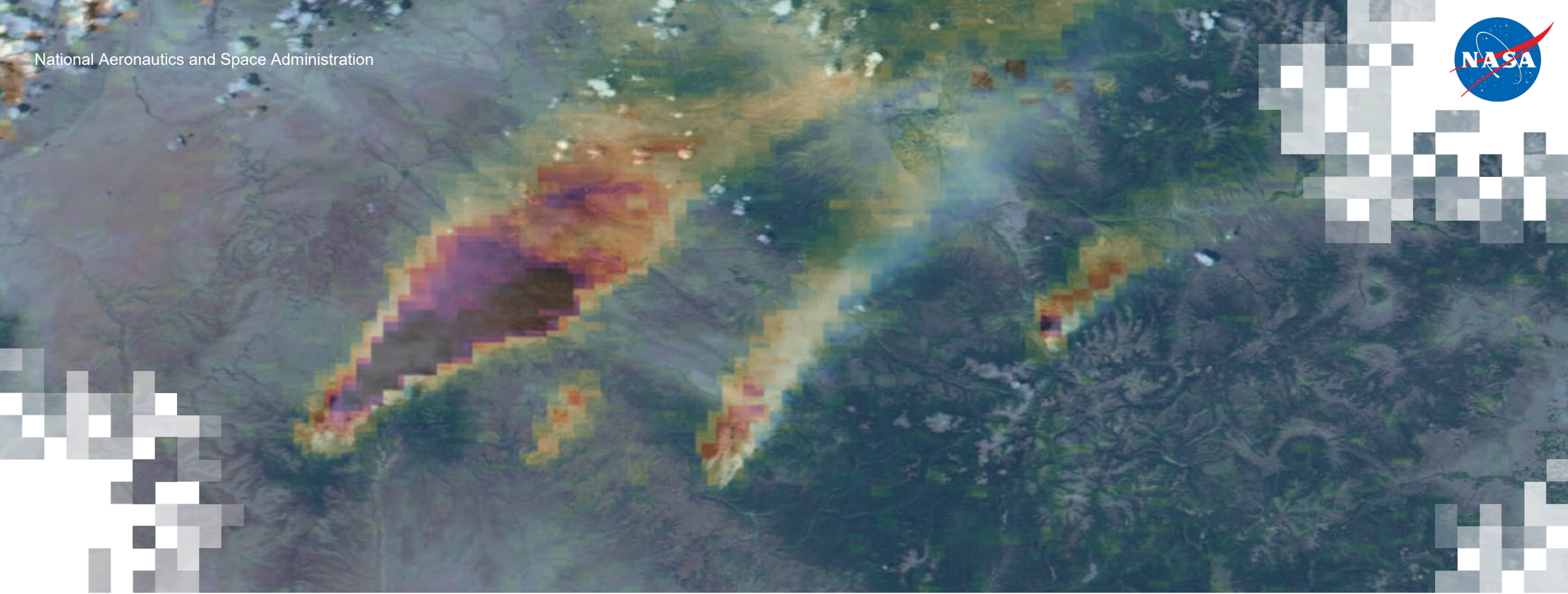




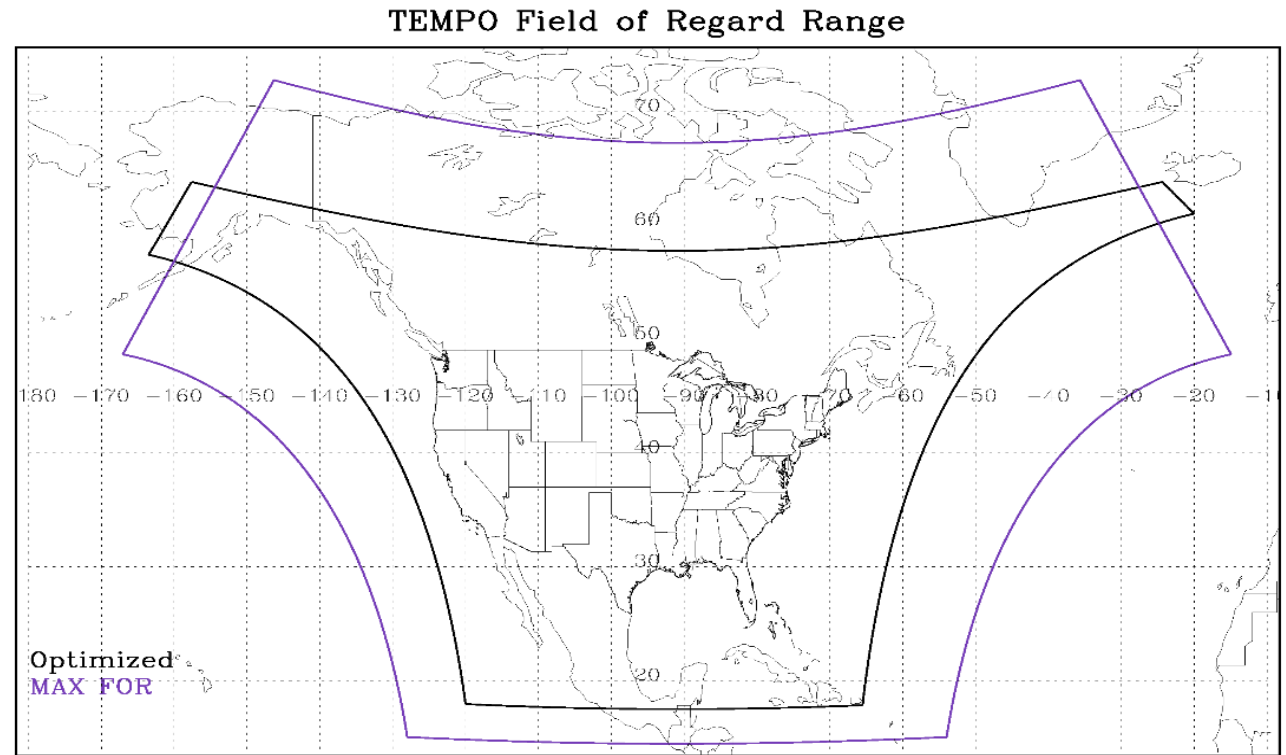
TEMPO Mission: Introduction, Data Products, & Use Case Demonstrations

Aaron Naeger (NASA Marshall Space Flight Center)

August 10, 2026

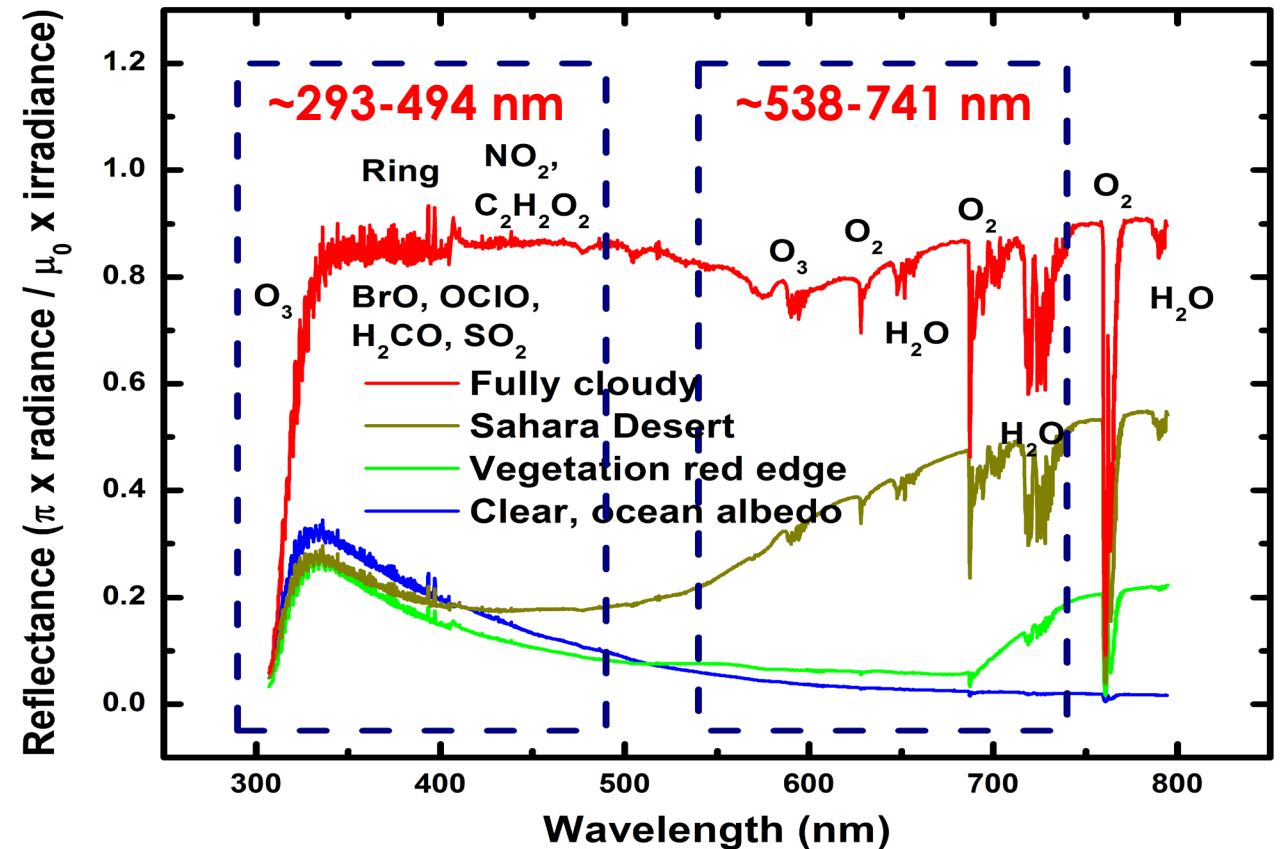
TEMPO Quick Facts

- **Launched Apr 7, 2023** into Geostationary Orbit on SpaceX rocket
- **First Light** operations were on **August 2, 2023**, with **nominal operations starting October 19, 2023**
- Baseline mission ended June 2025 with first mission extension ending September 2026
- Capable of a 15-year lifespan
- NASA's first Earth Venture Instrument (EVI) selected in 2012: a joint project with Smithsonian Astrophysical Observatory
- TEMPO Field of Regard (FoR) covers greater North America including most of Mexico, southern and central Canada, Puerto Rico, and southern Alaska

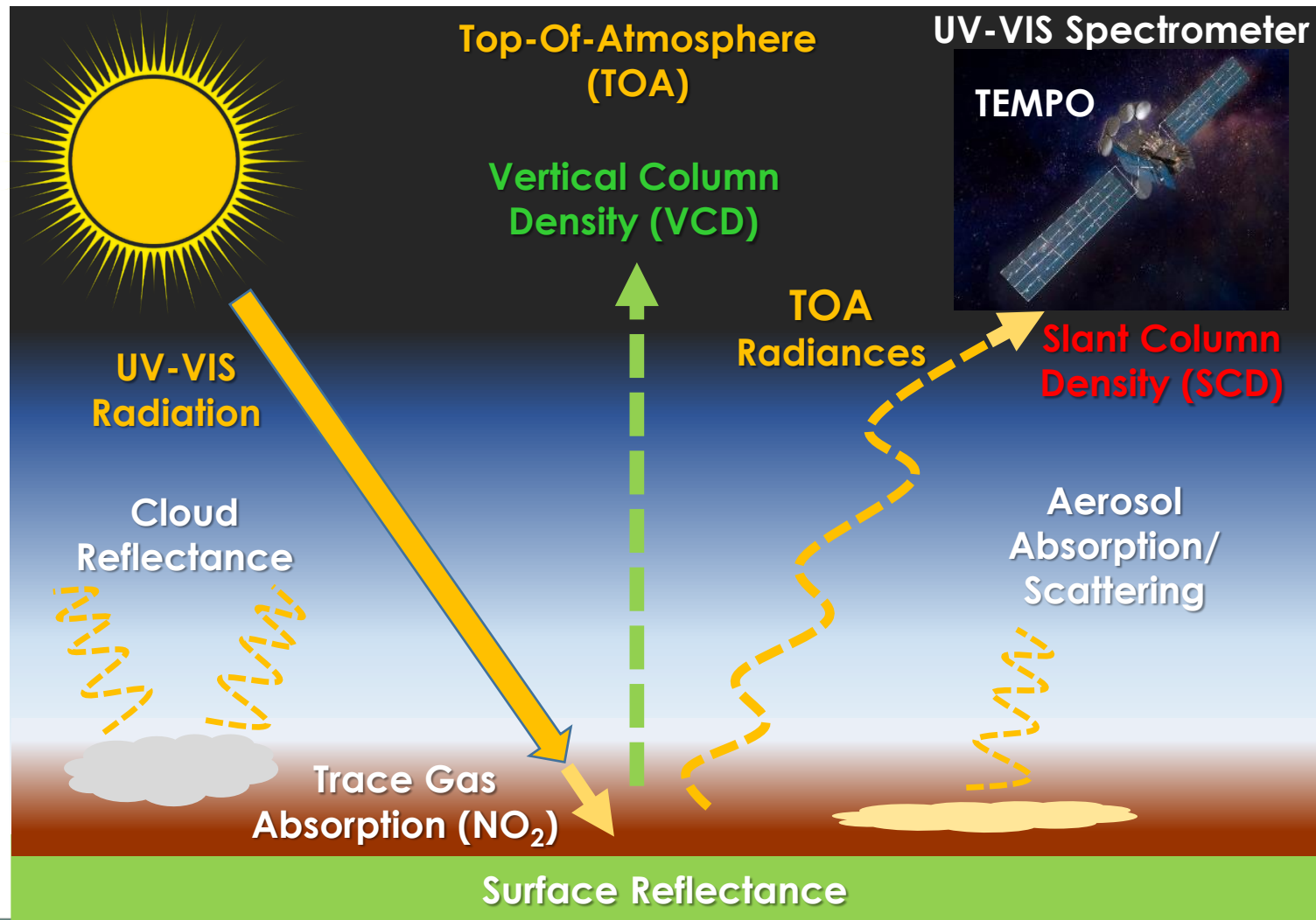


TEMPO Spectral Resolution

- UV/Visible grating spectrometer (0.6 nm spectral resolution) sensitive to **policy-relevant pollutants** (NO_2 , HCHO , O_3) and aerosols **during the daytime**



How Does TEMPO Observe Air Pollutants?



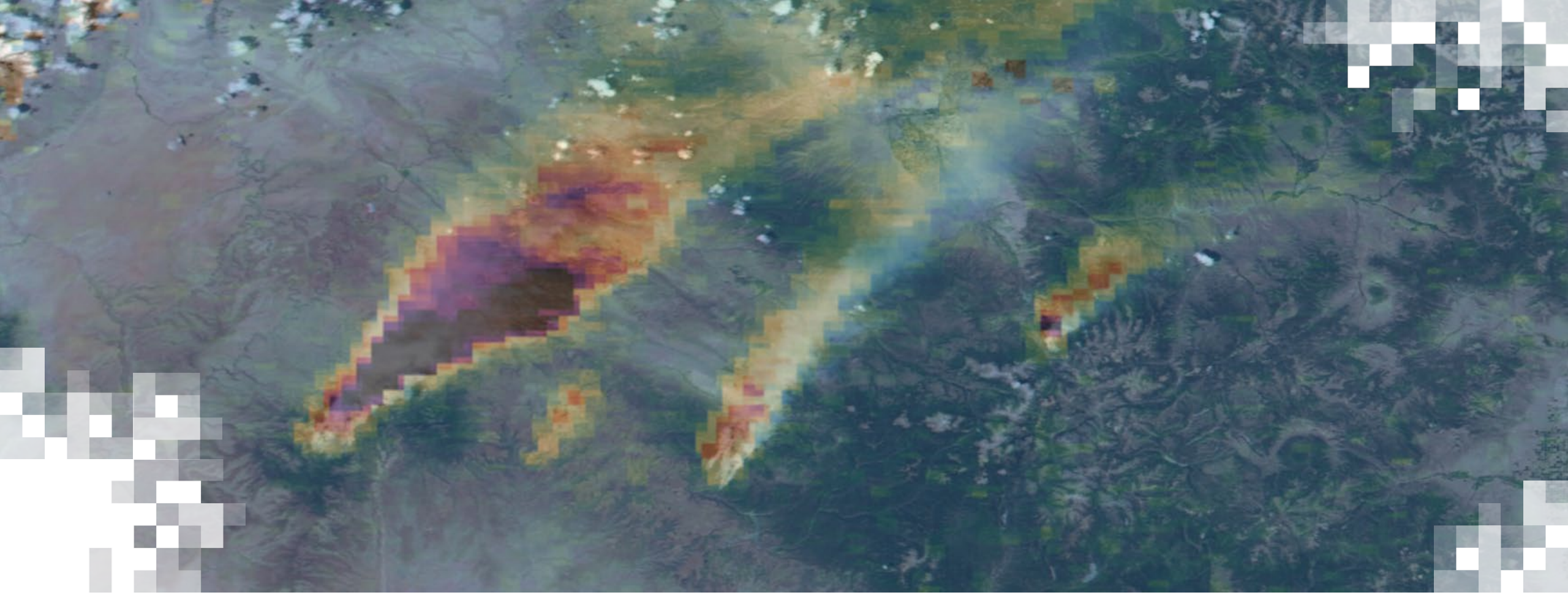
- TEMPO's trace gas retrievals are based on multi-step approach:
 - 1) Derive **slant column densities (SCD)** via spectral fitting to measured **TOA radiances** in known trace gas absorption windows
 - 2) Calculation of **vertical column densities (VCDs)** using **Air Mass Factors (AMF)** calculated offline with a radiative transfer model accounting for surface, atmospheric, and viewing geometry conditions

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

- 3) For NO₂ retrieval, perform Stratosphere-Troposphere separation for retrieving tropospheric NO₂ VCDs

Aerosol effects are not explicitly treated in the retrieval process.





