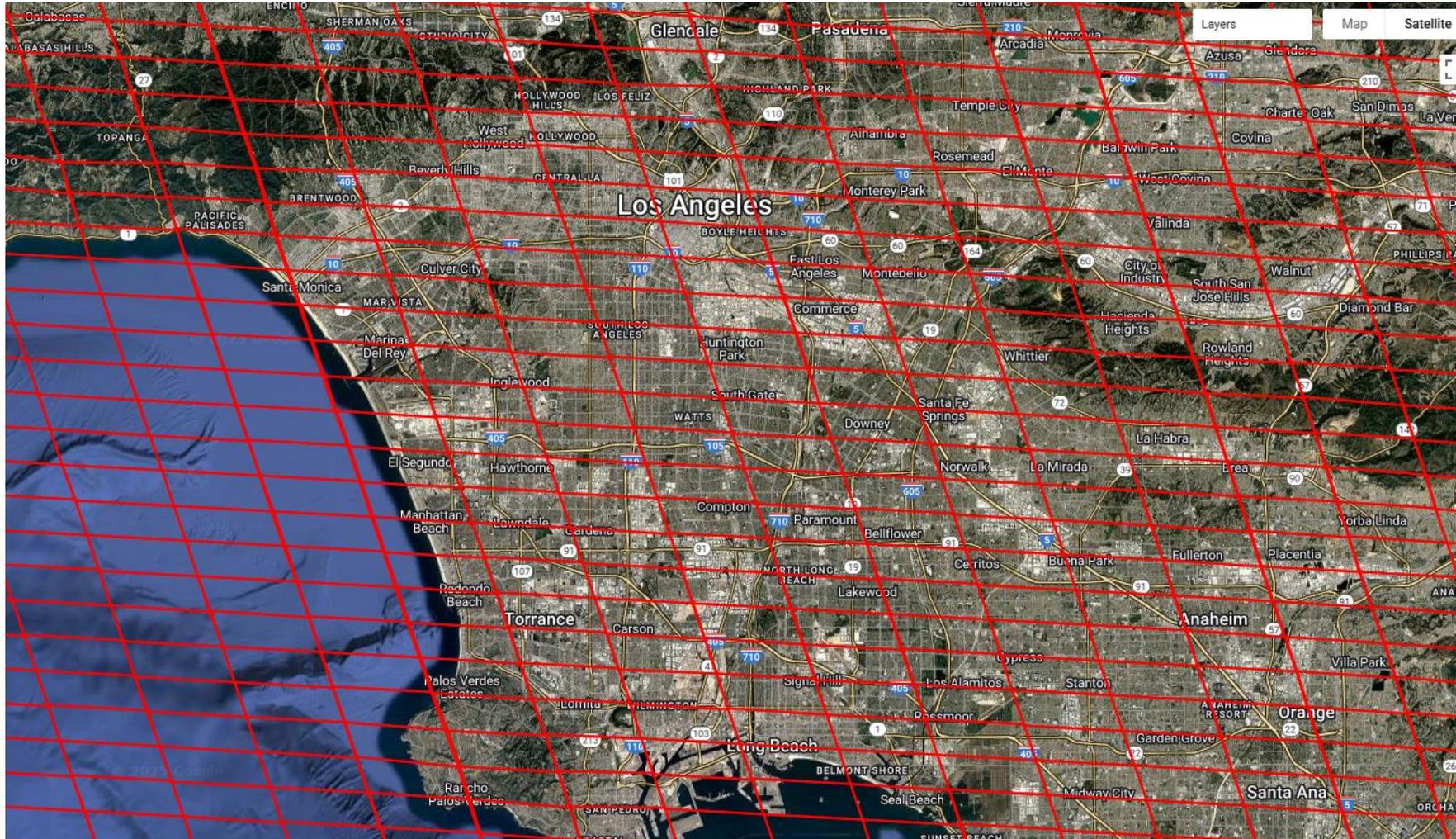
@Center of Field of Regard
33.7°N, 91.7°W

Location	N/S (km)	E/W (km)	VZA (°)
33.7°N, 91.7°W	2.0	4.8	39.1
Washington, DC	2.3	5.1	47.3
Seattle	3.3	6.5	62.5
Los Angeles	2.2	5.8	49.0
Boston	2.5	5.4	52.9
Miami	1.8	4.8	32.4
San Juan	1.7	5.4	35.8
Mexico City	1.6	4.7	24.6
Can. Oil Sands	4.2	5.7	67.4
Juneau	5.9	9.1	75.9



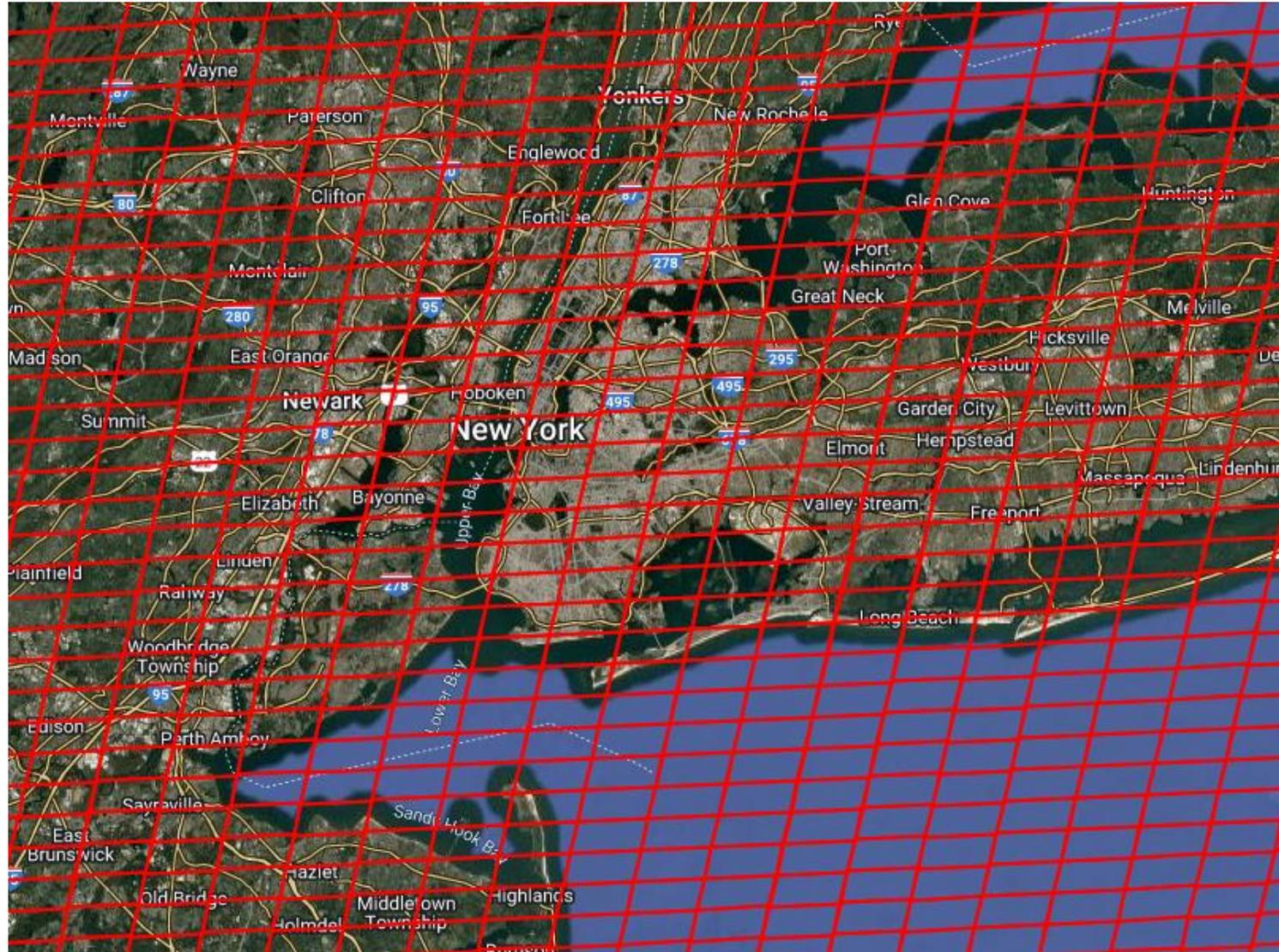
TEMPO's Footprints Across Los Angeles

~ 2.2 km x 5.8 km



TEMPO's Footprints Across New York City

~ 2.4 km x 5.2 km



TEMPO Data Products: Baseline + SNWG NRT + NOAA Aerosol

	Level	Product	Filename	Source	Notable File Variables	Validation Status	Resolution (km ²) *
	L1	Radiance	RAD	Baseline + SNWG	Radiances	Provisional	2.0 x 4.75
		Radiance (twilight)	RADT	Baseline	Radiances	Provisional	2.0 x 4.75
Vertical Column Density (VCD)	L2	Cloud	CLDO4	Baseline + SNWG	Cloud Fraction, Cloud Pressure	Provisional	2.0 x 4.75
		Ozone Total Column	O3TOT	Baseline	Total Column O ₃ , UV Aerosol Index	Provisional	2.0 x 4.75
Aerosol Optical Depth (AOD)	L2	Nitrogen Dioxide	NO ₂	Baseline + SNWG	Tropospheric VCD, Total VCD	Provisional	2.0 x 4.75
		Formaldehyde	HCHO	Baseline + SNWG	Total VCD, Cloud Fraction	Provisional	2.0 x 4.75
		Ozone Profile	O3PROF	Baseline	O ₃ Profile, Tropospheric O ₃ column	Beta	8.0 x 4.75
Aerosol Layer Height (ALH)	L2	AOD & ALH	AODALH	NOAA	AOD, ALH	N/A	2.0 x 4.75
		Aerosol Detection Product (ADP)	ADP	NOAA	Dust/Smoke Discrimination, UV Aerosol Index	N/A	2.0 x 4.75
	L3	Same as L2	Same as L2	Baseline + SNWG	Same Variables as L2	Same as above	0.02°x 0.02° *
	L4	Surface PM _{2.5}	PM25	NOAA	Hourly PM _{2.5} Estimation	N/A	2 km x 2 km

Satellite Needs Working Group (SNWG, low latency version) * @Center of Field of Regard 33.7°N, 91.7°W

National Oceanic and Atmospheric Administration (NOAA) * O3PROF L3 Product → 0.04 x 0.04° Resolution



Future TEMPO Data Products: SNWG NRT + Enhanced

These products have no formal release date yet but are officially funded for the TEMPO mission

Level	Product	Filename	Source	Key Product Variables	Resolution (km ²) *
L2	Glyoxal (C ₂ H ₂ O ₂)	GLYX	SNWG Enhanced	Total VCD, Cloud Fraction	2.0 x 4.75
	Water Vapor (H ₂ O)	H2O	SNWG Enhanced		2.0 x 4.75
	Bromine (BrO)	BRO	SNWG Enhanced		2.0 x 4.75
	Sulfur Dioxide (SO ₂)	SO2	SNWG NRT	Total VCD	2.0 x 4.75
	UVAOD	TBD	SNWG Enhanced	TBD	2.0 x 4.75
	ALH	TBD	SNWG Enhanced	TBD	2.0 x 4.75
	UVB	TBD	SNWG Enhanced	TBD	2.0 x 4.75

