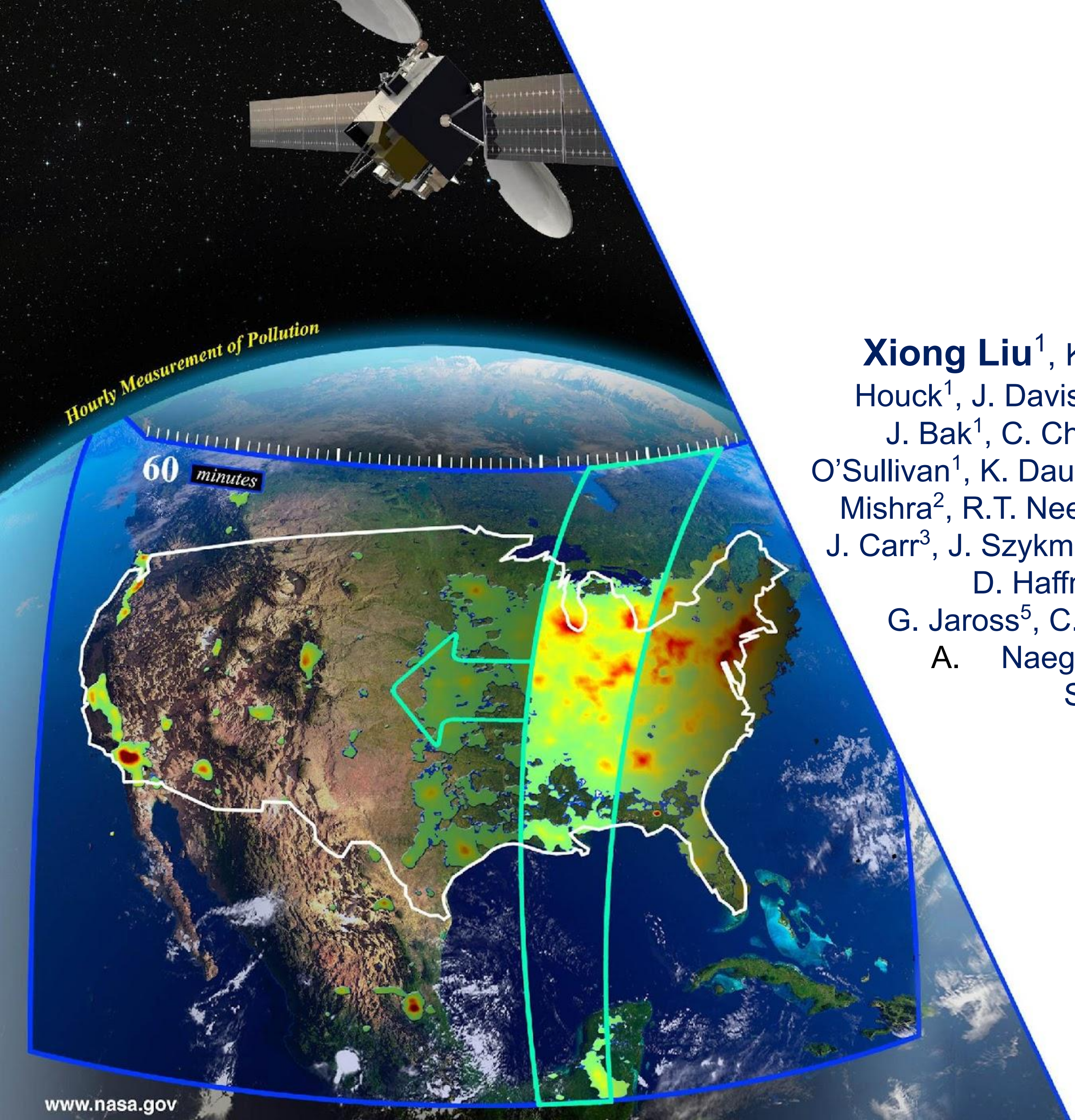


Tropospheric Emissions: Monitoring of Pollution

TEMPO

TEMPO Mission Status

Xiong Liu[1], K. Chance[1], C.R. Nowlan[1], G. Gonzalez Abad[1], R. Suleiman[1], J. Houck[1], J. Davis[1], H. Wang[1], H. Chong[1], W. Hou[1], J. Park[1], M. Ghahremanloo[1], J. Bak[1], C. Chan Miller[1], J. Fitzmaurice[1], L. Yatsuhashi[1], A. Oppenheimer[1], E. O'Sullivan[1], K. Daugherty[2], D.E. Flittner[2], C. Fenn[2], D. Rosenbaum[2], C. Brown[2], N. Mishra[2], R.T. Neece[2] , E. Roback[2], J. Strickland[2], L. Judd[2], P. Rawat[2], K. Travis[2], J. Carr[3], J. Szykman[4], B. Henderson[4], L. Valin[4], J. Joiner[5], Z. Fasnacht[5], S. Frith[5], D. Haffner[5], E. Knowland[5], N. Kramarova[5], N. Krotkov[5], C. Li[5], W. Qin[5], G. Jaross[5], C. Seftor[5], A. Vasilkov[5], E.-S. Yang[5], J. Ziemke[5], M. Newchurch[6], A. Naeger[6], R. Cohen[7], J. Geddes[8], J. Herman[9], B. Pierce[10], R. Spurr[11], S. Kondragunta[12], J. Wang[13], O. Torres[5], H. Zhang[12], P. Ciren[12], X. Zhao[14], and **the TEMPO Team**

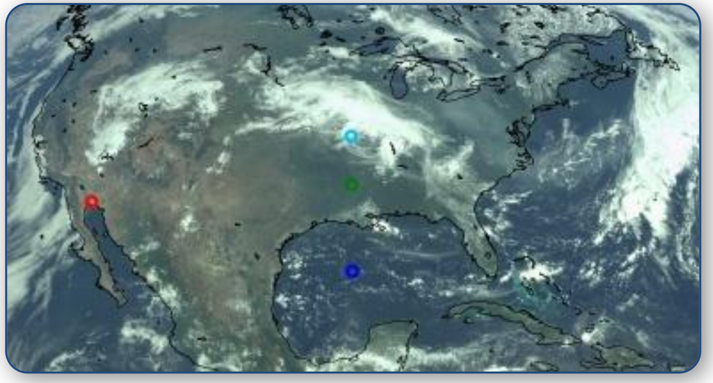
[1]Smithsonian Astrophysical Observatory (SAO), CfA
[2]NASA LaRc [3]Carr Astro. [4]EPA [5]NASA GSFC [6]UAH [7]UCB
[8]BU [9]UMBC [10]UWM [11]RT Sol. Inc [12]NOAA [13]UI [14]ECCC