Latest TEMPO Mission Data Product Updates

TEMPO Products: Baseline + Near Real-Time (NRT) + Aerosol

Level	Product	Notable File Variables	Validation Status	Resolution (km ²) *
L1	Radiance <i>NRT</i>	Radiances	Provisional	2.0 x 4.75
	Radiance (twilight)	Radiances	Provisional	2.0 x 4.75
L2	Cloud <i>NRT</i>	Cloud Fraction, Cloud Pressure	Provisional	2.0 x 4.75
	Ozone (O ₃) Total Column	Total Column O ₃ , UV Aerosol Index	Provisional	2.0 x 4.75
<i>NRT</i>	Nitrogen Dioxide (NO ₂)	Tropospheric VCD, Total VCD	Provisional	2.0 x 4.75
<i>NRT</i>	Formaldehyde (HCHO)	Total VCD, Cloud Fraction	Provisional	2.0 x 4.75
	Ozone (O ₃) Profile	O ₃ Profile (0-2 km O ₃ column), Tropospheric O ₃ column	Beta	8.0 x 4.75
	AOD & ALH	AOD 550 nm, ALH	TBD	2.0 x 4.75
	Aerosol Detection Product (ADP)	Dust/Smoke Discrimination, UV Aerosol Index	TBD	2.0 x 4.75
L3	Same as L2	Same Variables as L2	Same as above	0.02° x 0.02° *
L4	Surface PM _{2.5}	Hourly PM _{2.5} Estimation	TBD	2 km x 2 km

AOD: Aerosol Optical Depth

ALH: Aerosol Layer Height

VCD: Vertical Column Density

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

* O₃ Profile L3 Product → 0.04 x 0.04° Resolution



Future TEMPO Products: Near Real-Time (NRT) + Enhanced

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

- **UVB (Ultraviolet B) radiation** retrievals support analyses on UV exposure trends, human health risks (skin cancer), and environmental impacts such as ecosystem damage.
- **Glyoxal** forms from vegetation and wildfires with human activities (i.e., fossil fuels burning) contributing smaller amounts.
- **Bromine** sources include volcanic emissions, biomass burning, industrial emissions, and marine processes.

If you have interest in these products especially NRT SO₂ and UVB, reach out!

aaron.naeger@nasa.gov

Level	Product	Key Product Variables	Resolution* (km ²)
L2	Glyoxal (C ₂ H ₂ O ₂)	Total VCD, Cloud Fraction	2.0 x 4.75
	Water Vapor (H ₂ O)		2.0 x 4.75
	Bromine (BrO)		2.0 x 4.75
NRT	Sulfur Dioxide (SO ₂)	Total VCD	2.0 x 4.75
	UVAOD	AOD 354, 388, 500 nm	2.0 x 4.75
	ALH	Aerosol Layer Height	2.0 x 4.75
	UVB	UVB radiation	2.0 x 4.75

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



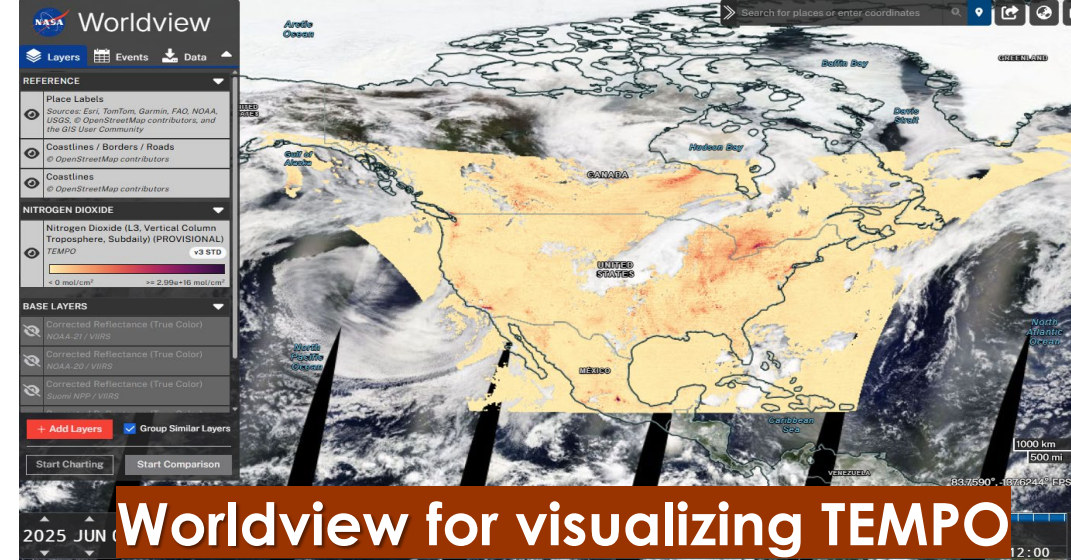
TEMPO Product Release

Public Release	Date	Details
V01	2/5/2024	Limited 3 weeks released
V02	2/26/2024	Level 1 (spectra) released
V03	5/20/2024	L1, L2/3 cloud, NO₂, H₂CO, total O₃ (provisional) V3 O₃ profile (ASDC 6/9/2025, not for the public)
V04	9/17/2025	Ozone Profile (beta), L1 + other L2/L3 (provisional) Reprocessing starting this week
NRT V02	9/17/2025	L1, L2/3 cloud, NO₂, H₂CO (funded by SNWG)



TEMPO Tools

- TEMPO data publicly available at NASA's ASDC (~6 hours latency, NRT with 2-3 hours latency).
- Wealth of tools:
 - Earthdata Search
 - **NASA Worldview**
 - NASA ArcGIS services
 - RSIG (EPA)
 - TEMPO-Lite (SAO)
 - **NASA SPoRT Viewer**
 - Google Earth Engine
 - NOAA AerosolWatch

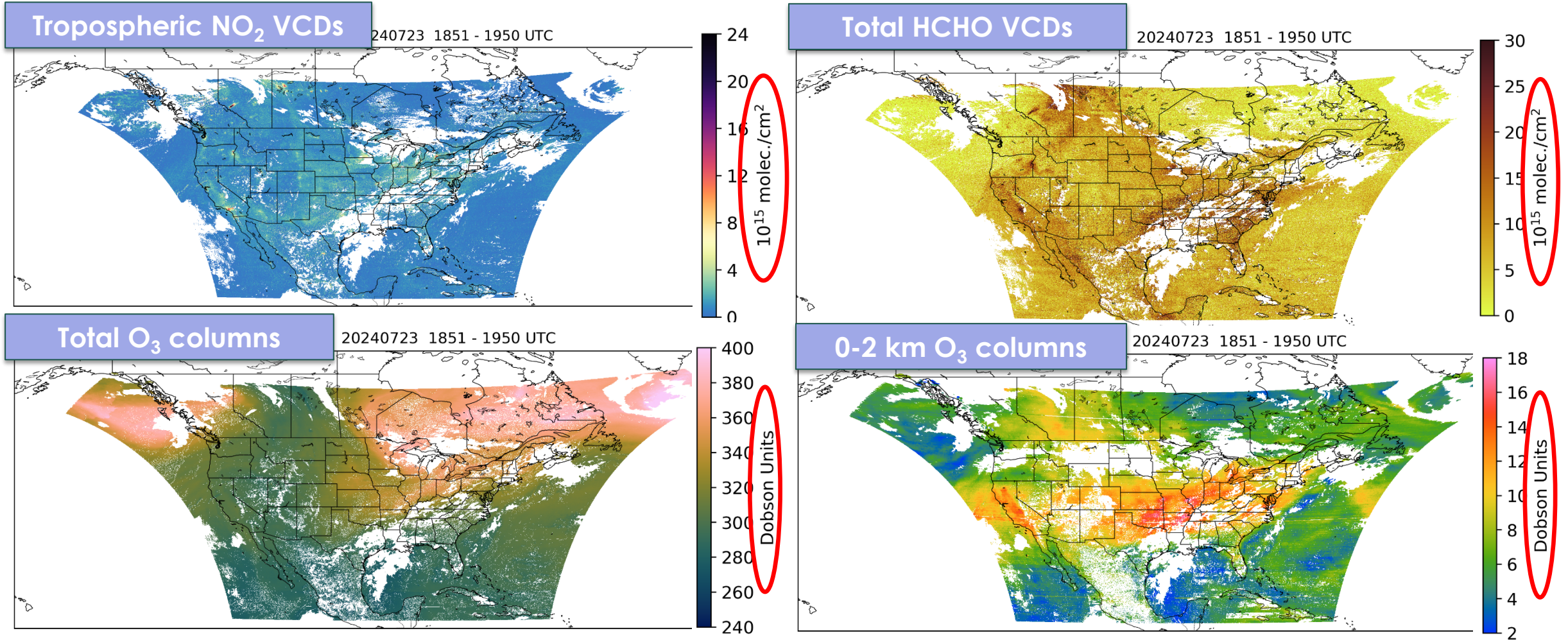


TEMPO website

Data access, visualization
tools, and user guides links



TEMPO Level 2 Trace Gas Product Examples



- **VCDs** – total amount of trace gas in the vertical column of air directly above a specific area of Earth's surface to the top of the atmosphere
 - **Molecules/cm⁻²** - total number of gas molecules found in the vertical column of air
 - **Dobson Units (DU)** – measures thickness of a gas layer if compressed to sea-level pressure



Data Filtering Guidance – TEMPO NO₂ and 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°	> 80°
Main Data Quality Flag (QF)	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

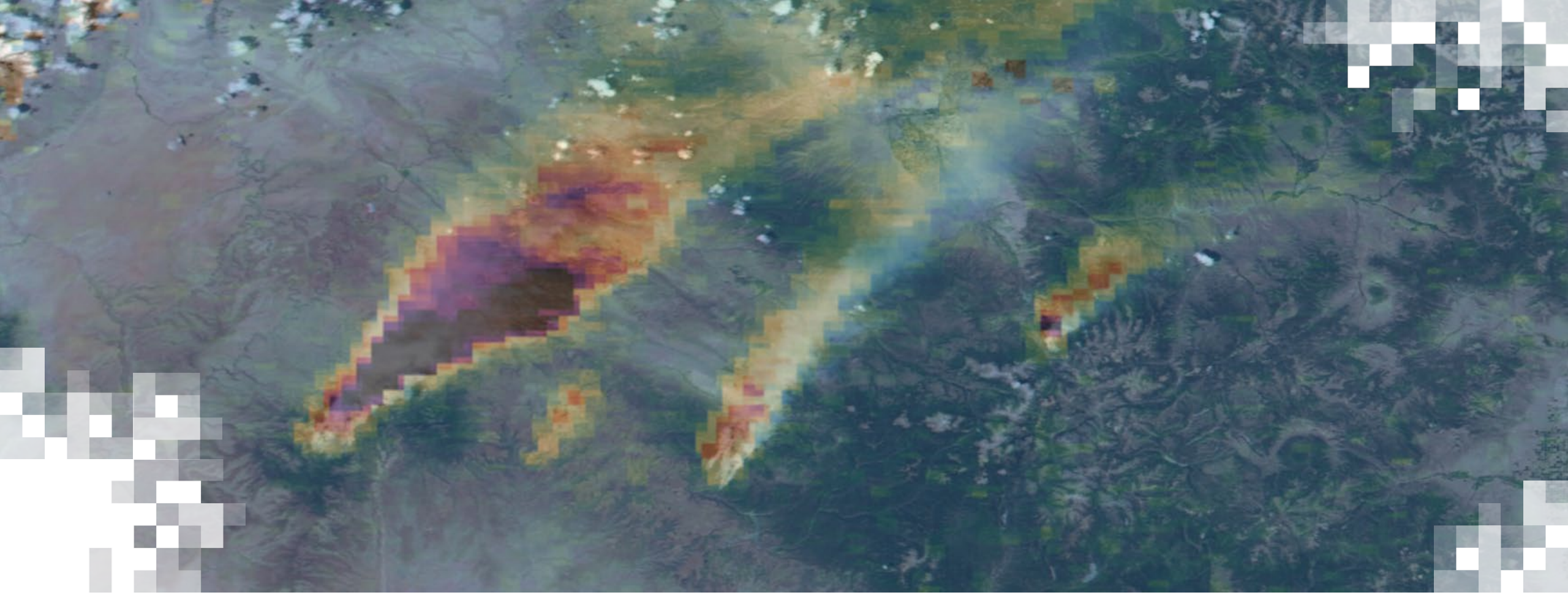
Users must apply data filtering for both Level 2 and Level 3 NO₂ and HCHO products.