* @Center of Field of Regard 33.7°N, 91.7°W

- **NO₂ and HCHO VCDs** - in addition to **C₂H₂O₂, H₂O, BrO** - reported in units of molecules cm⁻²
 - Total number of molecules of a trace gas within a vertical column of the atmosphere directly above a specific Earth surface point
- **Ozone** – in addition to **SO₂** - reported in Dobson Units (DU)
 - Similar to VCDs, except indicates physical thickness (in 0.01 mm units) that a gas would occupy if compressed to standard sea-level pressure and temperature



TEMPO Retrievals – Deriving Slant to Vertical Column Data

$$VCD = \frac{SCD}{AMF}$$

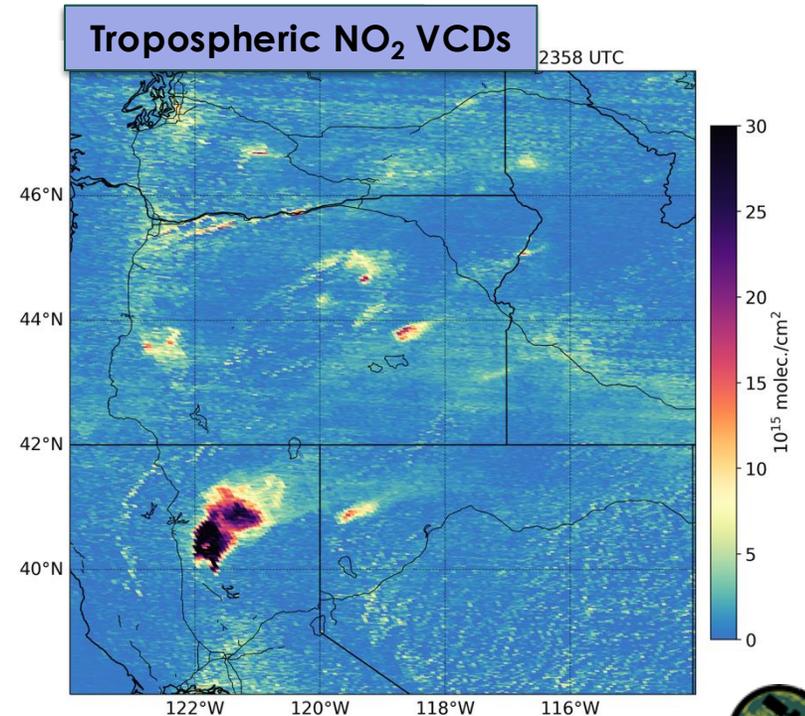
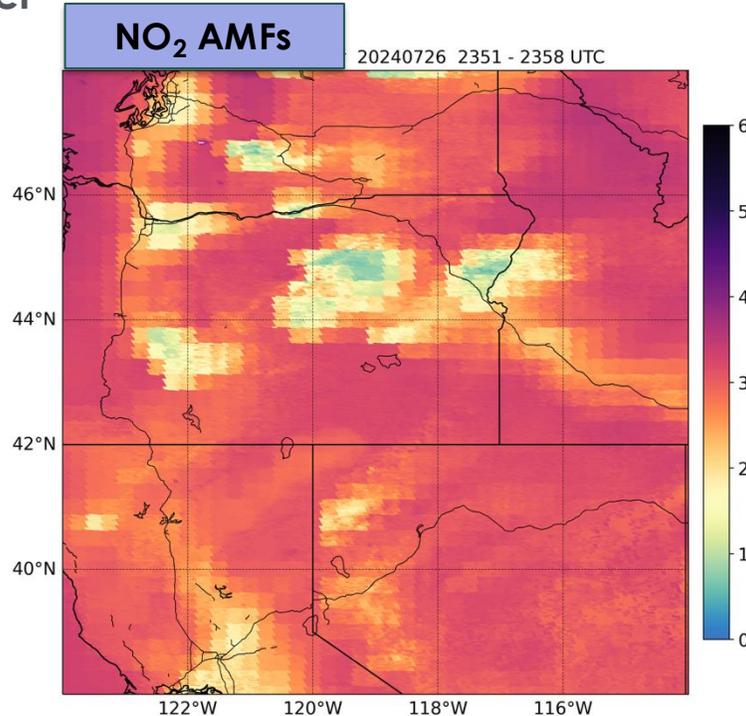
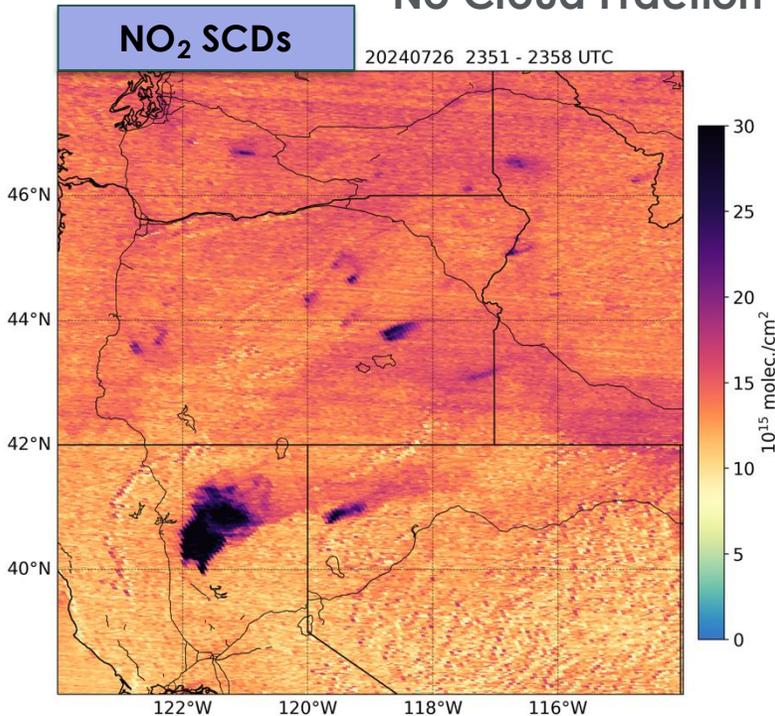
SCD – Slant Column Density

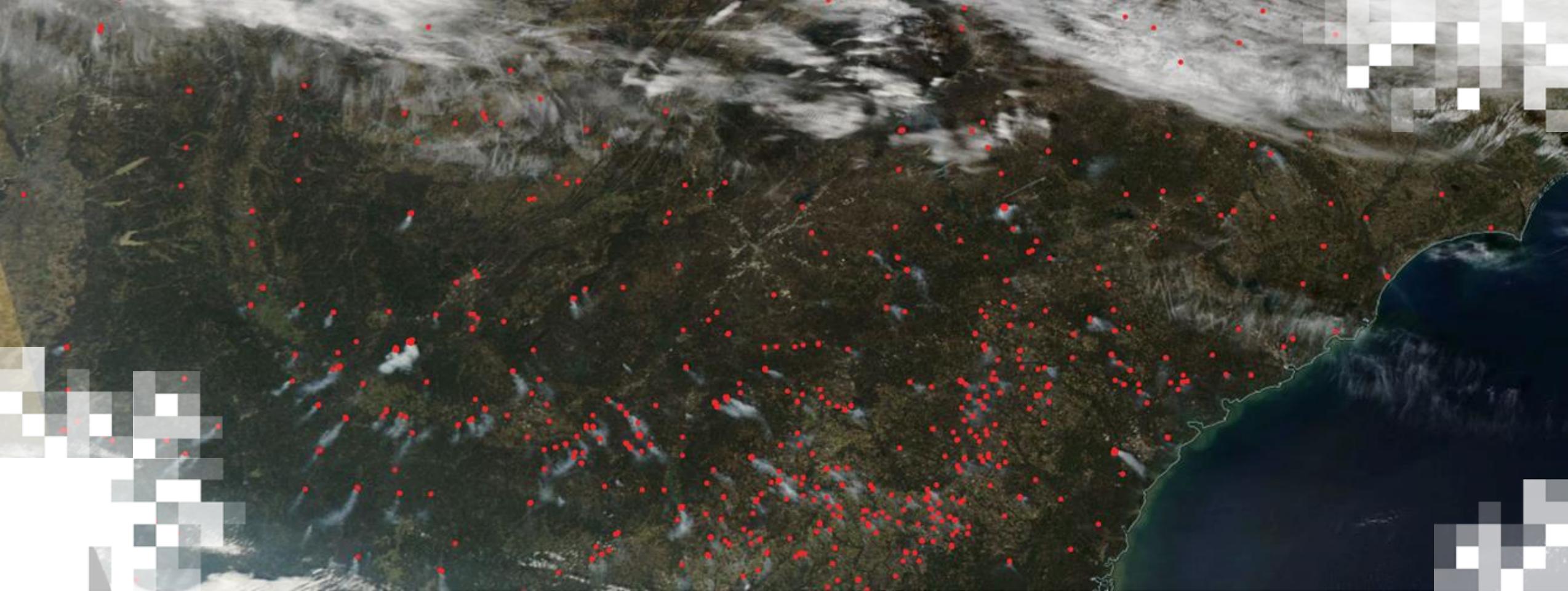
AMF – Air Mass Factor

VCD – Vertical Column Density

- TEMPO's trace gas retrievals are retrieved through the following process:
 - Derive **Slant Column Densities (SCDs)** from measured TOA radiances
 - **Vertical Column Densities (VCDs)** calculated using **Air Mass Factors (AMFs)**
 - **AMFs** calculated offline using radiative transfer model and input from a global 3-D atmospheric composition model [i.e., Goddard Earth Observing System Composition Forecasting (GEOS-CF) System]

No Cloud Fraction Filter

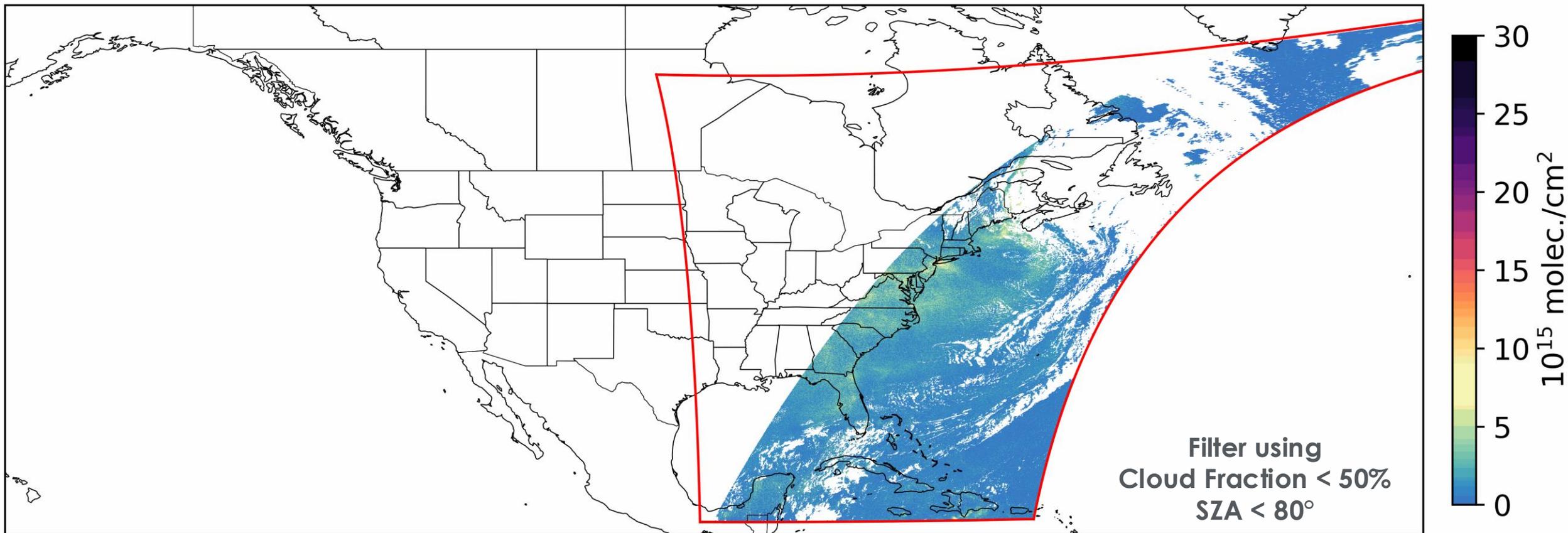




TEMPO Operational Scan Modes

Nominal Operational Scans – Example for November 4, 2025

TEMPO Tropospheric NO₂ 20251104 1232 - 1305 UTC



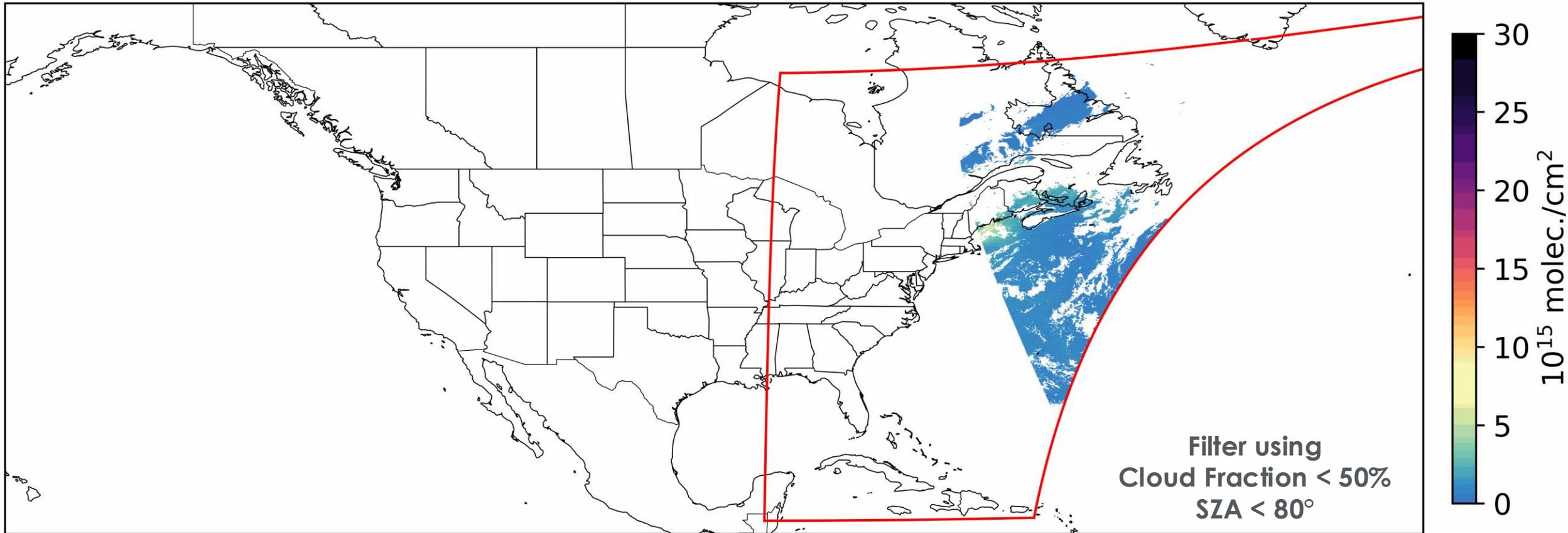
Nominal operations consist of both:

- Standard (hourly) daytime scans over full FoR and
- “Optimized”, shorter (30-40 minute) morning and afternoon scans over daylight portions of FoR



Special Operation Scans – Example for July 25, 2025

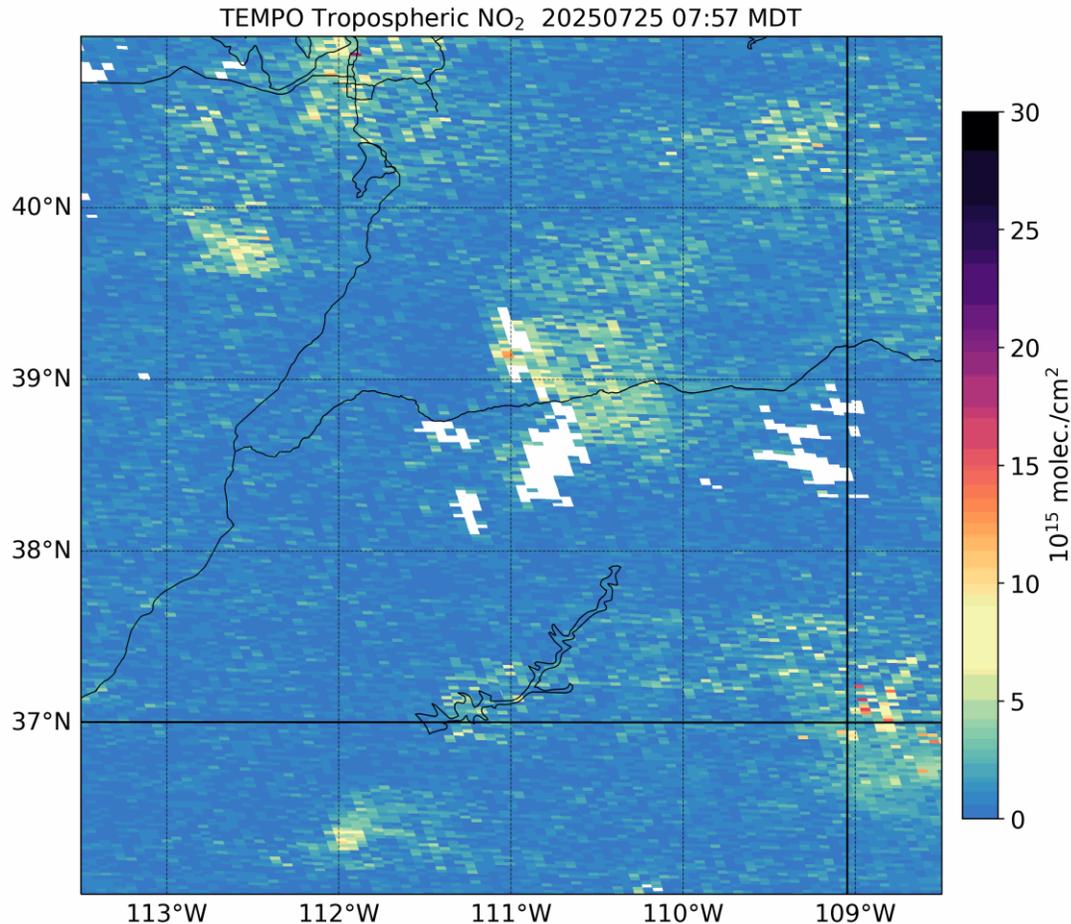
TEMPO Tropospheric NO₂ 20250725 1037 - 1103 UTC



- Special operations scans (~10 minutes) were conducted for a 4-day period from July 25-28, 2025, over the West U.S region every other hour throughout the daytime.



U.S. West Zoom on July 25, 2025 & TEMPO Operations Log



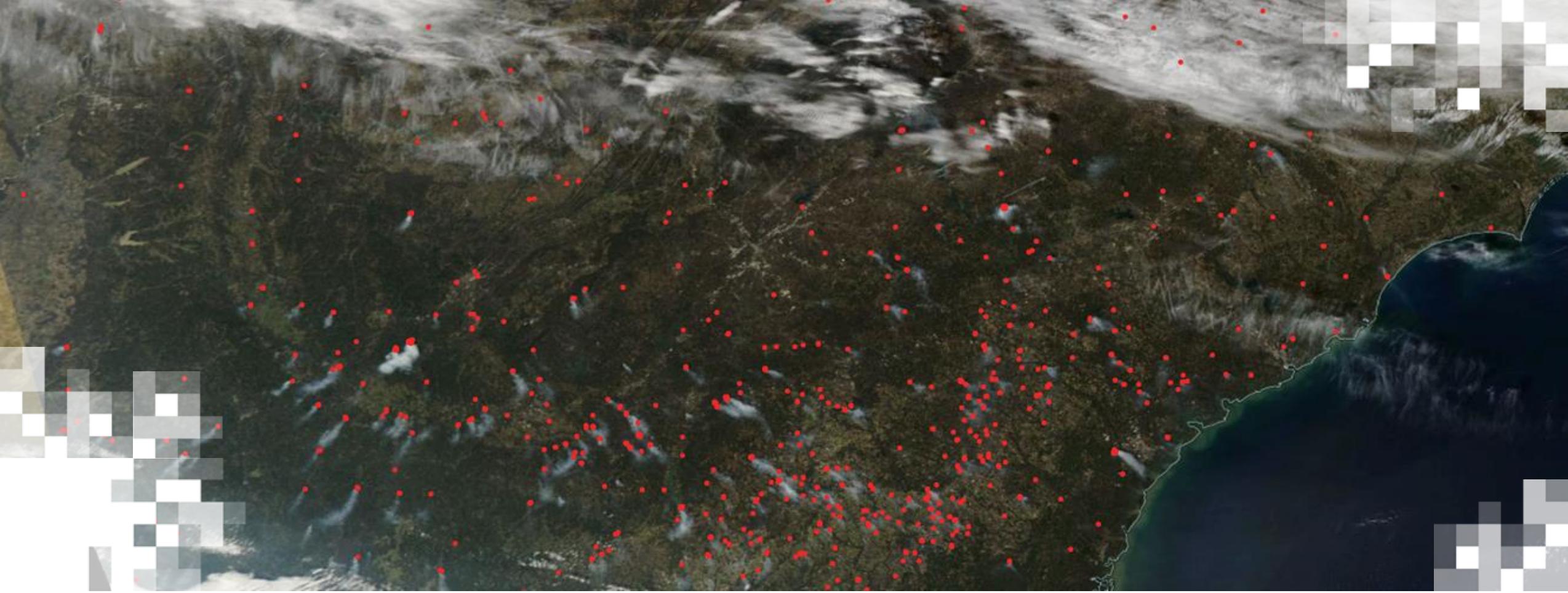
- Days when special operations were conducted can be found in the TEMPO [Operations Log](#)

QR Code for TEMPO Operations Log



- Zoom to the location of special operations in U.S West region shows a strongly evolving NO₂ plumes associated with two wildfire smoke events, Dragon Bravo and Monroe Canyon fires.