Data Filtering Guidance – TEMPO O₃ Total

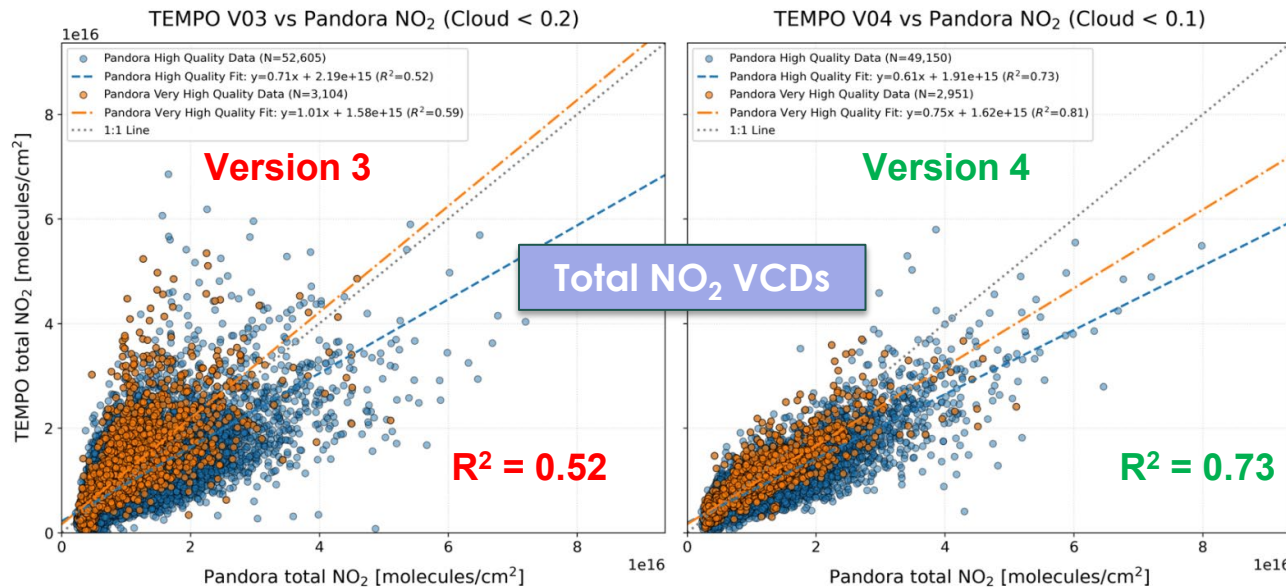
QA Parameter	Variable (group)	Range	Qualitative Use (Worldview)	Quantitative Use
Quality Flag	quality_flag (product) 0 = highest-quality 1 = Glint contamination 2 = SZA > 84° 5 = SO2 present <1024 = ONLY disregard radiance/irradiance data which are missing or contain errors	0 to 32768	≠ [0, 1, 2, 5] (adequate)	> 0 (best)
Effective Cloud Fraction (ECF)	fc (product)	0 – 1.0	No Filter	> 0.5
Solar Zenith Angle (SZA)	solar_zenith_angle (geolocation)	0 – 90°	> 80°	> 80°
Viewing Zenith Angle (VZA)	viewing_zenith_angle (geolocation)	0 – 90°	> 80°	> 80°



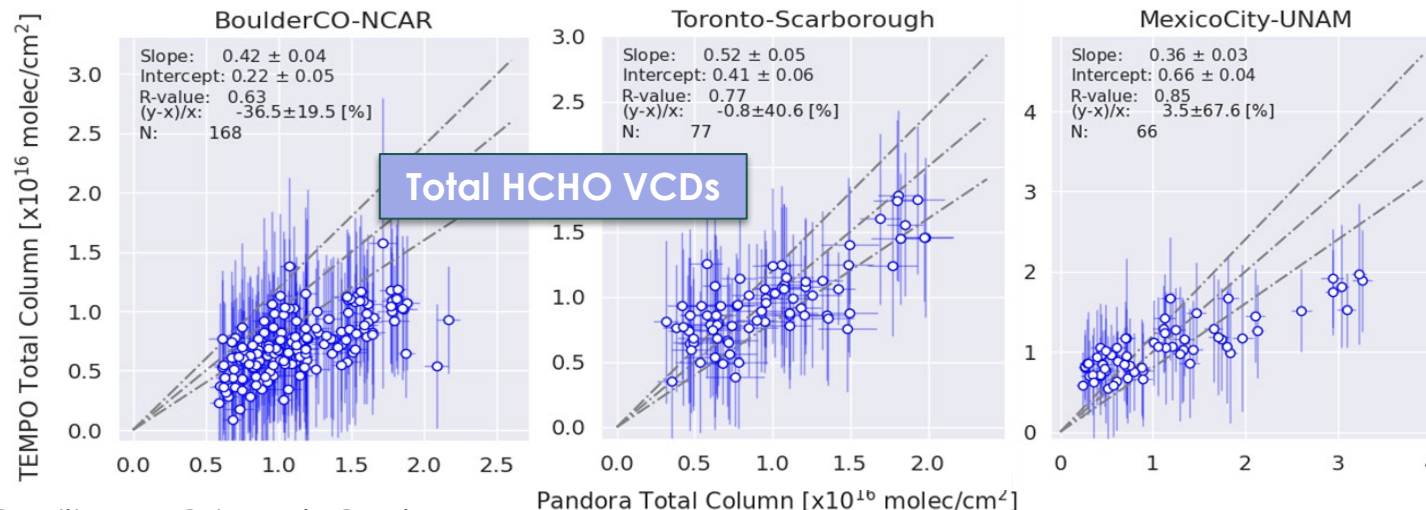


TEMPO Version 4 Product Validation

TEMPO NO₂ & HCHO Shows Strong Correlations with Pandora Network



Credit: Caroline Nowlan (SAO)



Credit: Ivan Ortega (NCAR)

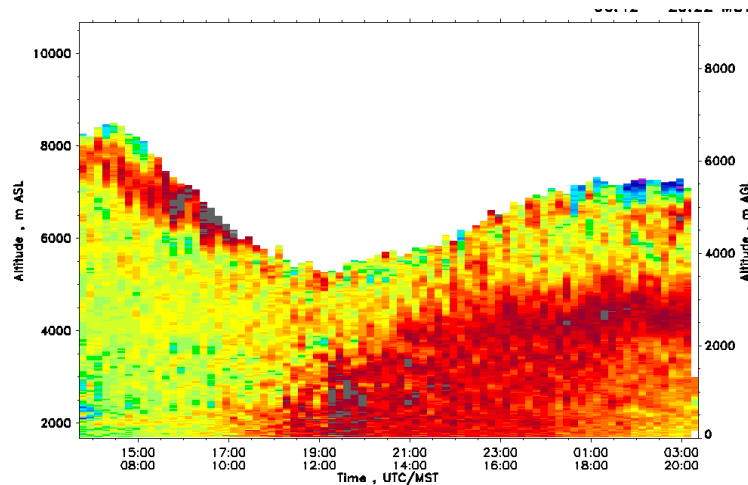
- Significant improvement in TEMPO Version 4 NO₂ product when compared to Version 3
- Correlation improves from ~0.52 to 0.73 from Version 3 to Version 4 against high-quality Pandora NO₂

- Moderate to strong correlations between TEMPO Version 4 and Pandora HCHO
- Slight improvement in Version 4 HCHO product but much less distinct than TEMPO NO₂ product

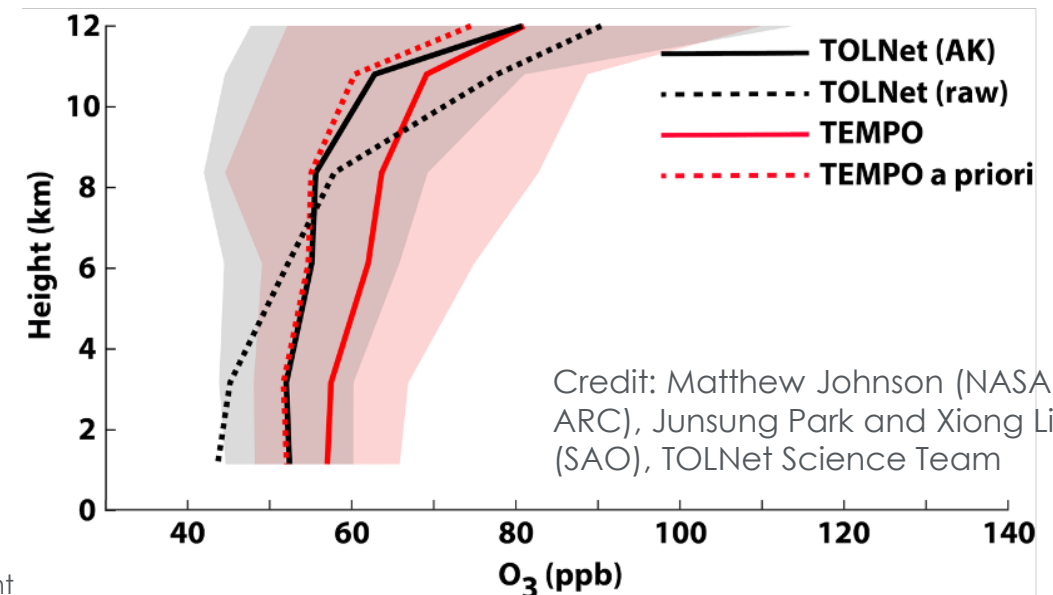
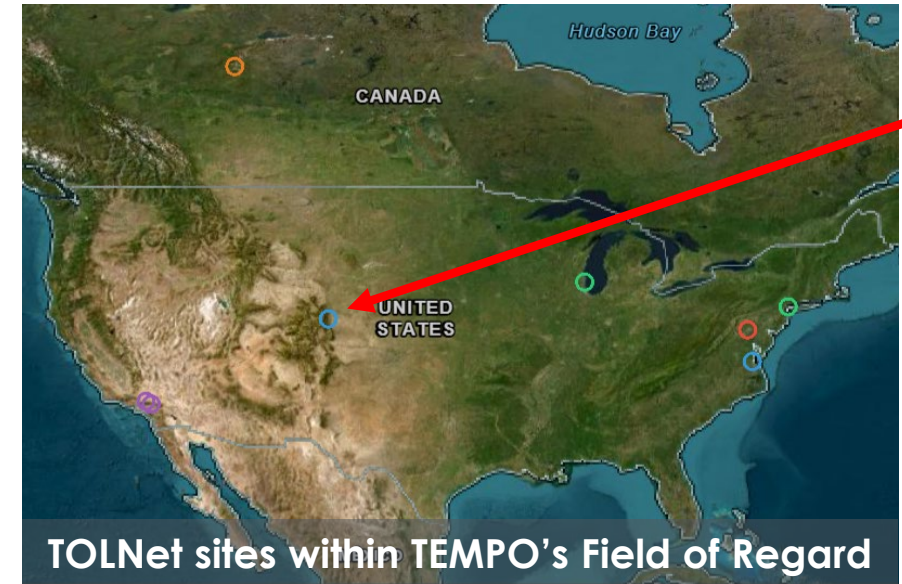


Ozone Profile Performance Exceeds Mission Precision Requirements

- Conducted validation of first full season (Sept. – Nov. 2025) of ozone profile product against TOLNet O₃ profiles
- TEMPO's O₃ profiles have low biases and high precision (~7 ppb) in troposphere
- TEMPO retrieval meets its tropospheric O₃ precision requirement (± 10 ppb)

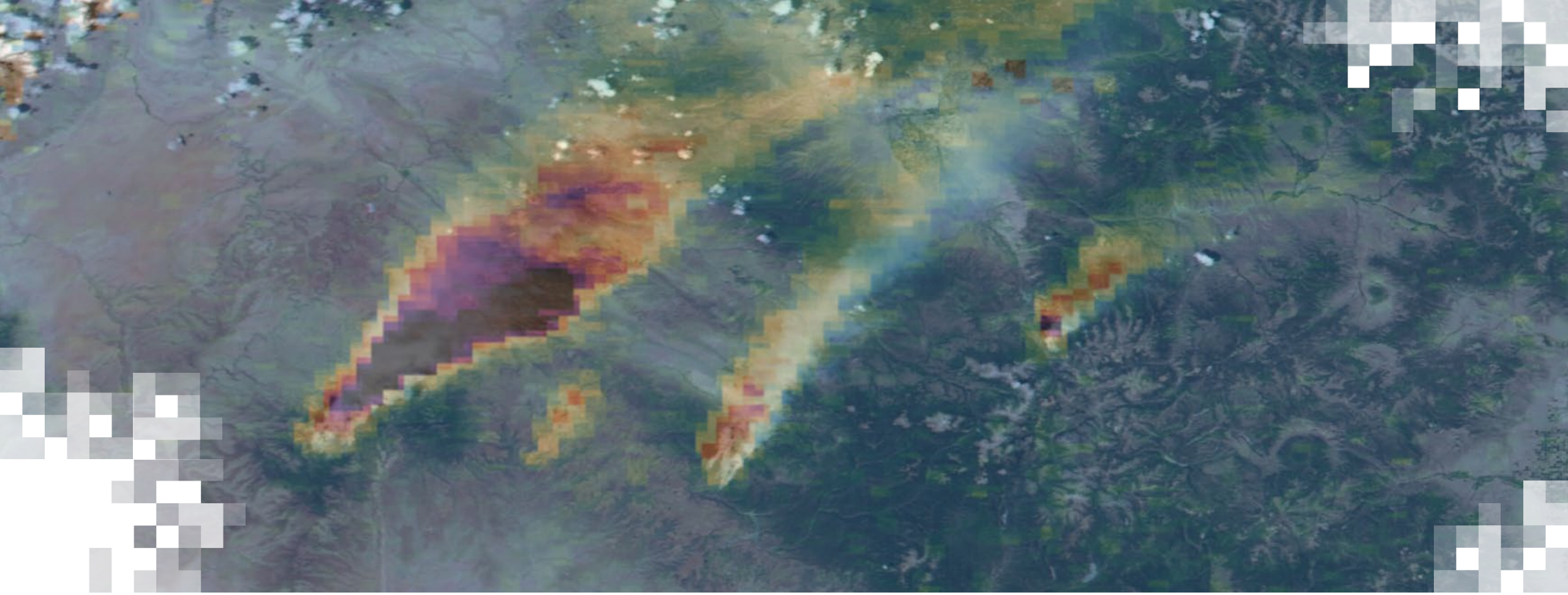


Ozone profiles from Boulder site, observing a high O₃ day along the CO Front Range



Credit: Matthew Johnson (NASA ARC), Junsung Park and Xiong Liu (SAO), TOLNet Science Team



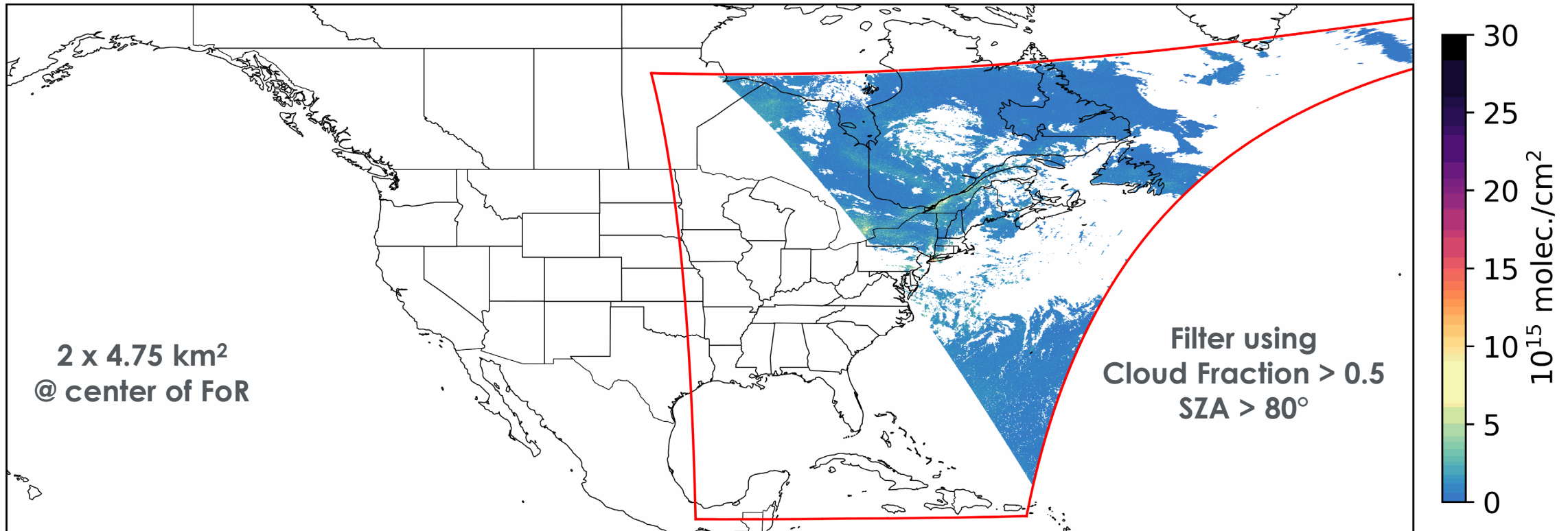


TEMPO Nominal “Standard” Operations

Nominal Operations w/ Level 2 NRT NO₂ Data Overlay – June 28, 2026

- Nominal operations consist of **standard (hourly) daytime scans** over full FoR and **optimized (~30-40 minute) scans** over daylight portions of the FoR during the morning and afternoon.