Quality Assurance & Data Filtering

Quality Assurance Recommendations – TEMPO NO₂ & HCHO

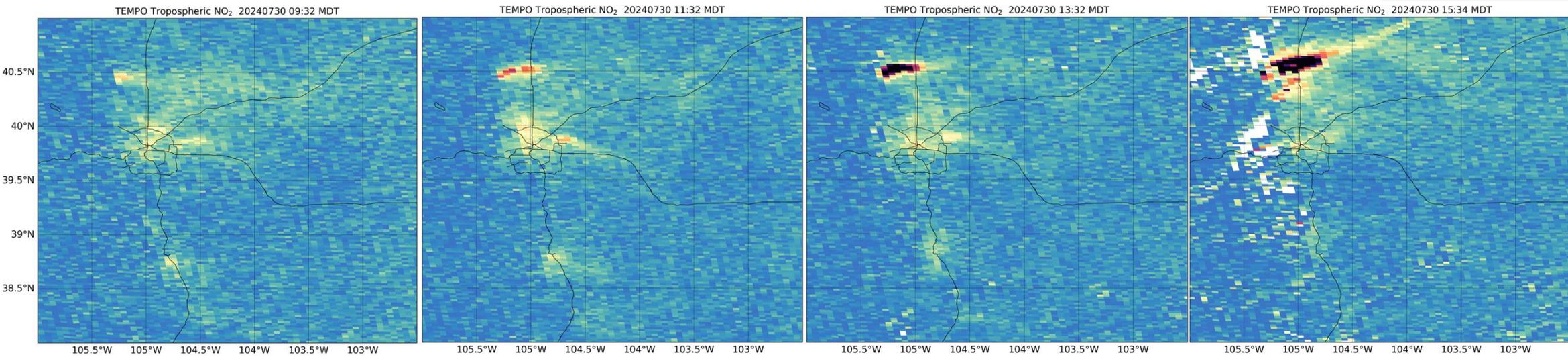
QA Parameter	Variable (group)	Range	Qualitative Use (Worldview)	Quantitative Use
Effective Cloud Fraction (ECF)	eff_cloud_fraction (support_data)	0 – 1.0	< 0.5	< 0.1
Solar Zenith Angle (SZA)	solar_zenith_angle (geolocation)	0 – 90°	< 80°	< 70°
Main Data Quality Flag	main_data_quality_flag (product) “0” = High-quality “1” = Suspect due to AMF & viewing geometry “2” = Outlier retrievals or no successful AMF calculation	0 to 2	< 2	= 0



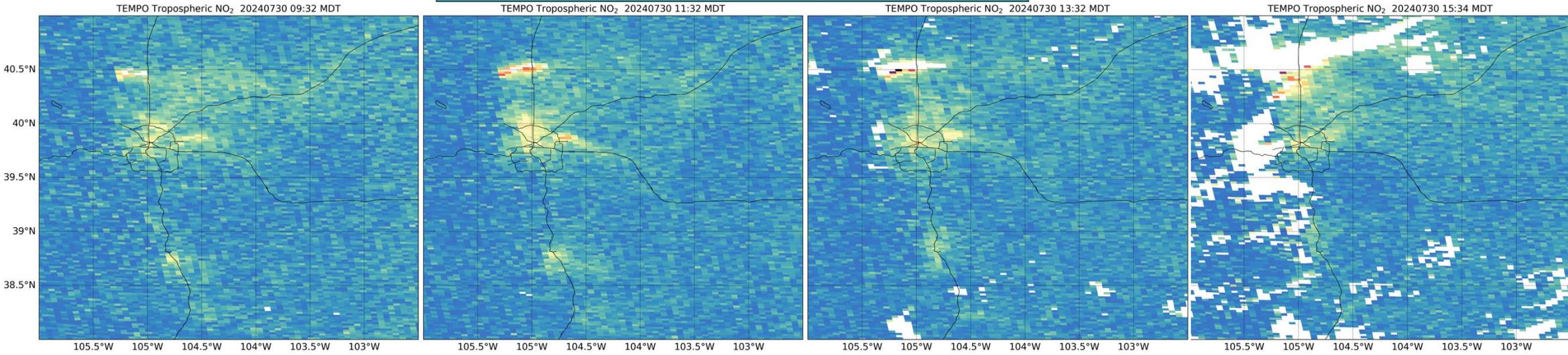
Comparing Quality Assurance Thresholds – TEMPO NO₂

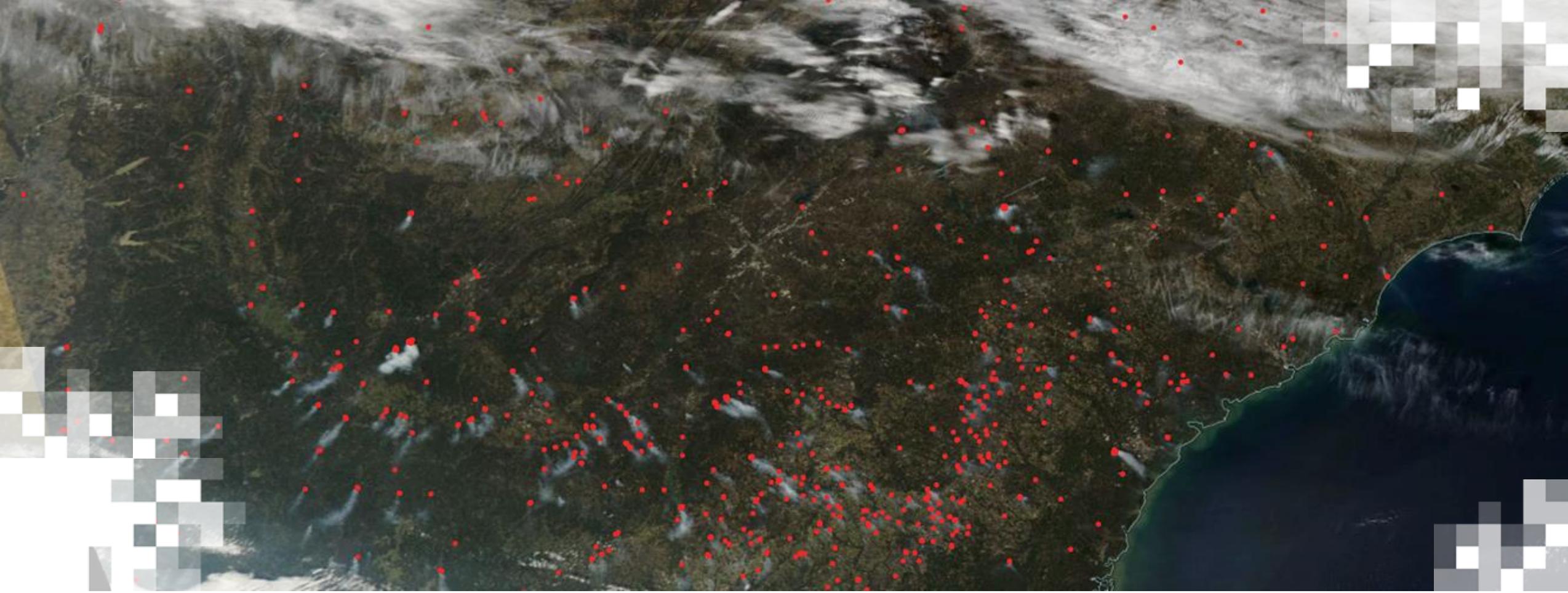
Thresholds used for Worldview visualizations

Cloud Fraction < 50%, SZA < 80°, Flag < 2



Cloud Fraction < 10%, SZA < 80°, Flag = 0

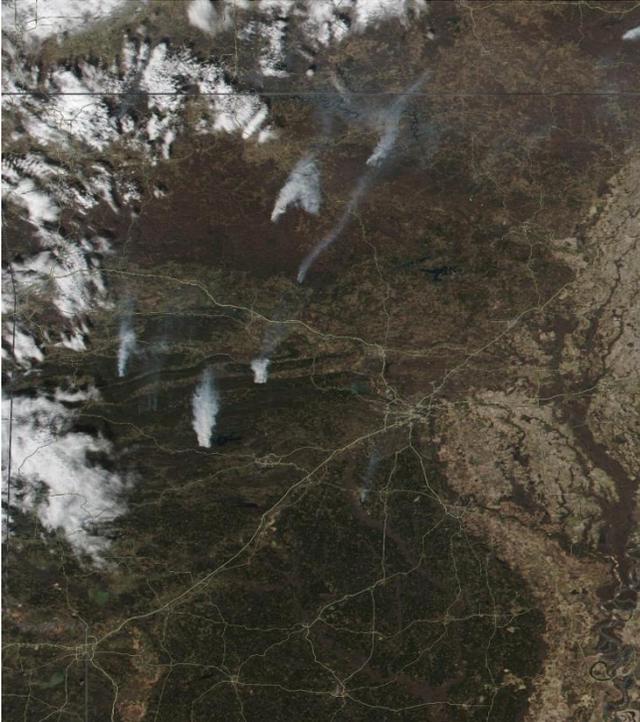




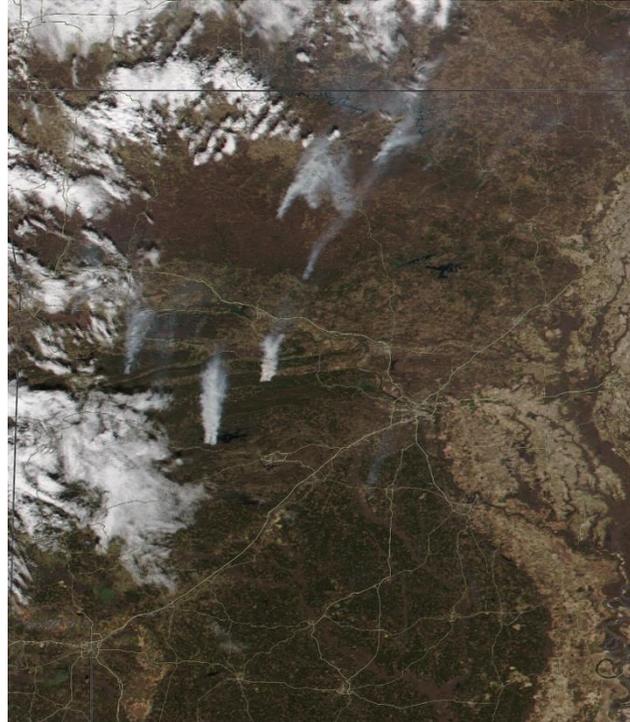
Wildfires in Arkansas – February 28, 2026

True Color Imagery from Worldview

Suomi-NPP VIIRS @ ~1910 UTC



NOAA-20 VIIRS @ ~1930 UTC



Aqua MODIS @ ~2025 UTC

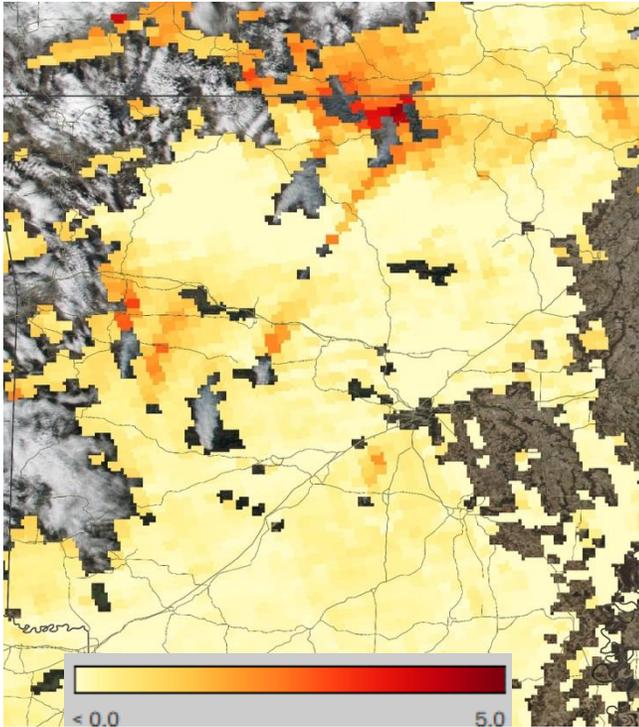


- Numerous wildfires erupted across Arkansas on Feb. 28, 2026.
- True color imagery (**resolution 250 m**) from VIIRS and MODIS shows the increase in smoke intensity during the midday through early afternoon period.



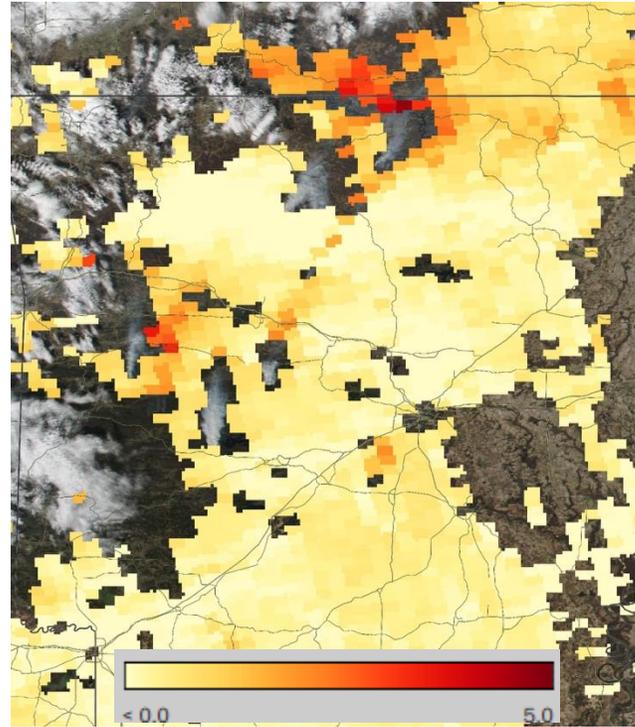
Aerosol Optical Depth (AOD) from Worldview

Suomi-NPP VIIRS @ ~1910 UTC



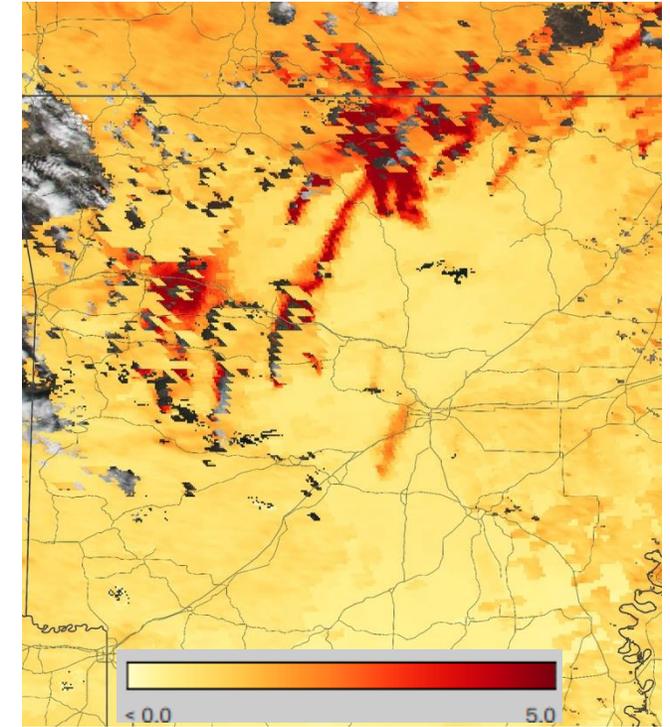
2 km resolution

NOAA-20 VIIRS @ ~1930 UTC



2 km resolution

Merged Terra + Aqua MODIS

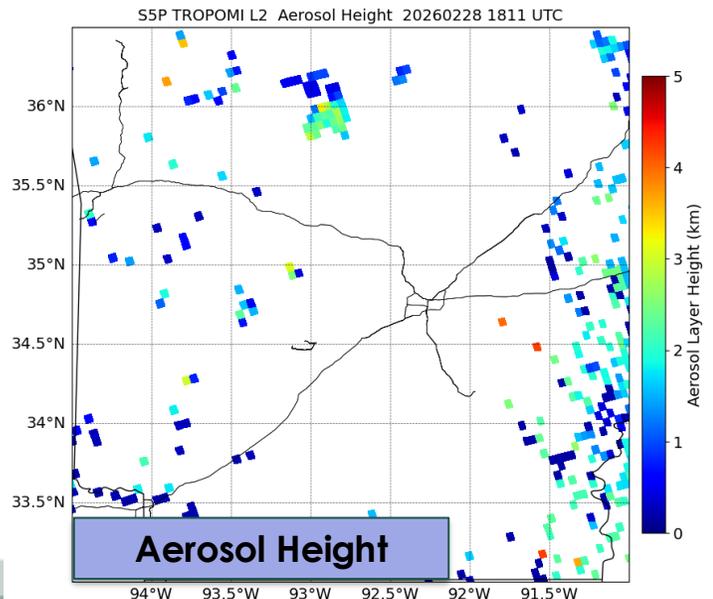
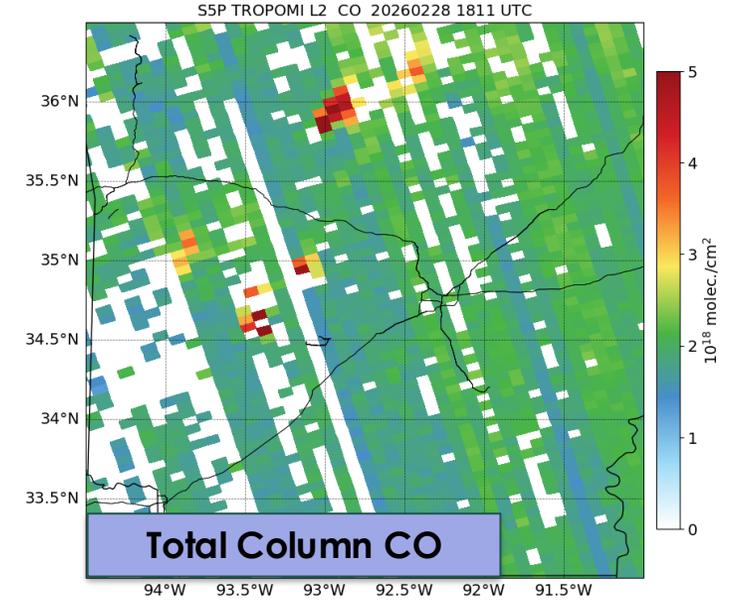
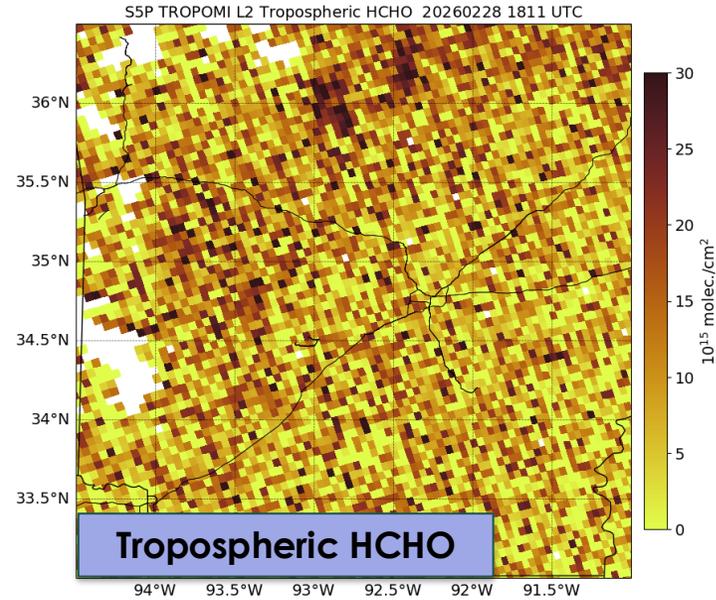
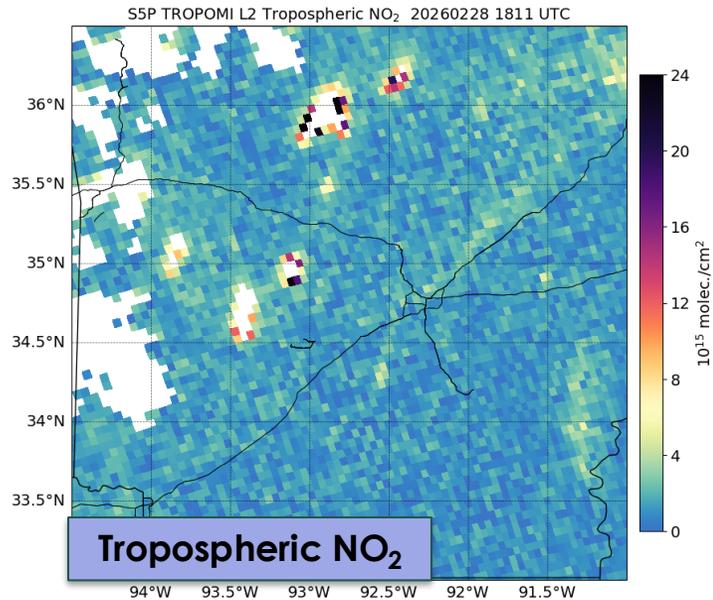


1 km resolution

- AOD - unitless quantity that measures the amount of light removed by scattering and absorption by aerosols along an atmospheric path.
- AOD measured at mid-visible wavelengths (500-550nm) is reasonably representative of total aerosol concentration.
- Dense clouds, smoke, and dust interfere with AOD retrieval.



TROPOMI Trace Gas & Aerosol Products

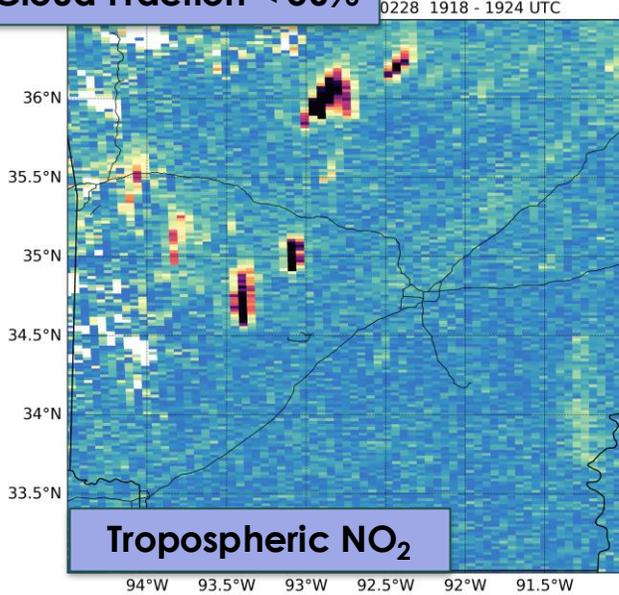


- TROPOMI provides NO₂, HCHO, and CO data during the midday period for supporting wildland fire smoke plume monitoring.
- Strictest quality assurance recommended for TROPOMI led to removal of NO₂ data within smoke plumes.
- CO is an excellent tracer for smoke plumes.
- TROPOMI Aerosol Height resolves information on the smoke plume height of the largest wildfire in the scene.