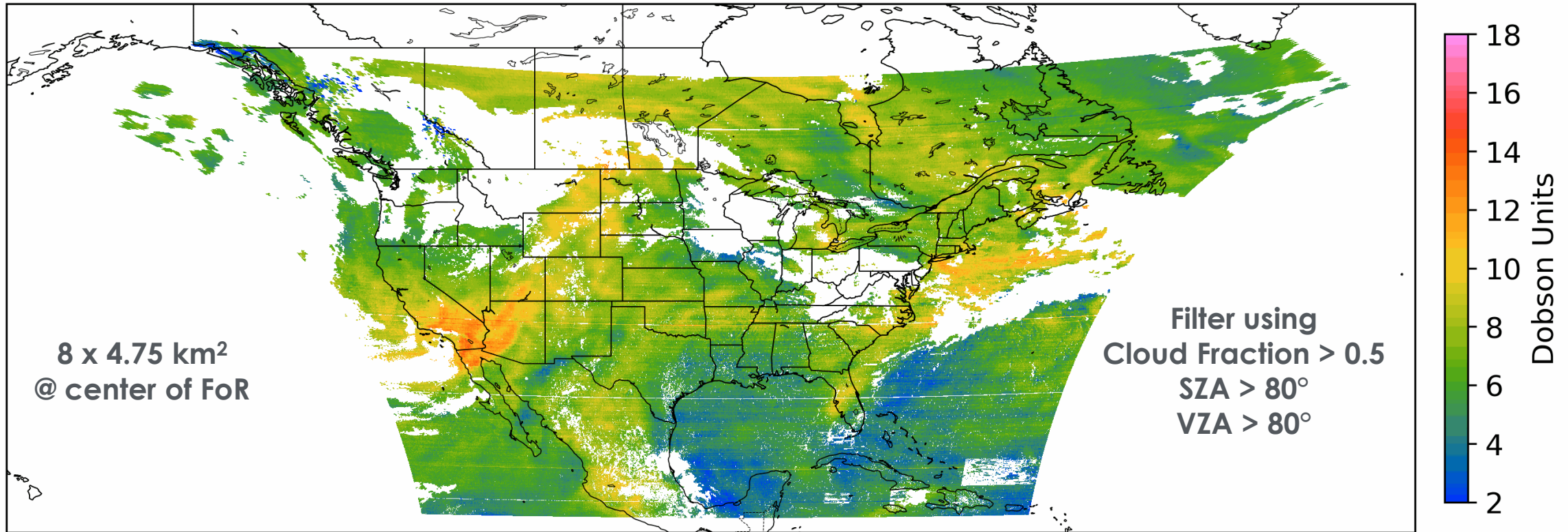
TEMPO NRT Tropospheric NO₂ 20260628 1031 - 1104 UTC

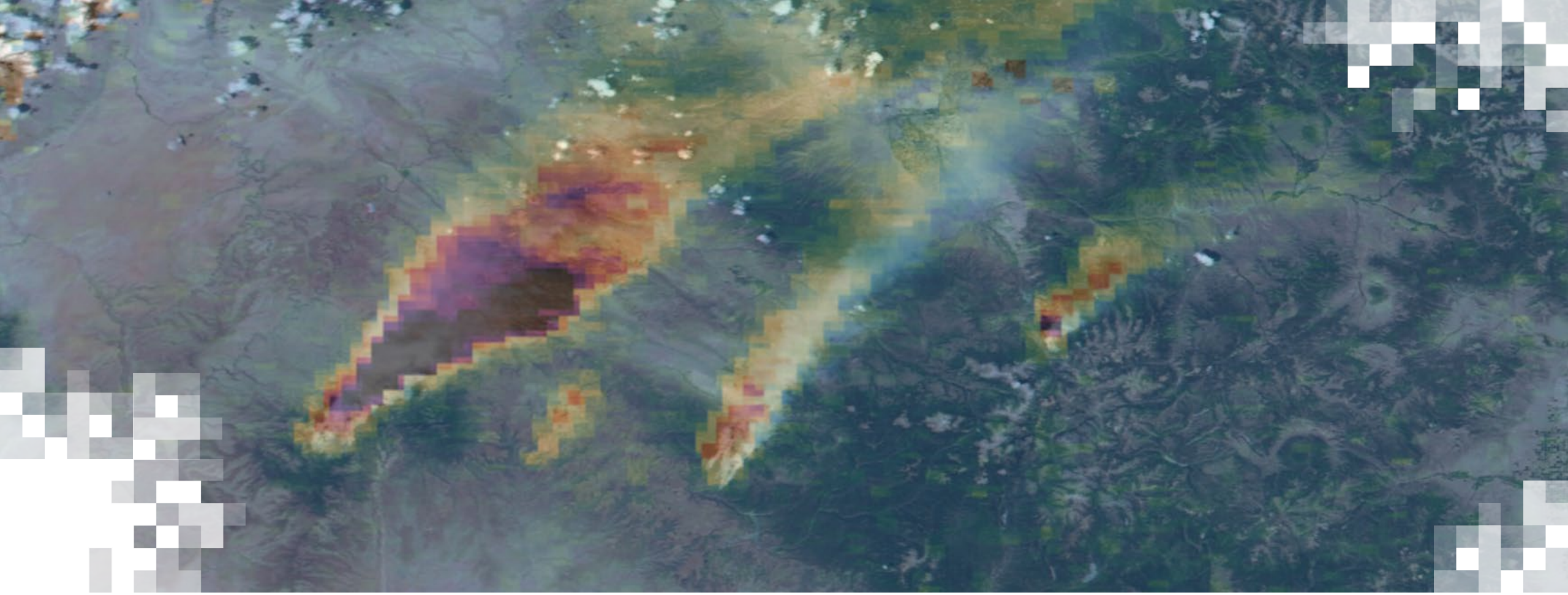


Nominal Operations w/ Level 2 O₃ Profile Data Overlay – June 28, 2026

- Nominal operations consist of **standard (hourly) daytime scans** over full FoR and **optimized (~30-40 minute) scans** over daylight portions of the FoR during the morning and afternoon.

TEMPO 0-2 km O₃ 20260628 1512 - 1611 UTC

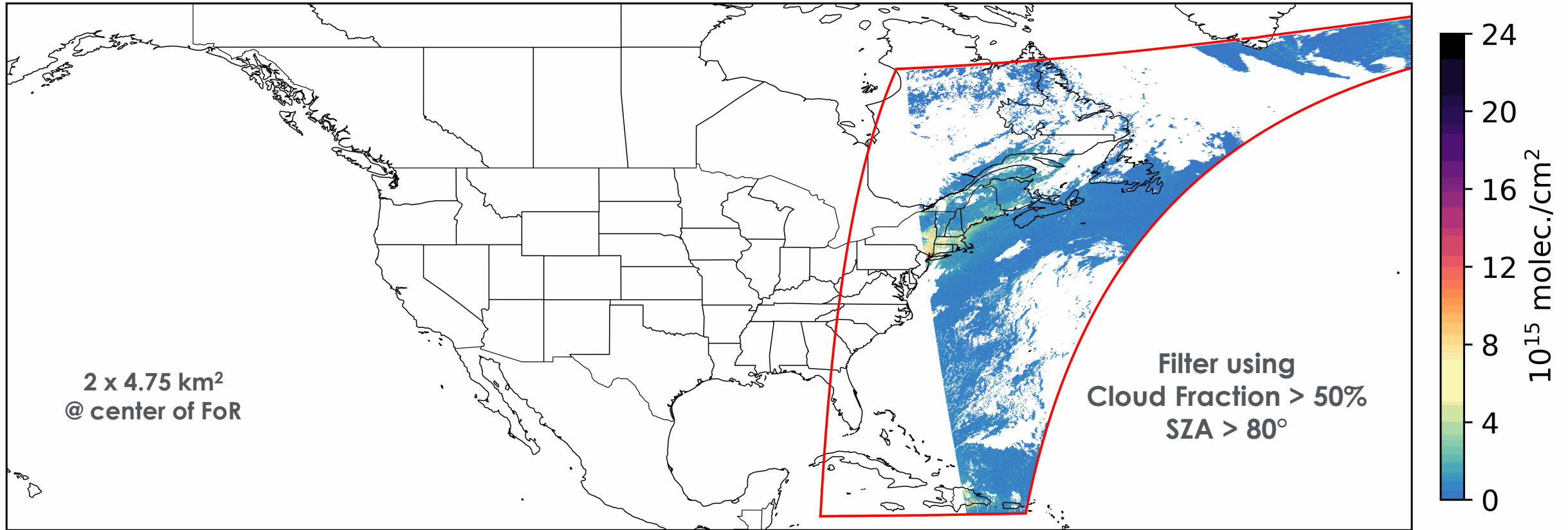




TEMPO Special Operations

Special Operations w/ Level 2 NO₂ Data Overlay – April 10, 2026

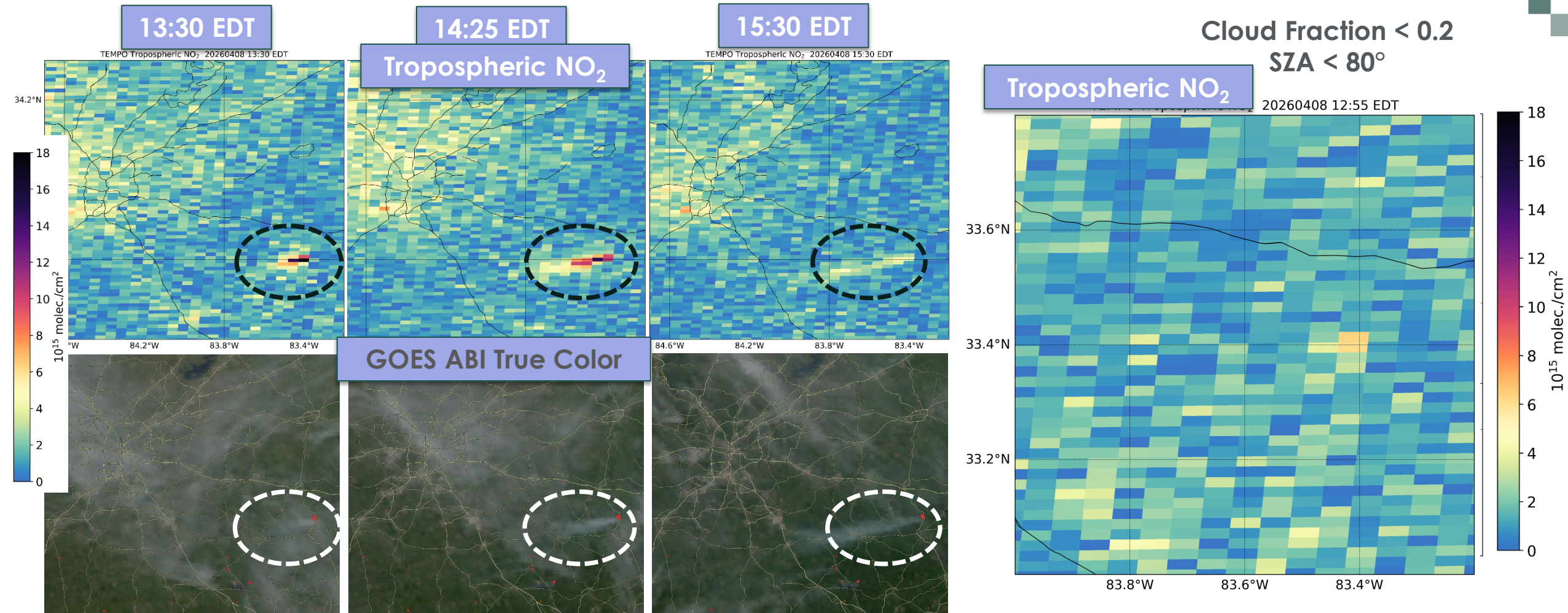
TEMPO Tropospheric NO₂ 20260410 1110 - 1129 UTC



- **Special operations** consisting of higher frequency scans over slices of the FoR can also be conducted on an infrequent, requested basis.
- **5-minute scans** were conducted for 4-days on April 8, 10, 11, and 12 every other hour throughout the daytime, targeting prescribed burning across Georgia.

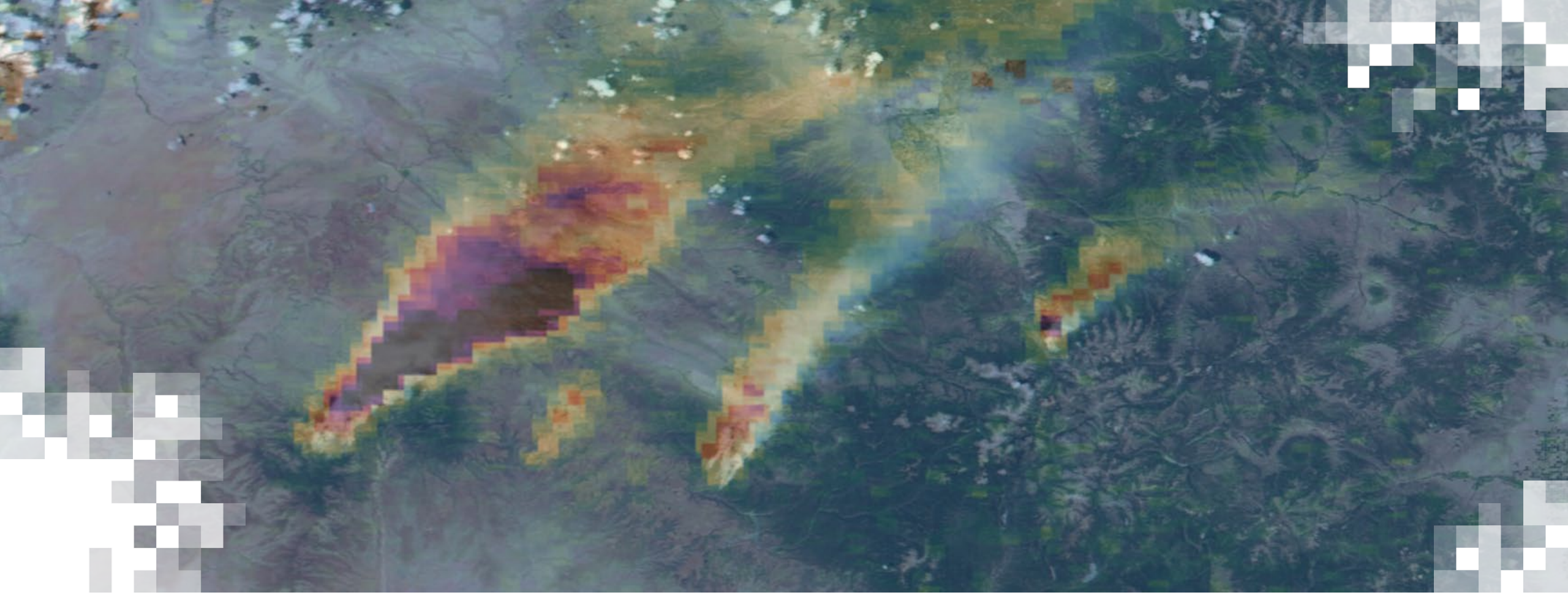


Prescribed Burn Zoom – April 10, 2026

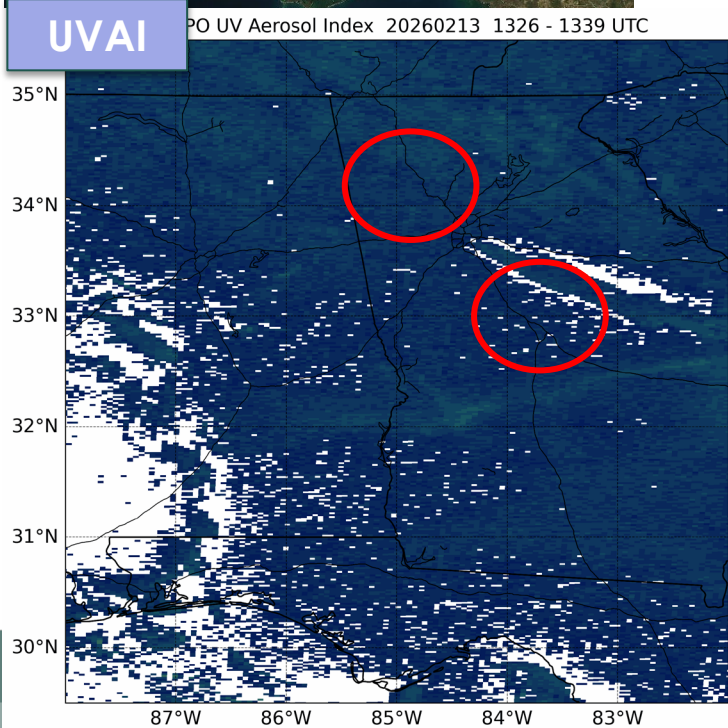
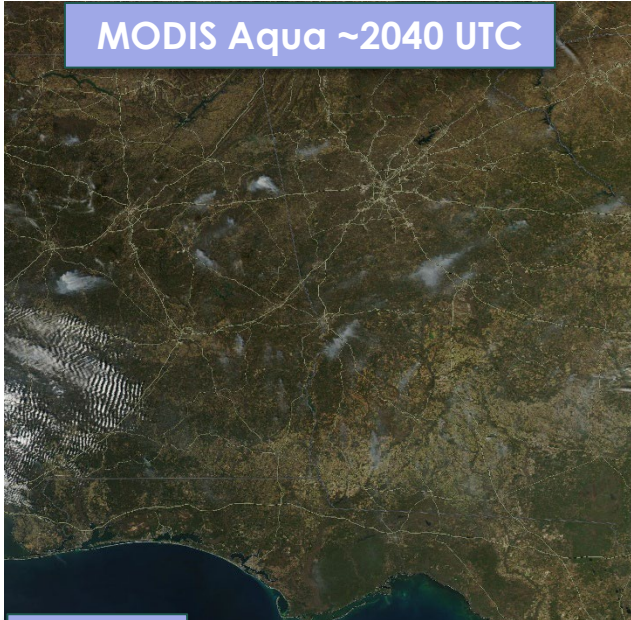


- A standard operation day would have provided 3 scans of the smoke plume from the burn.
- Special operation scans observed the full life cycle of the smoke plume from the initial NO₂ hot spot to the westward transport of the NO₂ plume over its ~ 2.5-hour lifetime.

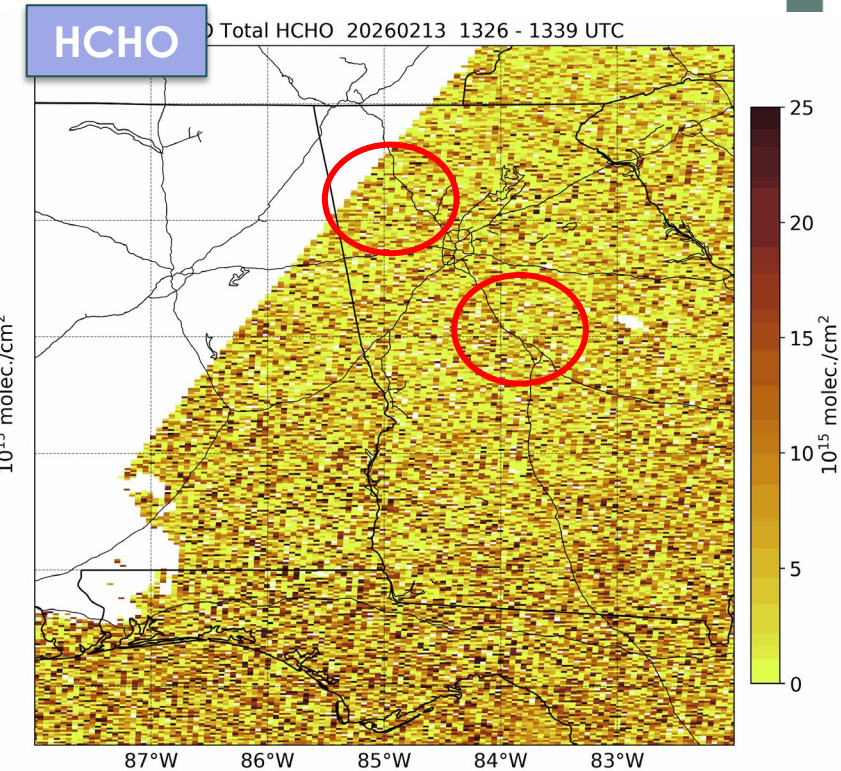
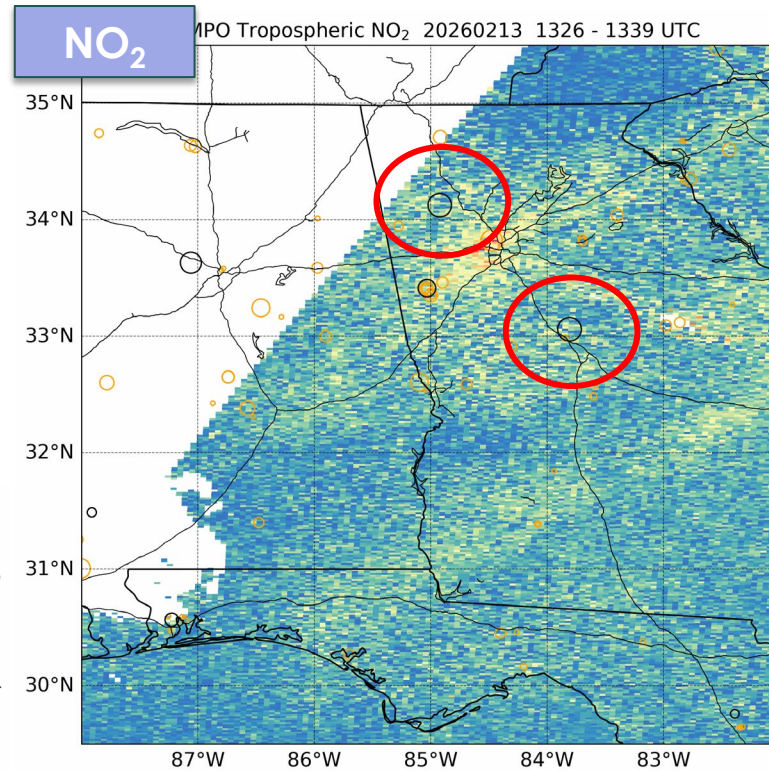




Use Case - Feb. 13, 2026
Prescribed Burns, Power Plants, & Urban Emissions Across
Southeast U.S.



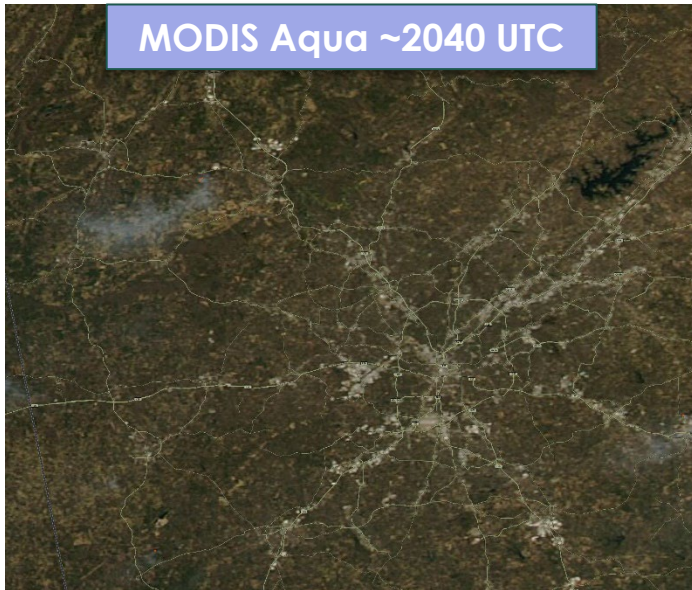
TEMPO Level 2 NO₂, HCHO, & UVAI Products



- TEMPO observed distinct increases in NO₂ columns associated with smoke from prescribed burns, coal-fired power plant emissions, and major urban areas.
- UVAI tracks the smoke aerosols from the burns as positive UVAI (331 / 360 nm ratio) indicate absorbing aerosols such as smoke and negative values indicate scattering aerosols or clouds.

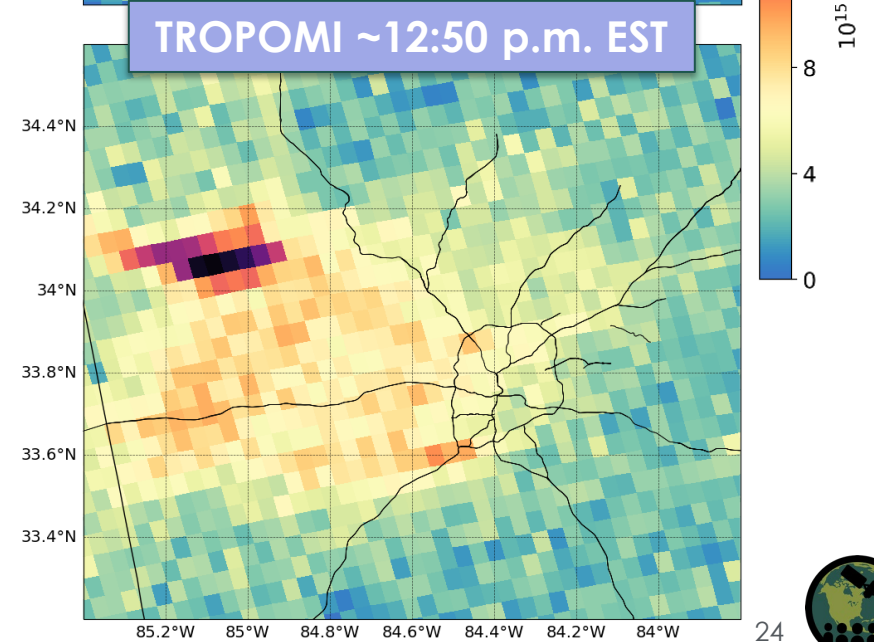
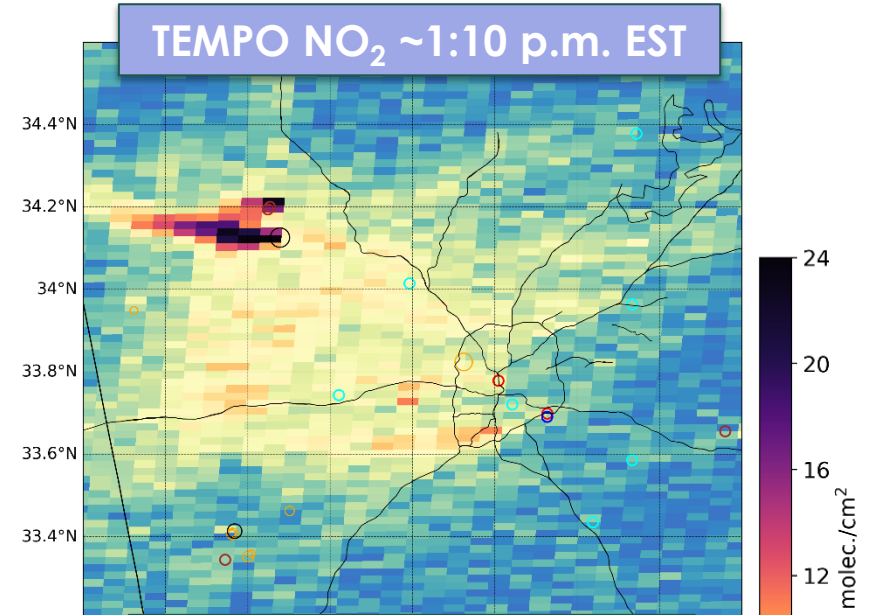
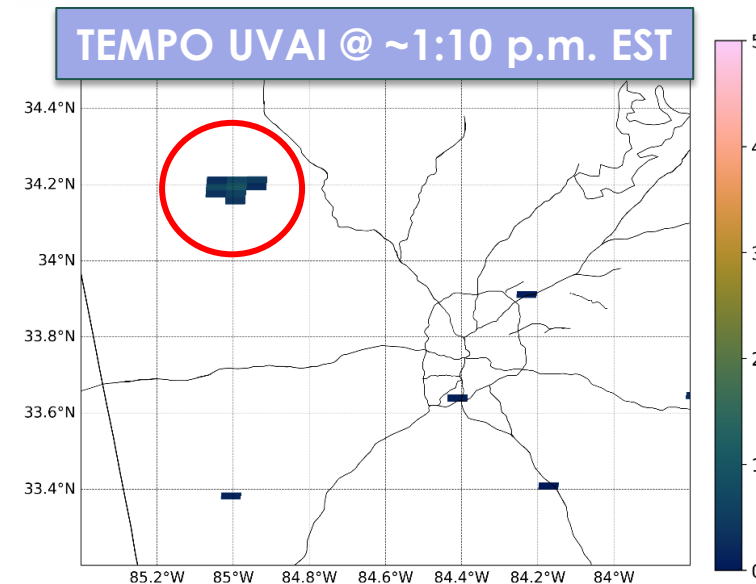
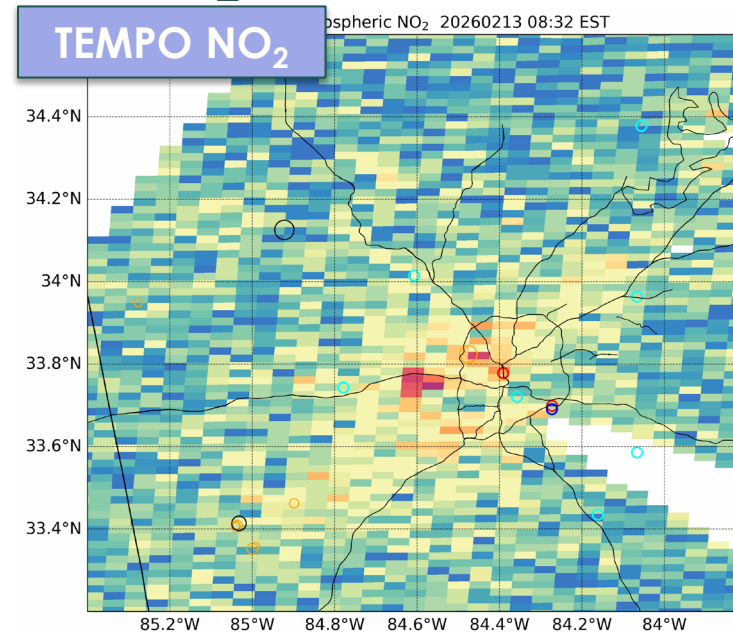


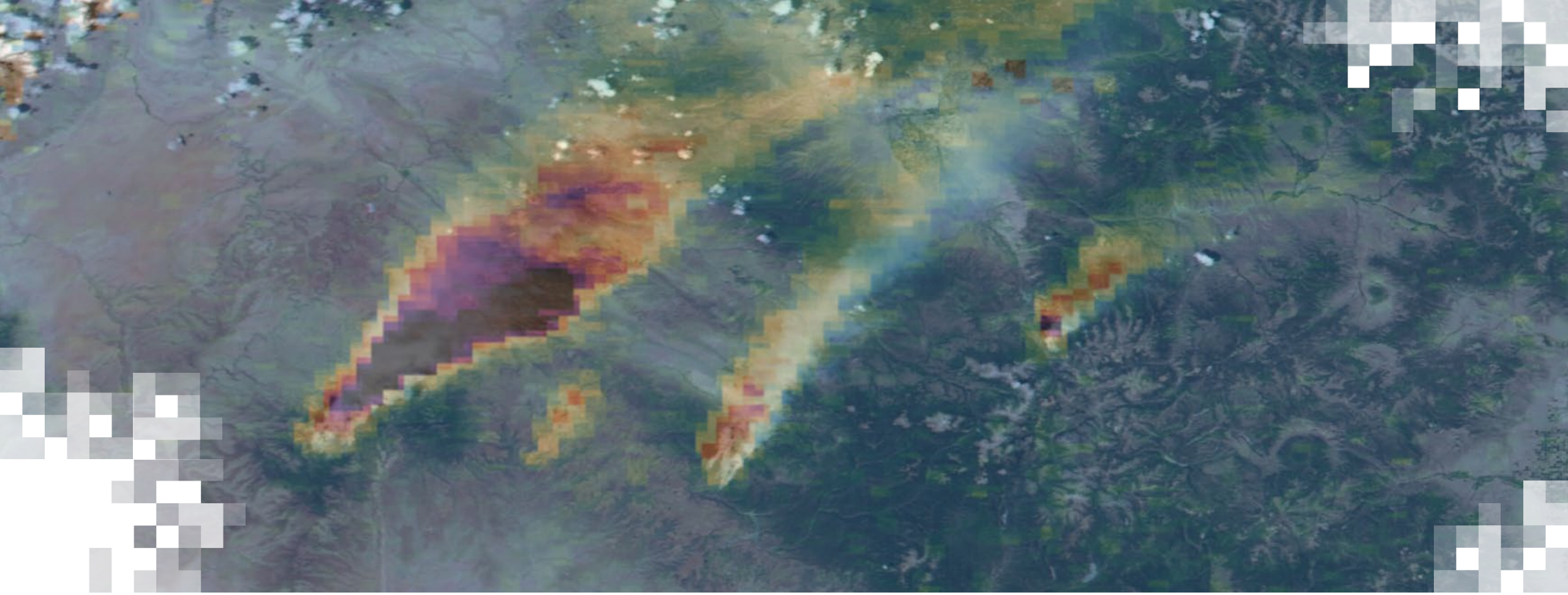
TEMPO vs TROPOMI Level 2 NO₂ & TEMPO UVAI – Atlanta Zoom