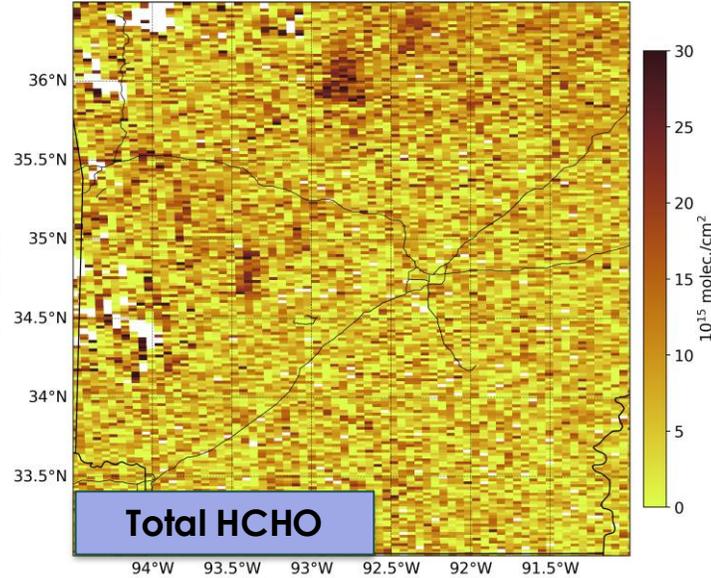


TEMPO Trace Data Comparisons - NO₂ & HCHO

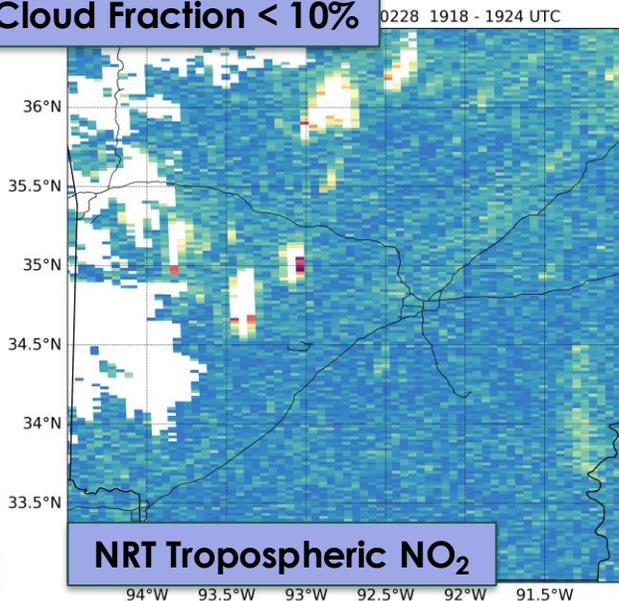
Cloud Fraction < 50%



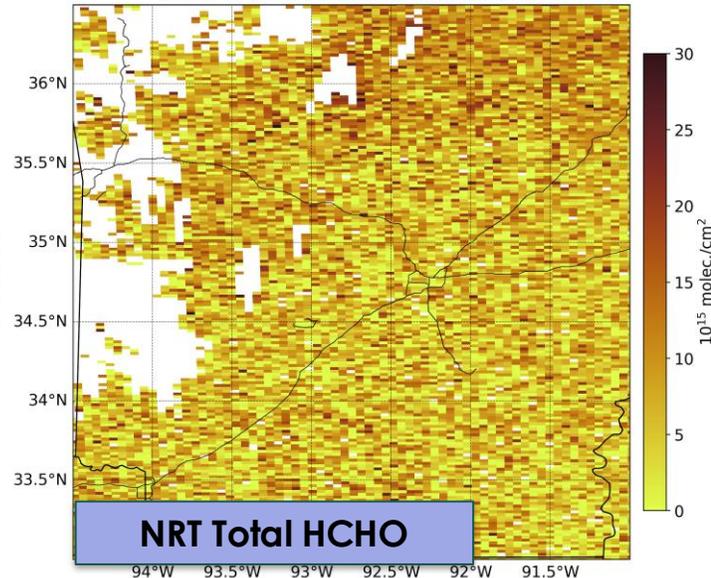
TEMPO Total HCHO 20260228 1918 - 1924 UTC



Cloud Fraction < 10%



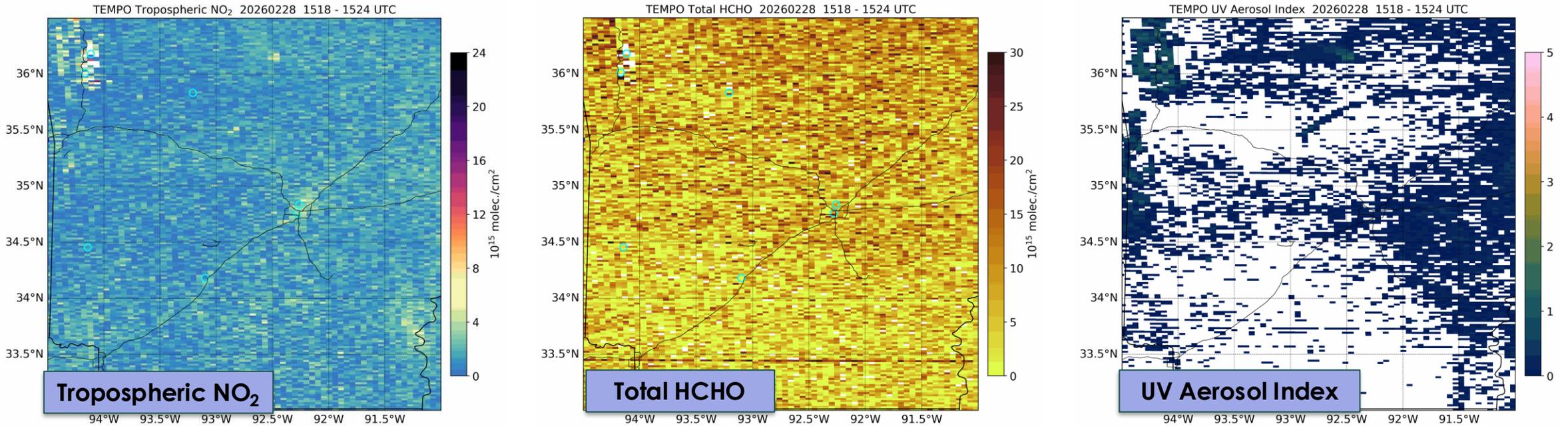
TEMPO Total HCHO 20260228 1918 - 1924 UTC



- TEMPO observes large NO₂ and HCHO plumes associated with the wildfire smoke plumes.
- Use of strictest recommended cloud fraction filter of 10% removes the NO₂ data within the smoke plumes.
- A close comparison between TEMPO near real-time (NRT) and standard data.
- More stripping in the HCHO NRT compared to the HCHO standard data due to less robust radiance calibration method in NRT retrieval.

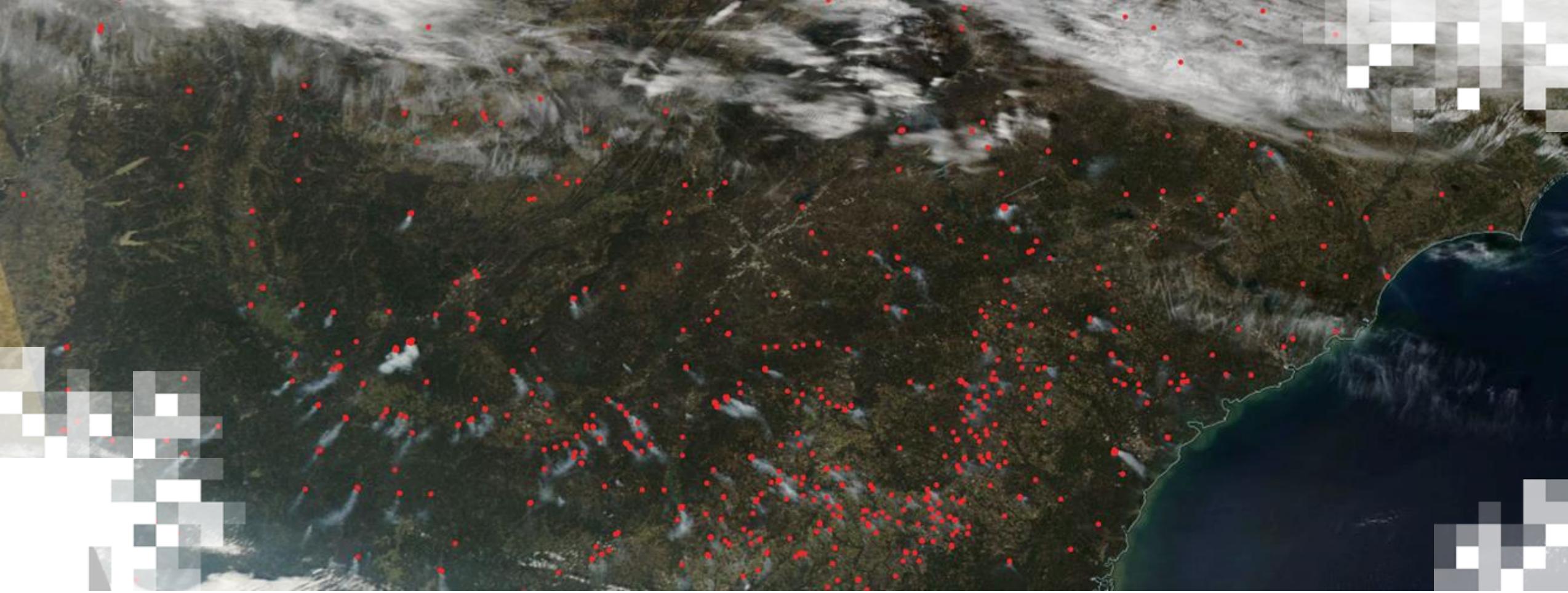


TEMPO Data - NO₂, HCHO, & UV Aerosol Index Animations



- TEMPO observes tracks the transport and evolution of the NO₂ and HCHO columns within smoke plumes.
- Strongly positive UV aerosol index associated with the absorbing smoke particles.
- Cloud cover limits TEMPO's ability to monitor the smoke plumes during the final several scans of the afternoon.