MODIS Aqua ~2040 UTC

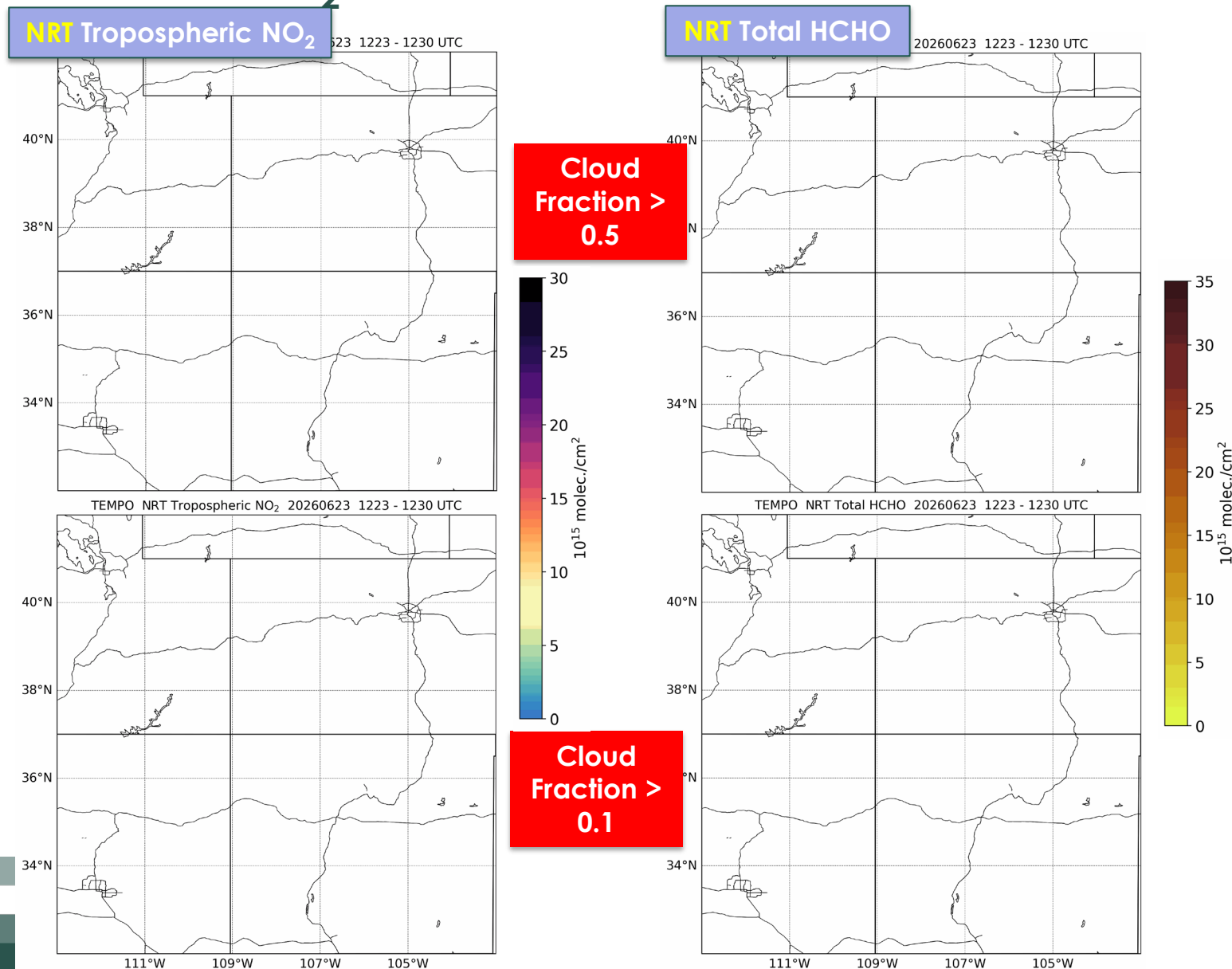
- TEMPO observed a NO₂ hot spot from a prescribed burn just north of an elongated NO₂ plume tied to a large power plant.
- UVAI showed positive values associated with the absorbing smoke aerosols from the burn.





**Use Case – June 28, 2026
Wildfires Across Western U.S.**

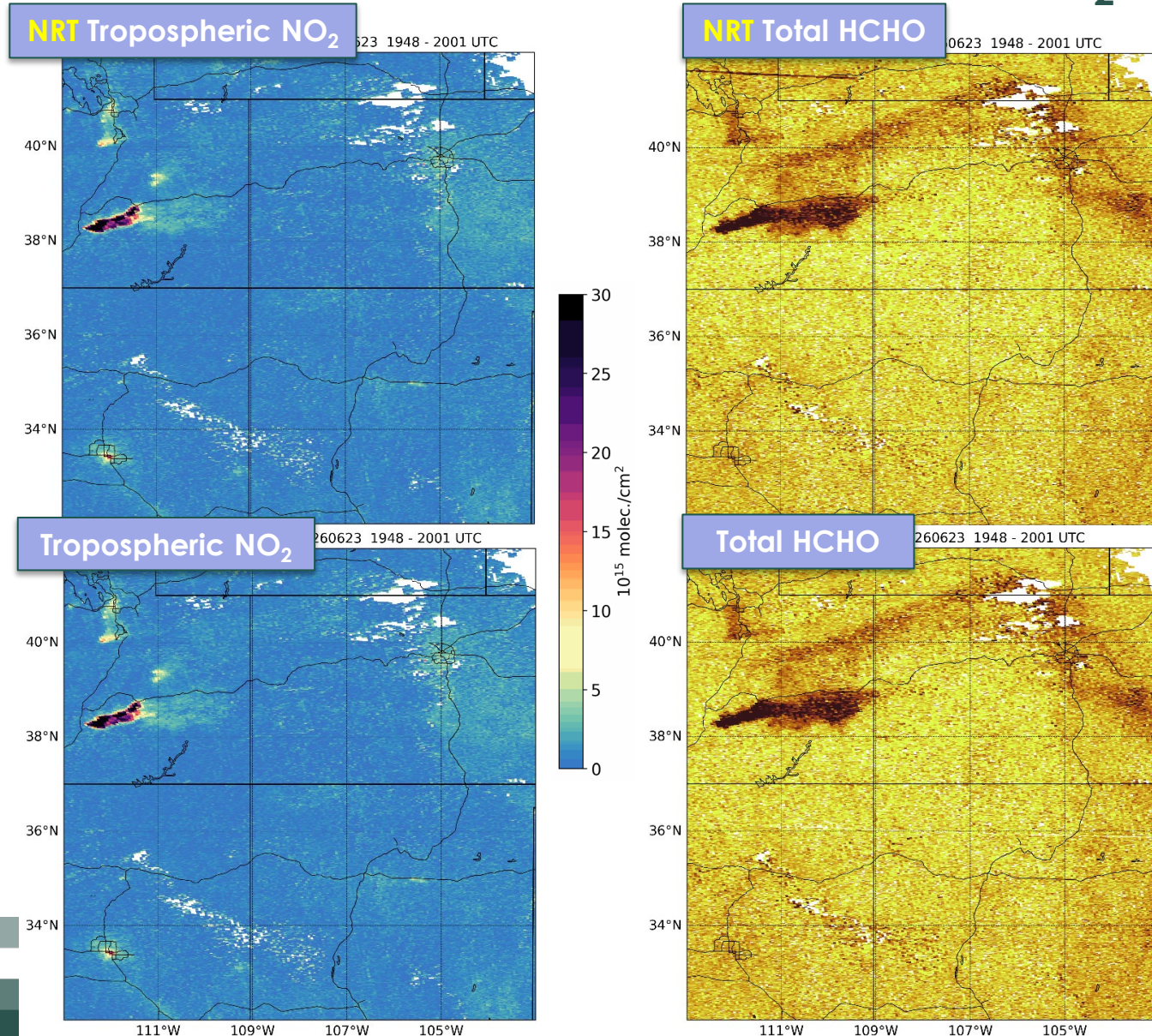
TEMPO NO₂ & HCHO within Smoke and Cloud Fraction Thresholds



- Effective cloud fraction of >10% is recommended for removing TEMPO NO₂ and HCHO data for quantitative research purposes.
- TEMPO data viewers (e.g., Worldview) use cloud fraction > 50% for filtering TEMPO NO₂ and HCHO data.
- Cloud fraction > 50% mostly retains NO₂ and HCHO data within the smoke plumes.
- Caution must be used when analyzing the NO₂ and HCHO values within smoke plumes.

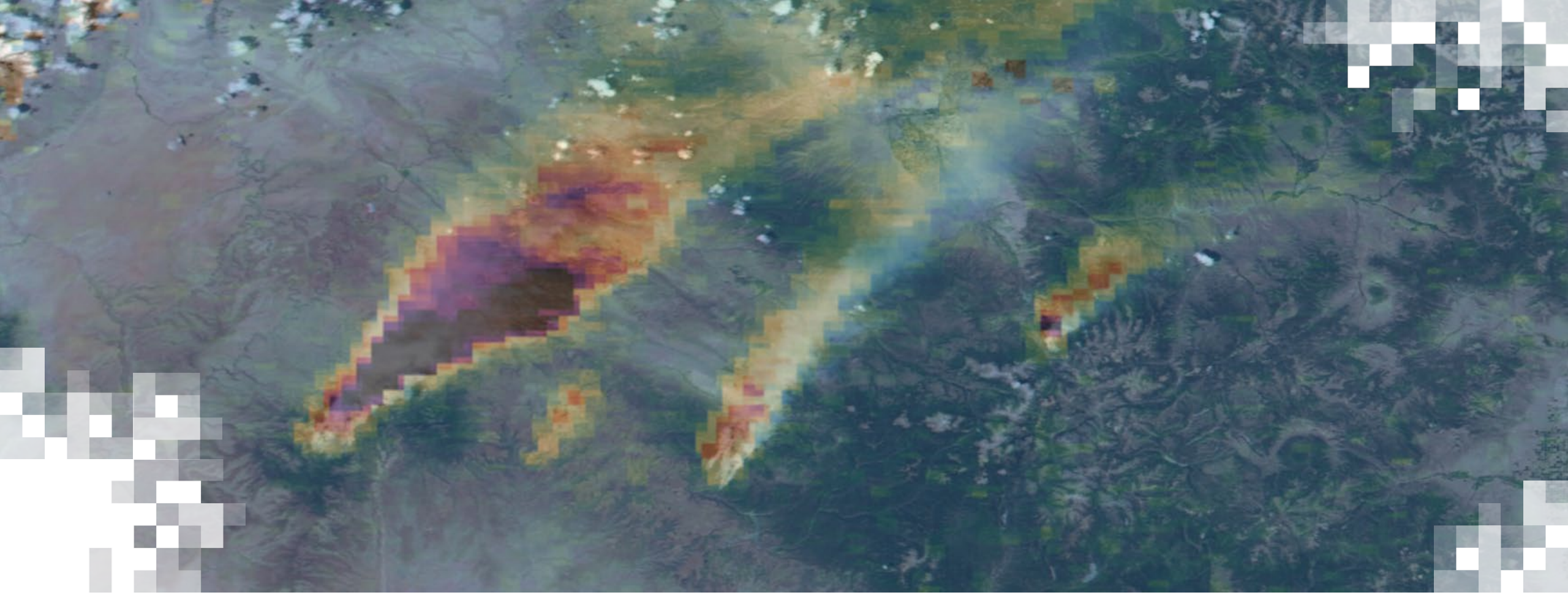


Near Real-Time vs Standard TEMPO NO₂ & HCHO



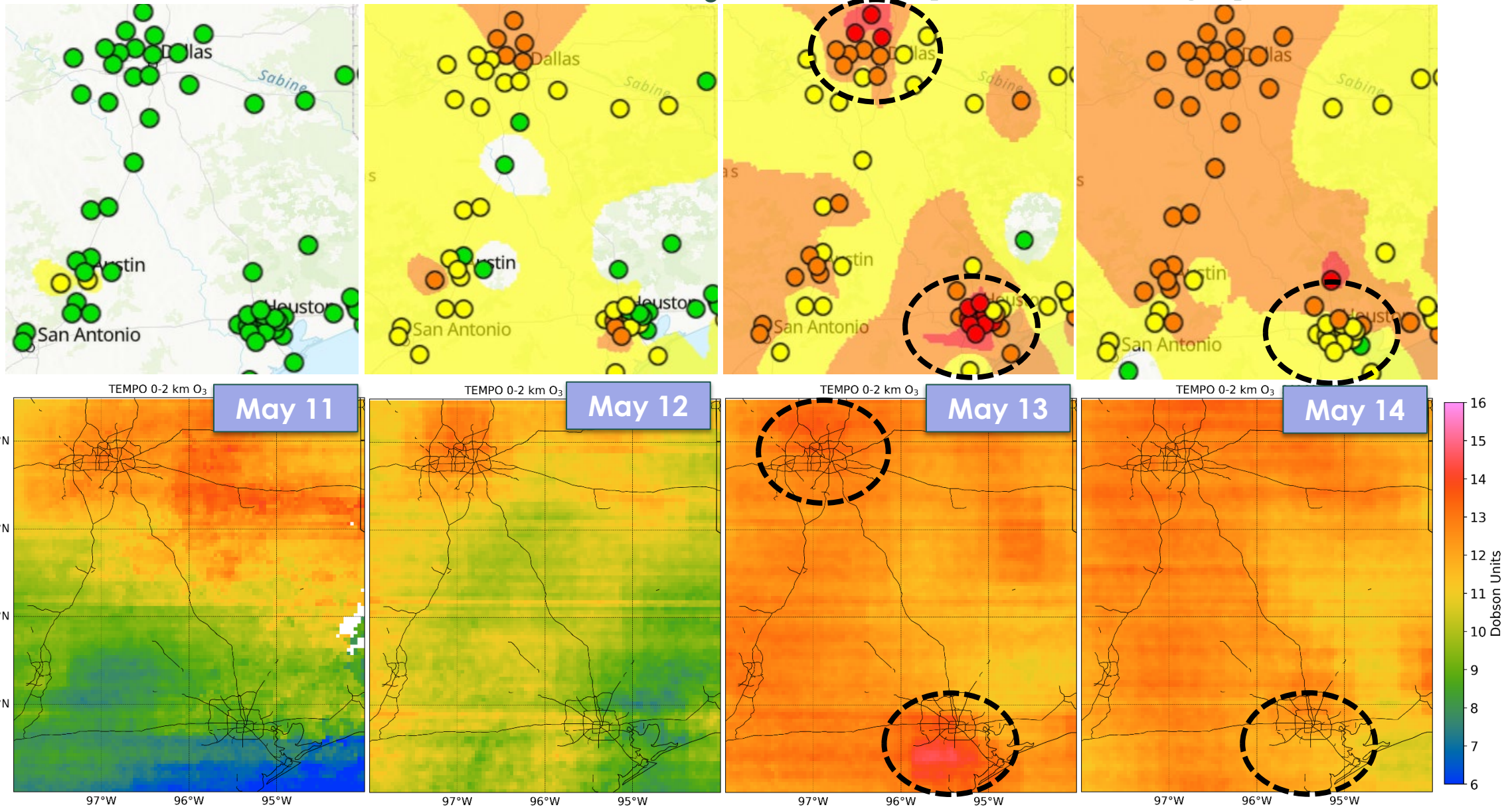
- NRT data latency is currently ~2.5 hours but work is underway to reduce the latency to ~2 hours.
- NRT and standard products show very similar VCDs for both NO₂ and HCHO.
- NRT HCHO encounters more stripping than the standard HCHO product.
- NRT data are ready for use in real-time operations.



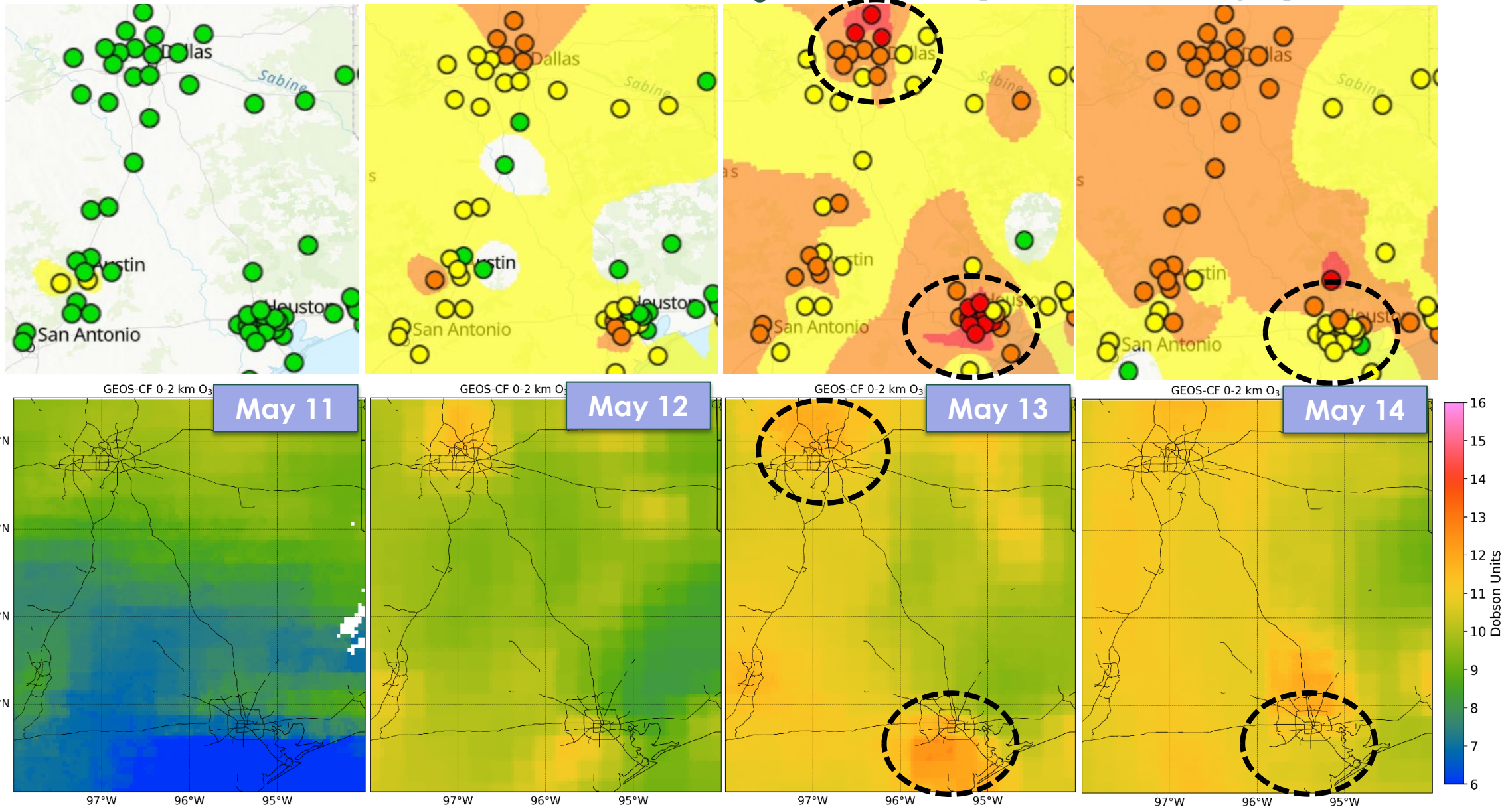


Use Case – May 11-14, 2026
O₃ Exceedances in Dallas and Houston

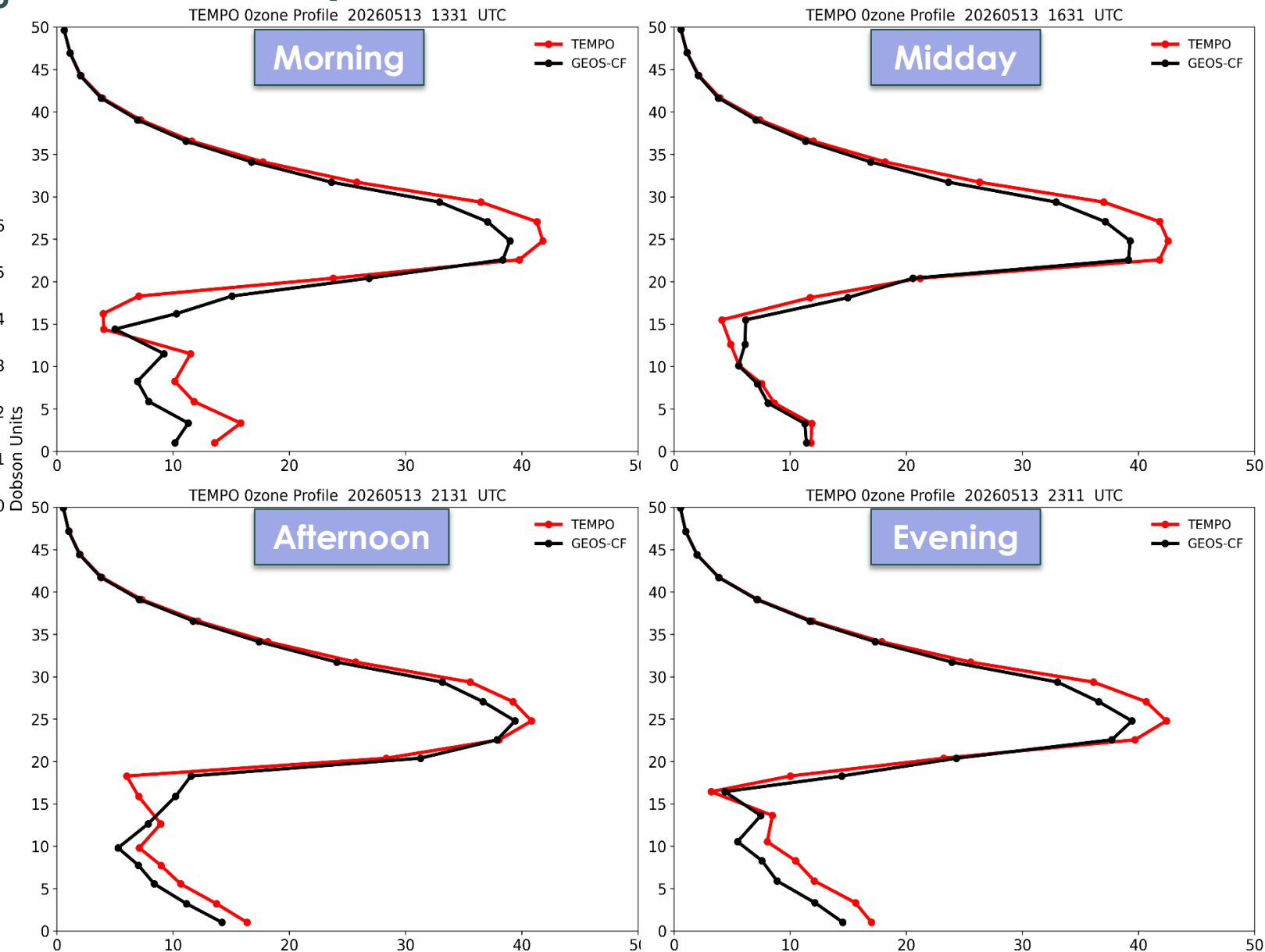
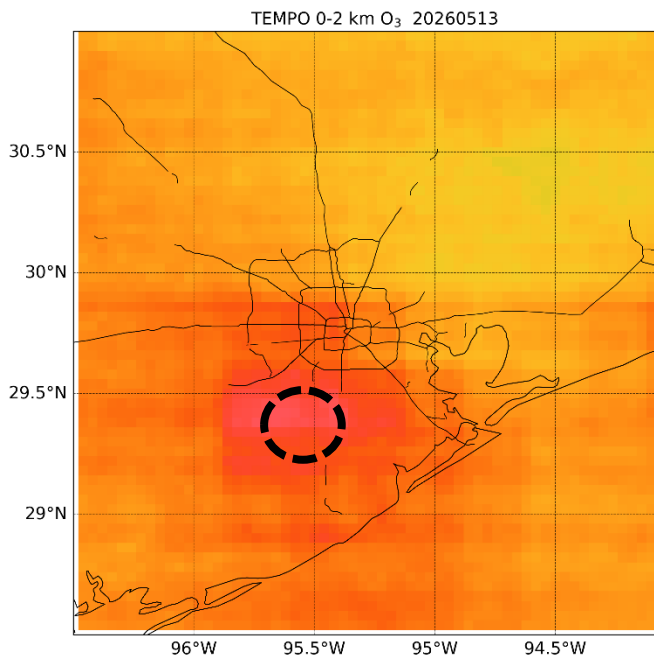
Ozone Monitors & TEMPO 0-2 km O₃ Columns (Daily Average)

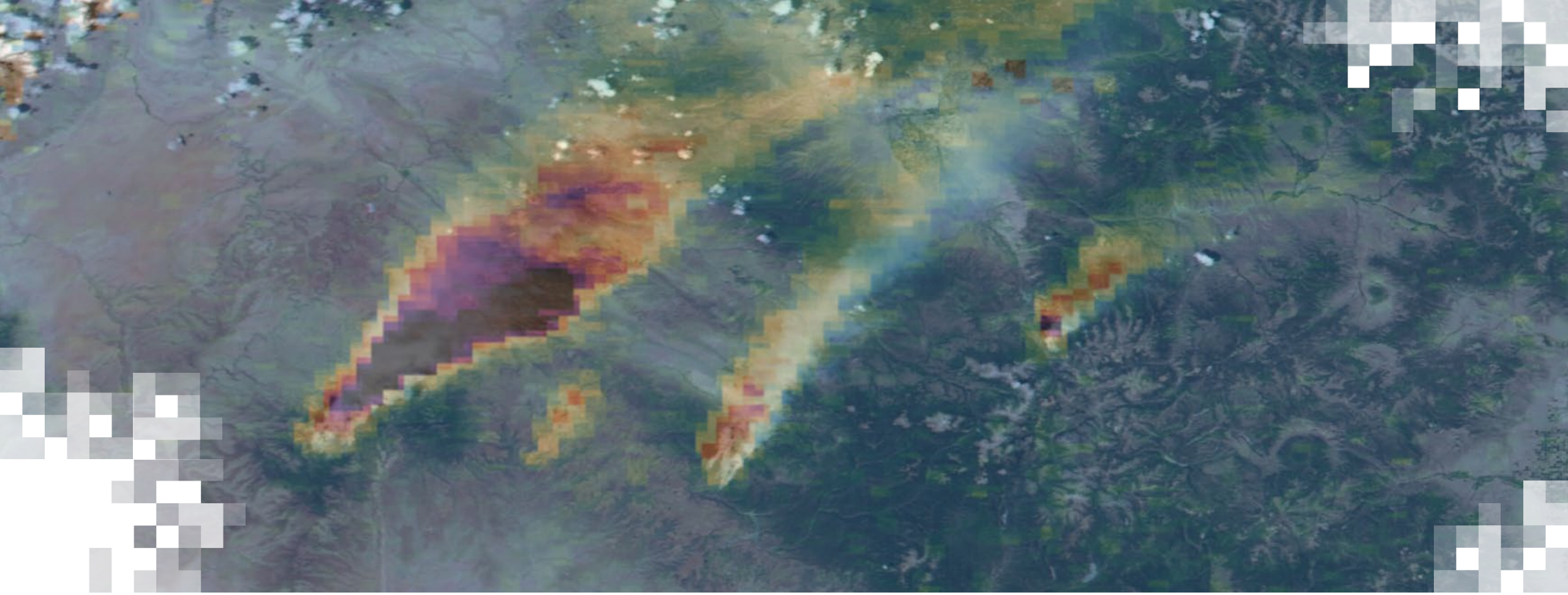


Ozone Monitors & GEOS-CF 0-2 km O₃ Columns (Daily Average)



TEMPO & GEOS-CF O₃ Profiles – May 13 in SW Houston



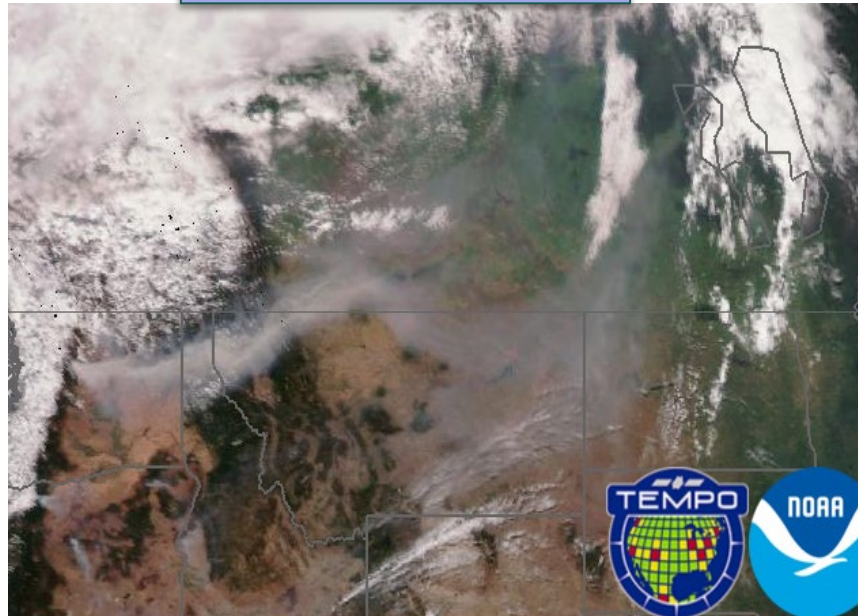


TEMPO Aerosol Products

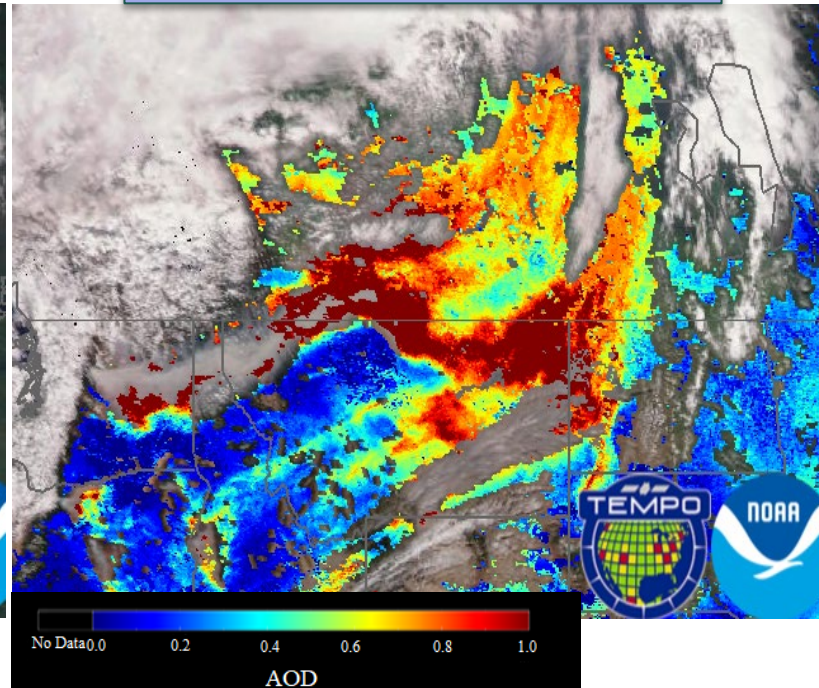
TEMPO True Color, AOD, & UVAI in AerosolWatch – August 2, 2026