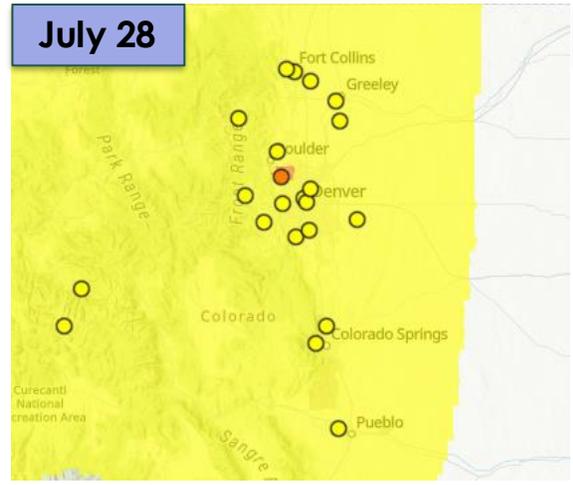


Wildfires in Colorado – July 28-31, 2024

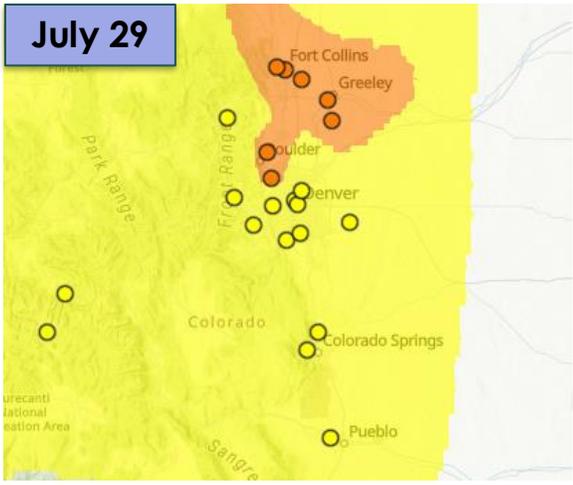
TEMPO Data – AirNow O₃ monitors & TEMPO Data



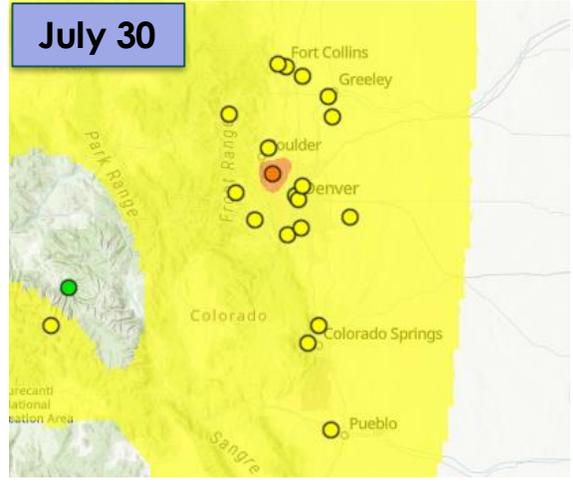
July 28



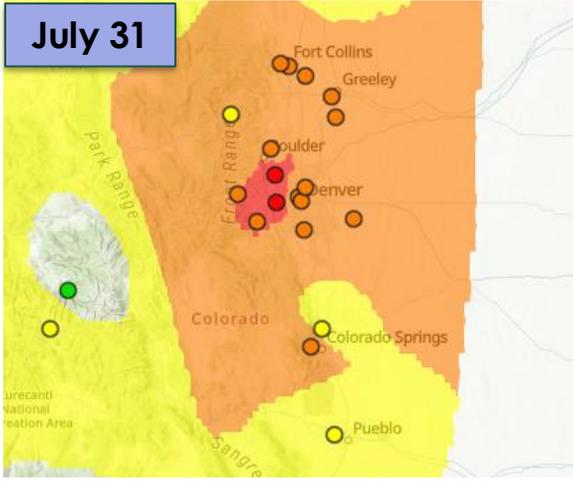
July 29



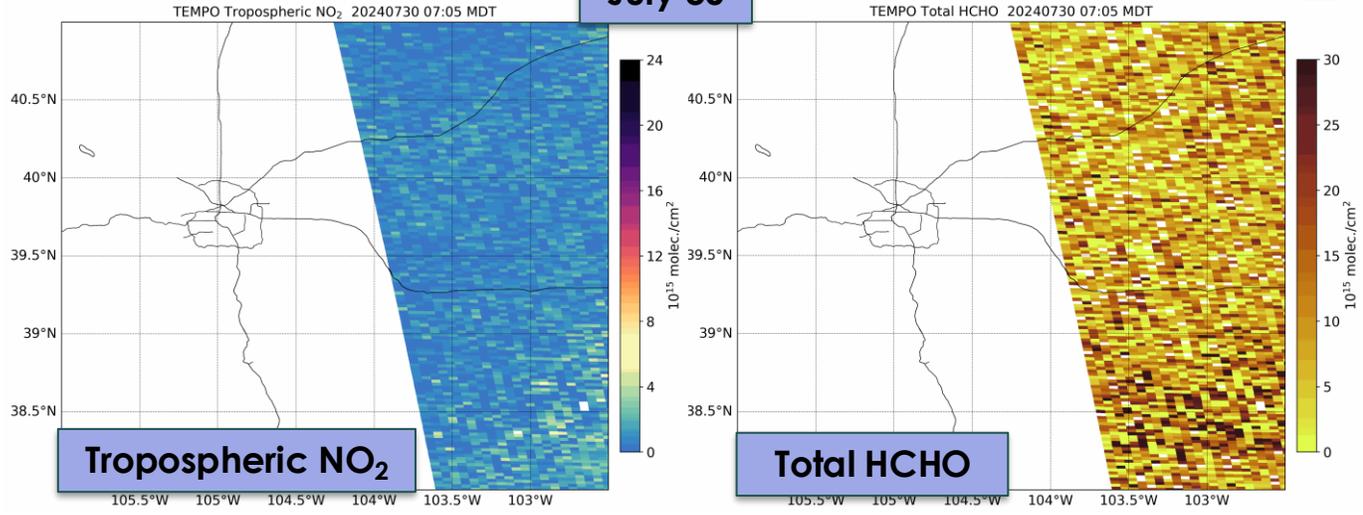
July 30



July 31

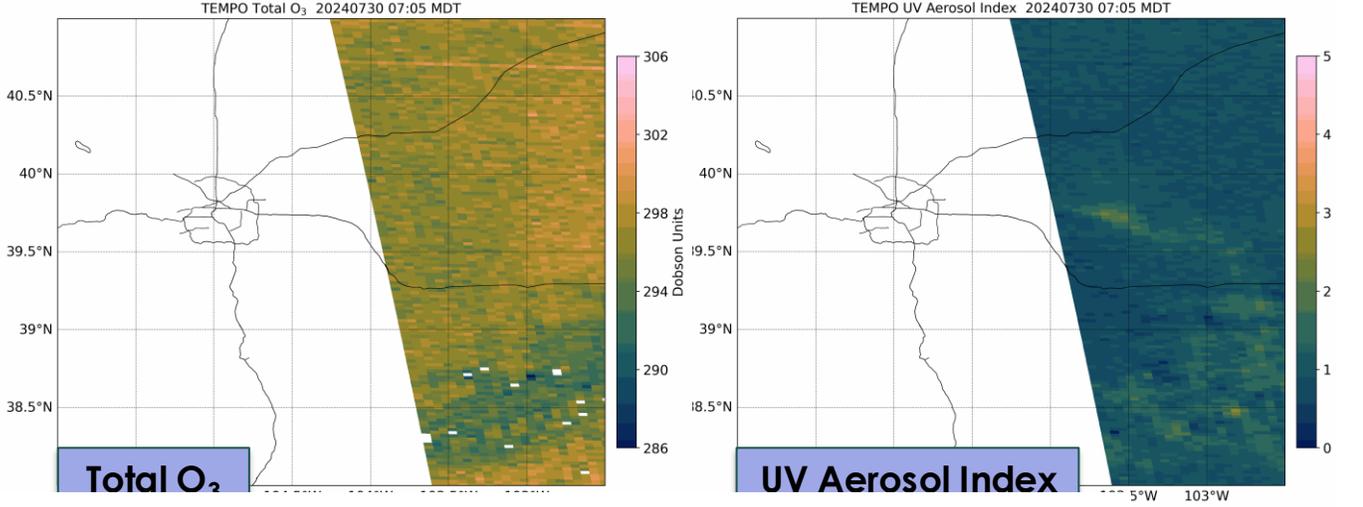


July 30



Tropospheric NO₂

Total HCHO



Total O₃

UV Aerosol Index

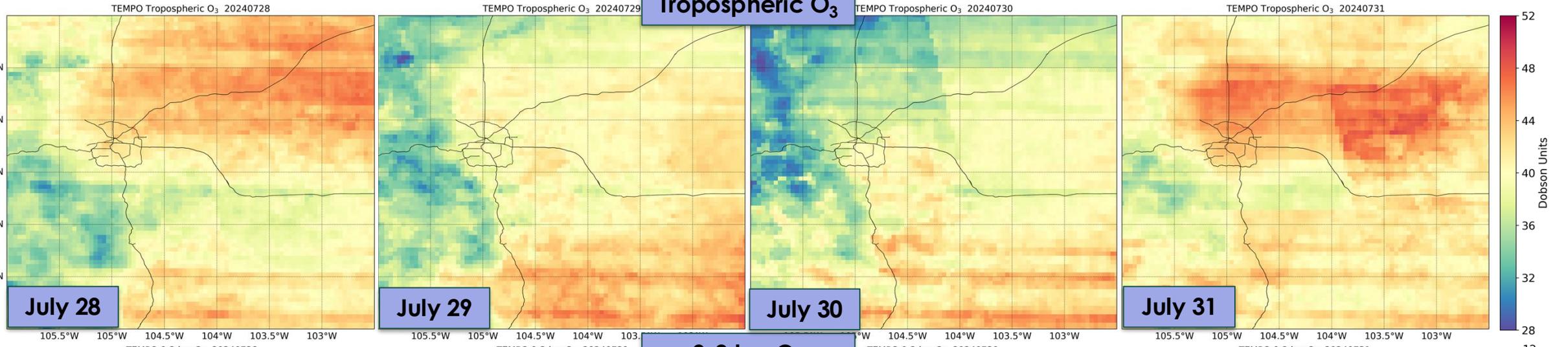
- Monitors measured unhealthy O₃ starting July 29 as multiple wildfires erupted along the CO Front Range.
- TEMPO observed the enhanced NO₂ and HCHO plumes in addition to increased O₃ columns associated with the wildfire smoke.