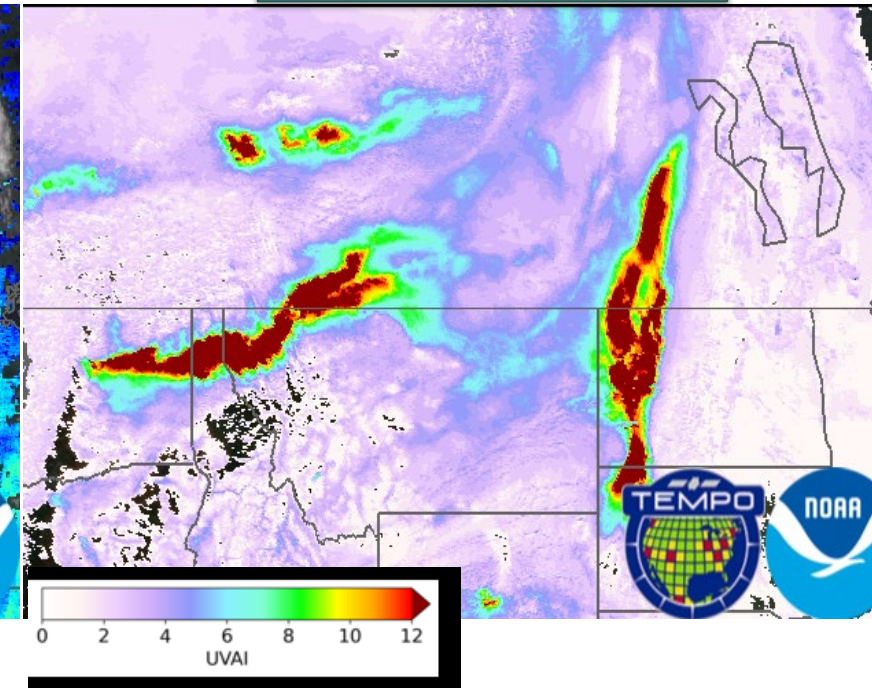
TEMPO True Color



Aerosol Optical Depth @550 nm



UV Aerosol Index

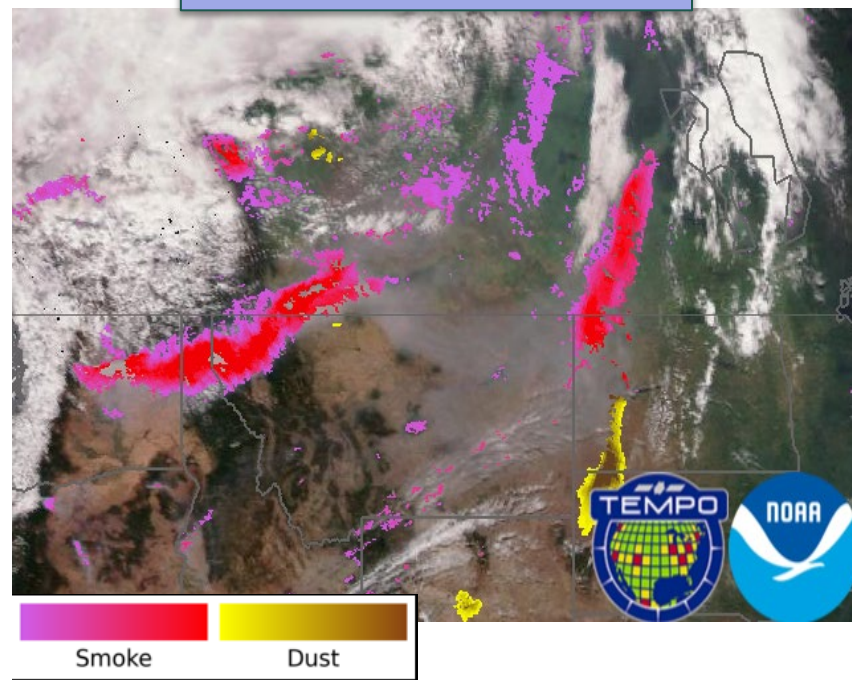


- Wildfire smoke plumes have been impacting air quality across the U.S.
- Smoke plume evident by the grayish color intensities in the TEMPO True Color imagery.
- TEMPO observed AOD values exceeding 1 across much of the smoke plume.
- Strongly positive UV Aerosol Index values within the absorbing smoke aerosols.

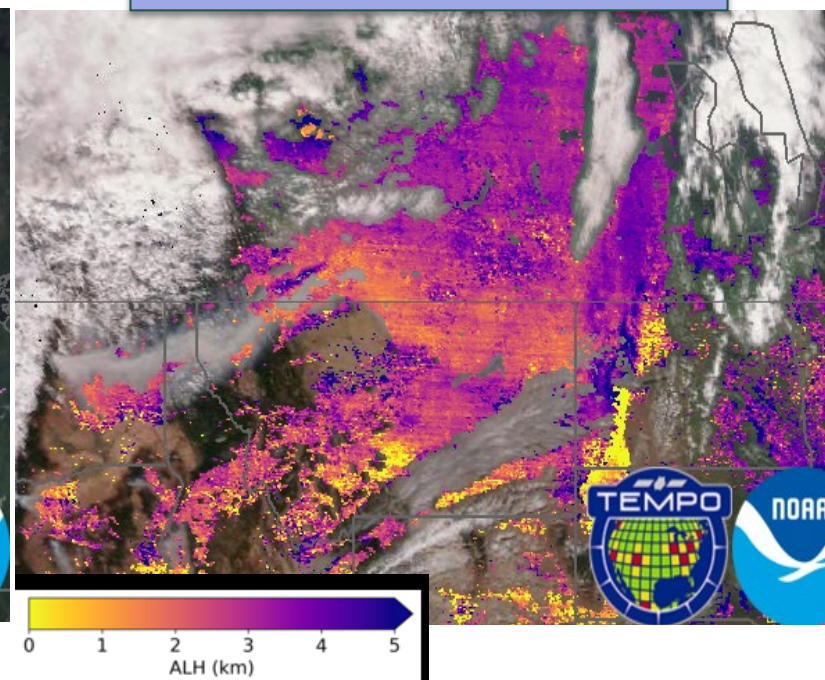


TEMPO ADP, ALH, & PM2.5 in AerosolWatch – August 2, 2026

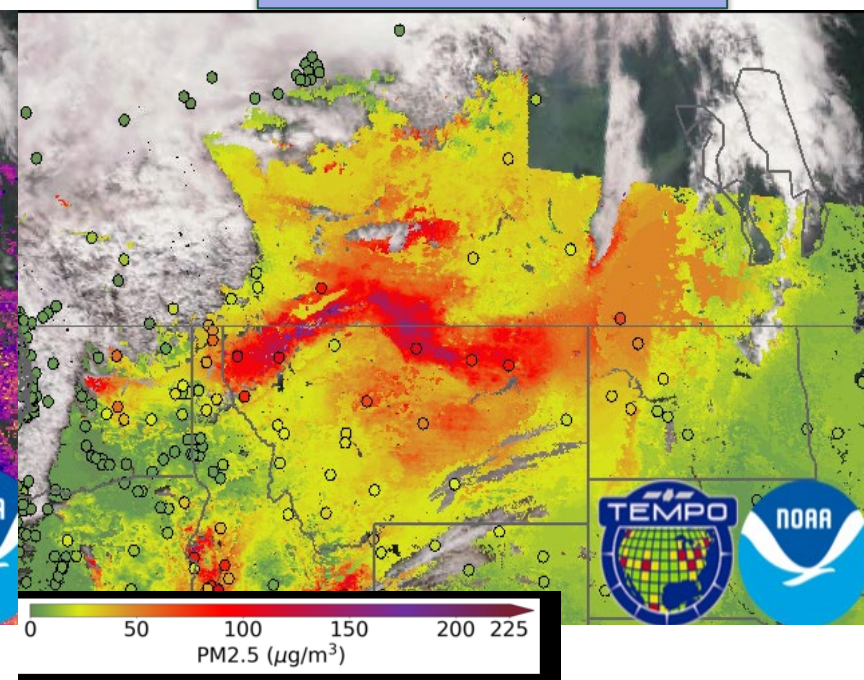
Aerosol Detection Product



Aerosol Layer Height

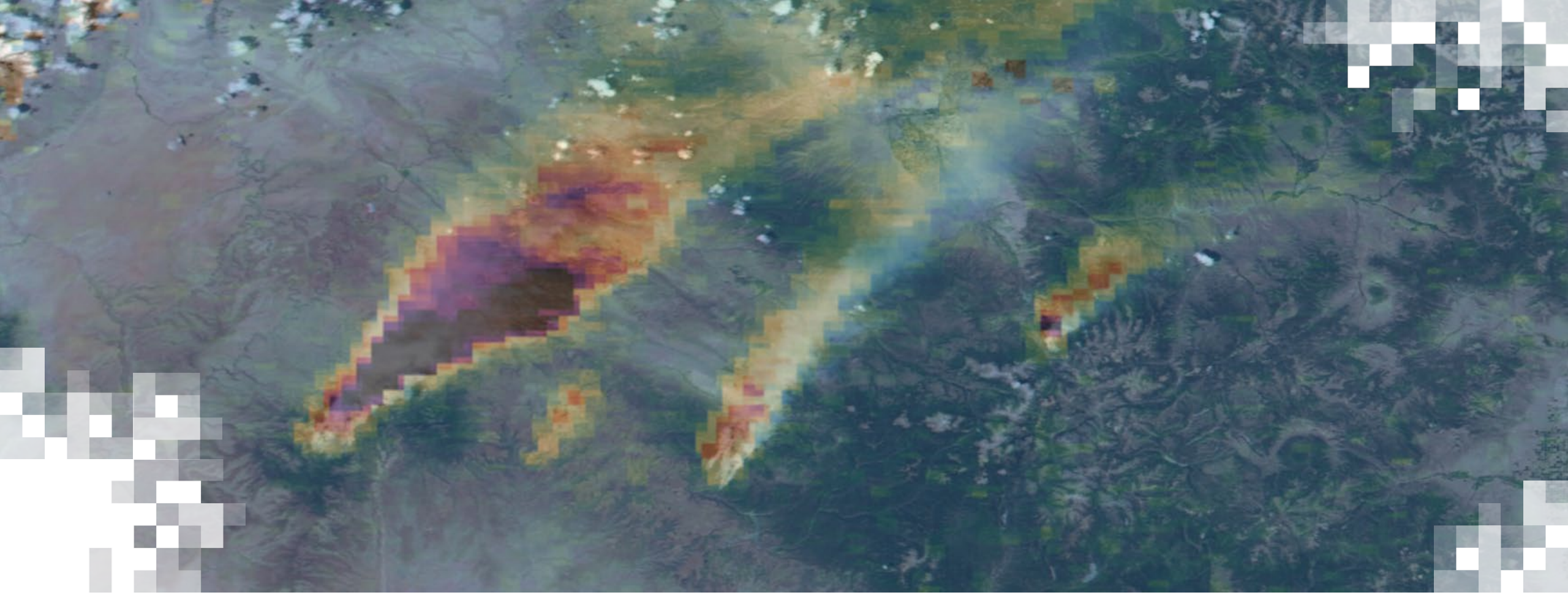


Hourly PM2.5



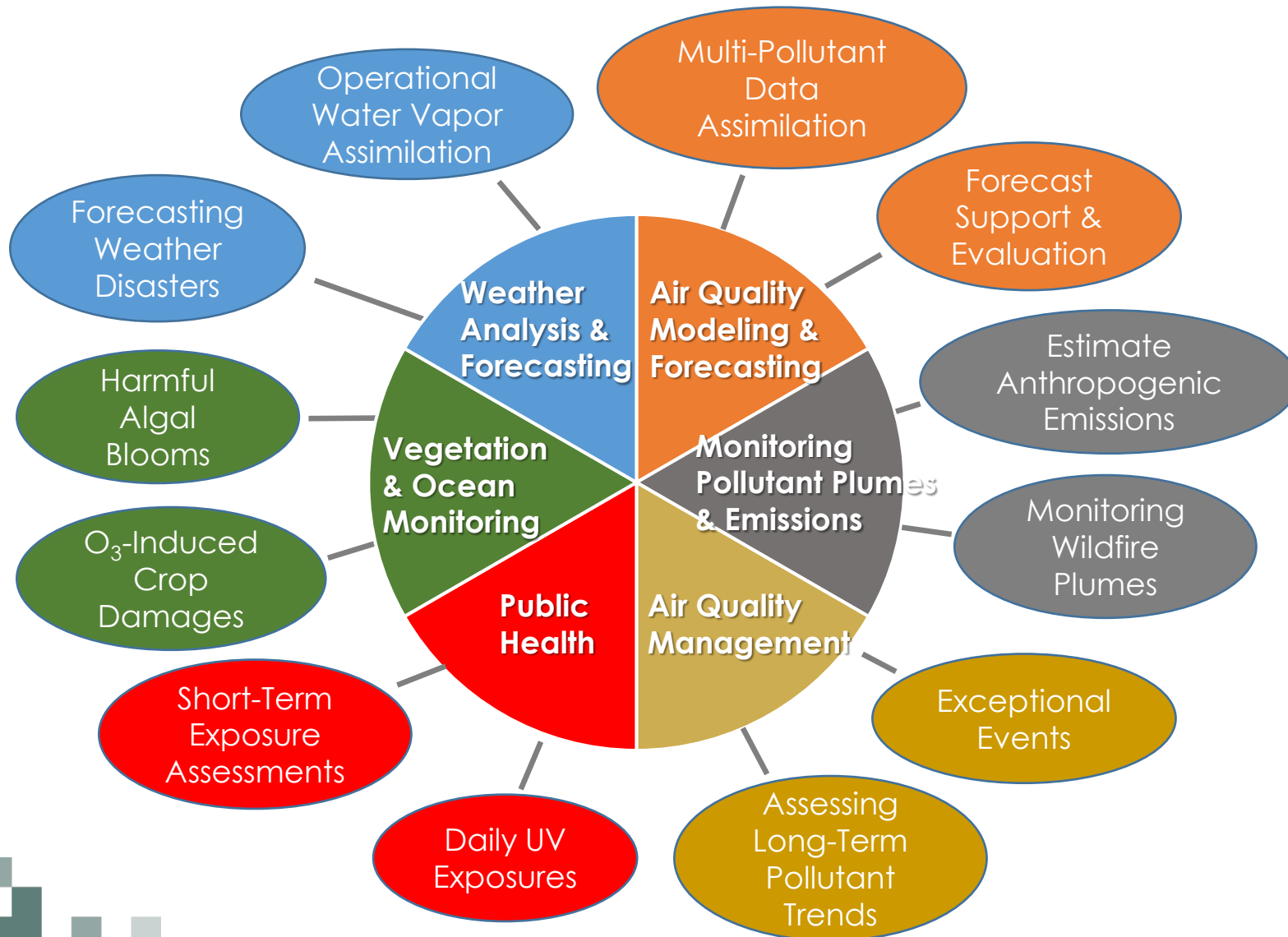
- Aerosol detection product identifies smoke and dust pixels with color maps relating to relative intensity of the aerosols.
- Aerosol Layer Height (ALH) shows large regions of the smoke plume where AOD exceeded 1 below about 2 km in height.
- Hourly PM2.5 estimates high surface-level PM2.5 especially in locations where ALH is below about 2 km and the PM2.5 estimates compare well with surface PM2.5 monitors.





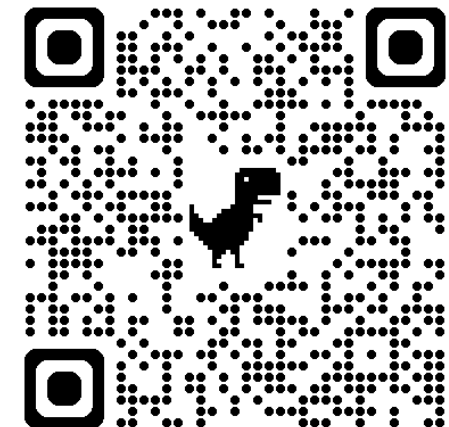
TEMPO Early Adopters & Applications

TEMPO Core Applications & Early Adopters



- TEMPO Early adopters provided key input on core applications of the mission.
- ~ 650 Early Adopters including 120+ from local, state, and regional air quality agencies.
- Transitioning Early Adopters to a Community of Practice.

Join the mailing list!



Summary

- TEMPO instrument observes precursor trace gases (NO_2 , HCHO) from a complexity of emission sources every hour throughout the daytime
- The O_3 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
- The suite of TEMPO products can track O_3 production from precursor gases and enable detailed analyses of O_3 production regimes
- The TEMPO aerosol products are planned for release no earlier than April 2027
- Planning a TEMPO Early Adopters meeting for the fall
- Beginning active engagement on the TEMPO NRT and Enhanced products



Upcoming Initiatives



ARSET training on TEMPO:
Geostationary Remote Sensing of
Trace Gases for Air Quality
Applications in North America

**ARSET training coming Nov.
2026:**

Geostationary Remote
Sensing of Aerosols for Air
Quality Applications in
North America



**Early Adopters
Mailing List**

Contact: aaron.naeger@nasa.gov





Thank You!