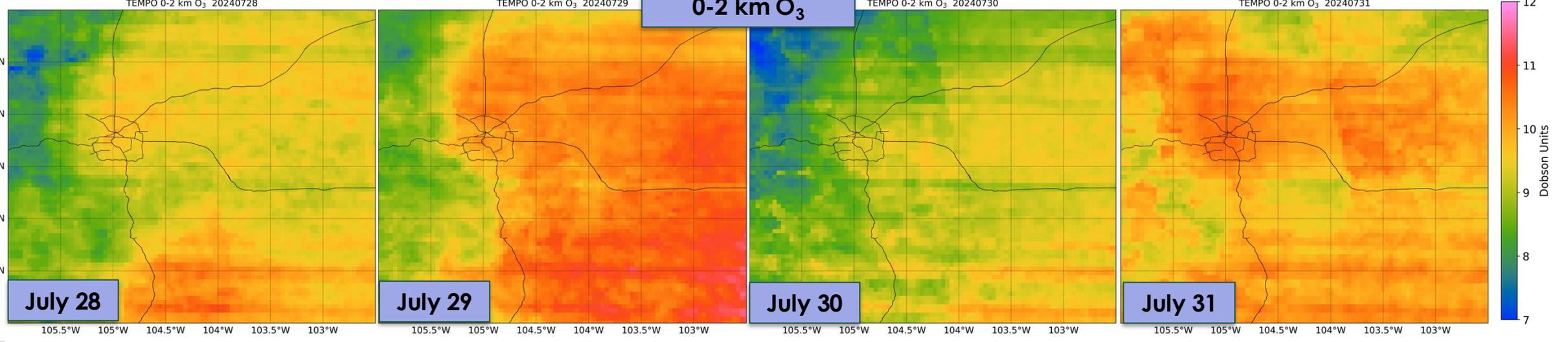
TEMPO Data – Tropospheric & 0-2 km O₃ (Daily Averages)



Tropospheric O₃

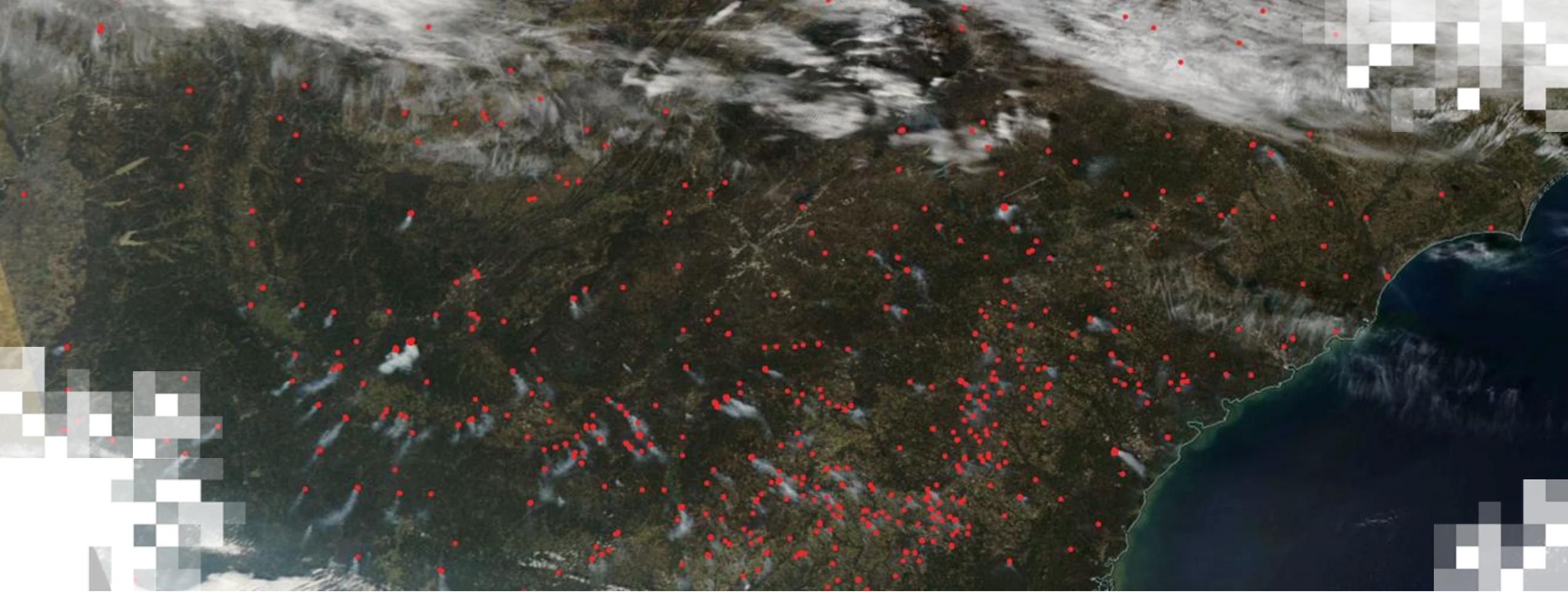


0-2 km O₃



- O₃ profile performed well in terms of capturing the general trends in O₃ levels observed by monitors.

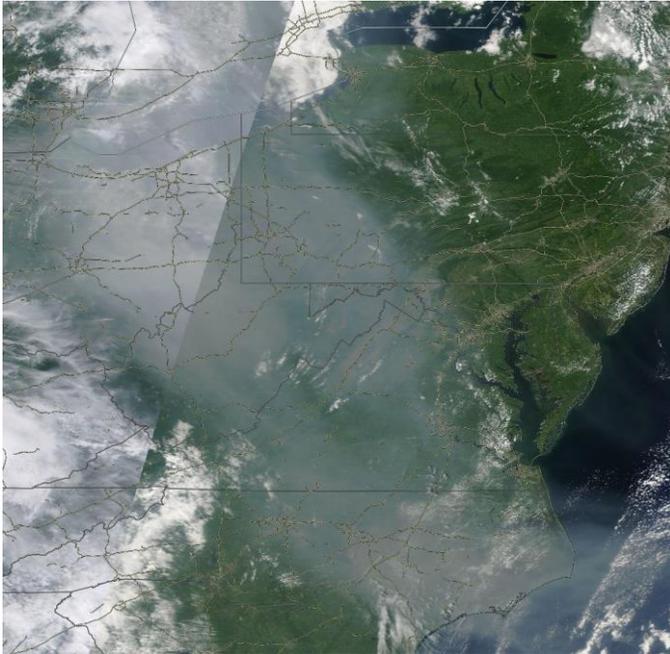




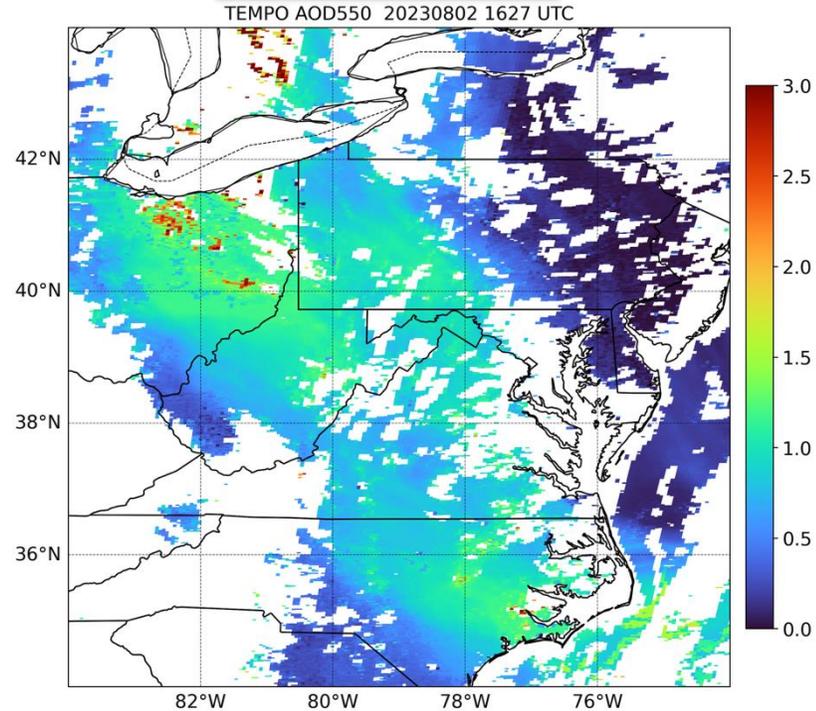
Canadian Wildfires – August 2, 2023

TEMPO Aerosol Data – AOD and Aerosol Layer Height (ALH)

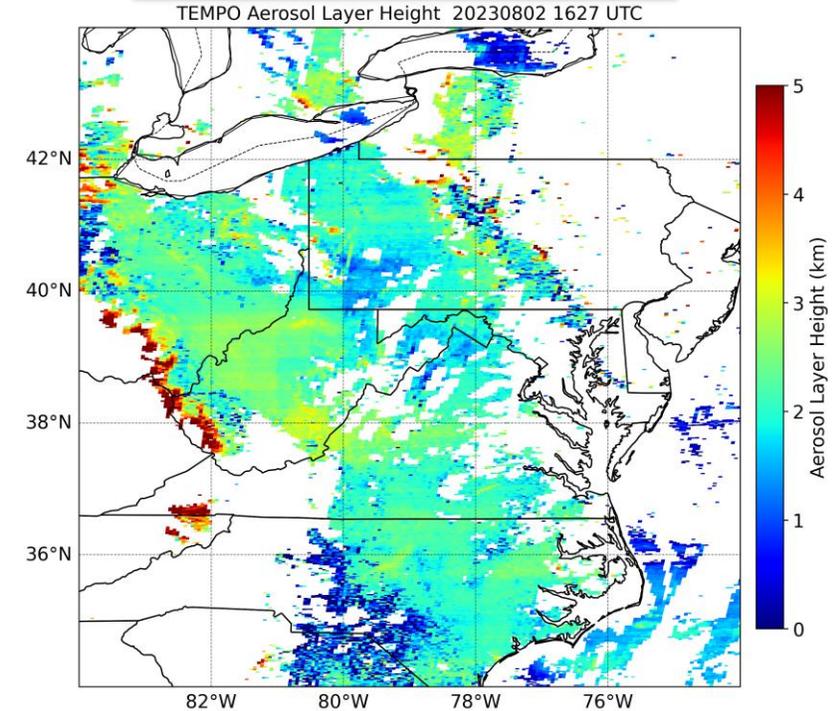
MODIS Terra True Color



TEMPO AOD



TEMPO Aerosol Layer Height



- Large smoke plumes were transported from Canada over the eastern U.S. in early August 2023.
- TEMPO AOD observed values exceeding 1 within much of the transported smoke plume.
- TEMPO ALH showed the variability of smoke plume height with generally lower heights (smoke plume closer to the surface) as the smoke was transported farther downwind from the source.



Summary

- TEMPO's hyperspectral capability across ultraviolet to visible wavelengths enables retrieval of criteria trace gas pollutants at unprecedented spatial and temporal resolution across North America.
- Its hourly, daylight observations and special observation modes allow for monitoring rapidly evolving pollutants from events such as wildland fires for supporting air quality analysis & forecasting.
- TEMPO's high spatial resolution resolves gradients in small-scale wildland fires, such as prescribed burns, which TROPOMI is unable to observe.
- TEMPO near real-time NO₂, HCHO, and aerosol (expected release Aug. 2026) data will be valuable for real-time smoke monitoring and forecasting.
- The newly-available O₃ profile product offers enhanced capabilities to monitor and characterize ozone in the troposphere and add more insight into air quality impacts of the near-surface ozone.
- TEMPO NO₂ and HCHO data has larger uncertainties in smoke since aerosols are not explicitly accounted for in the TEMPO retrieval method.
 - Qualitative use of NO₂ and HCHO is recommended in wildland fire smoke scenes.
 - Less strict cloud fraction threshold is usually required to visualize NO₂ and HCHO plumes in smoke.



Contact Information

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For questions, comments, or to share how you have applied our trainings to your work or studies, email nasa.arset@gmail.com.

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1. Send an email with no subject line to arset-join@lists.nasa.gov.
2. Follow the instructions sent in response.



Resources

- TEMPO Project page:
 - <https://asdc.larc.nasa.gov/project/TEMPO>
- NASA Worldview for Visualizations of TEMPO and TROPOMI:
 - <https://worldview.earthdata.nasa.gov/>
- Google Earth Engine for Visualizations of TEMPO and TROPOMI:
 - <https://developers.google.com/earth-engine/datasets/catalog/>
- NASA SPoRT viewer for TEMPO data
 - <https://weather.ndc.nasa.gov/sport/viewer/?dataset=tempo12nrt>





Thank You!