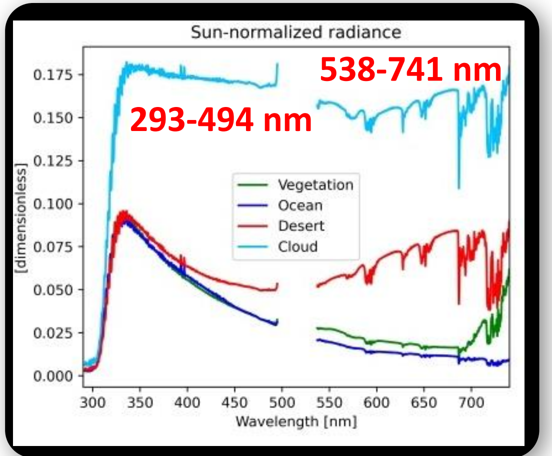
AC-VC-22 / WGCV-ACSG Joint Meeting 2026
Leiden, Netherlands (Virtual)
June 2, 2026

Smithsonian

TEMPO (Tropospheric Emissions: Monitoring of Pollution)

- NASA's first Earth Venture Instrument (EVI-1), selected in 2012
- Led by **Smithsonian Astrophysical Observatory (SAO)** in partnership with **NASA LaRC**, with instrument built by **Ball Aerospace (now part of BAE Systems)**
- NASA's first GEO & **host payload**, launched on board **IS-40e in April 2023** on to the GEO at 91 ˚ W
- **Hourly** daytime atmospheric observation over **North America** at **neighborhood scale** (**2x4.75 km^2** at the center of the field of regard), of foundational trace gases and aerosols, tied to 4 EPA criteria (O_3, NO_2, SO_2, PM) and 1 hazard (HCHO) air pollutants
- **Geostationary Air Quality Constellation** along with GEMS (2020) and Sentinel-4 (2025)





TEMPO first light RGB and examples of spectra
Credit: Heesung Chong

Credit: NASA's Scientific Visualization Studio

TEMPO Scanning

Nominal scans: hourly, 2.4M pixels

- 2035 N/S pixels x 1181 E/W steps per hour
- 2 x 4.75 km^2 at center of field of regard

Optimized scans

- Higher temporal resolution scans in early AM and late PM over coasts (40 mins)

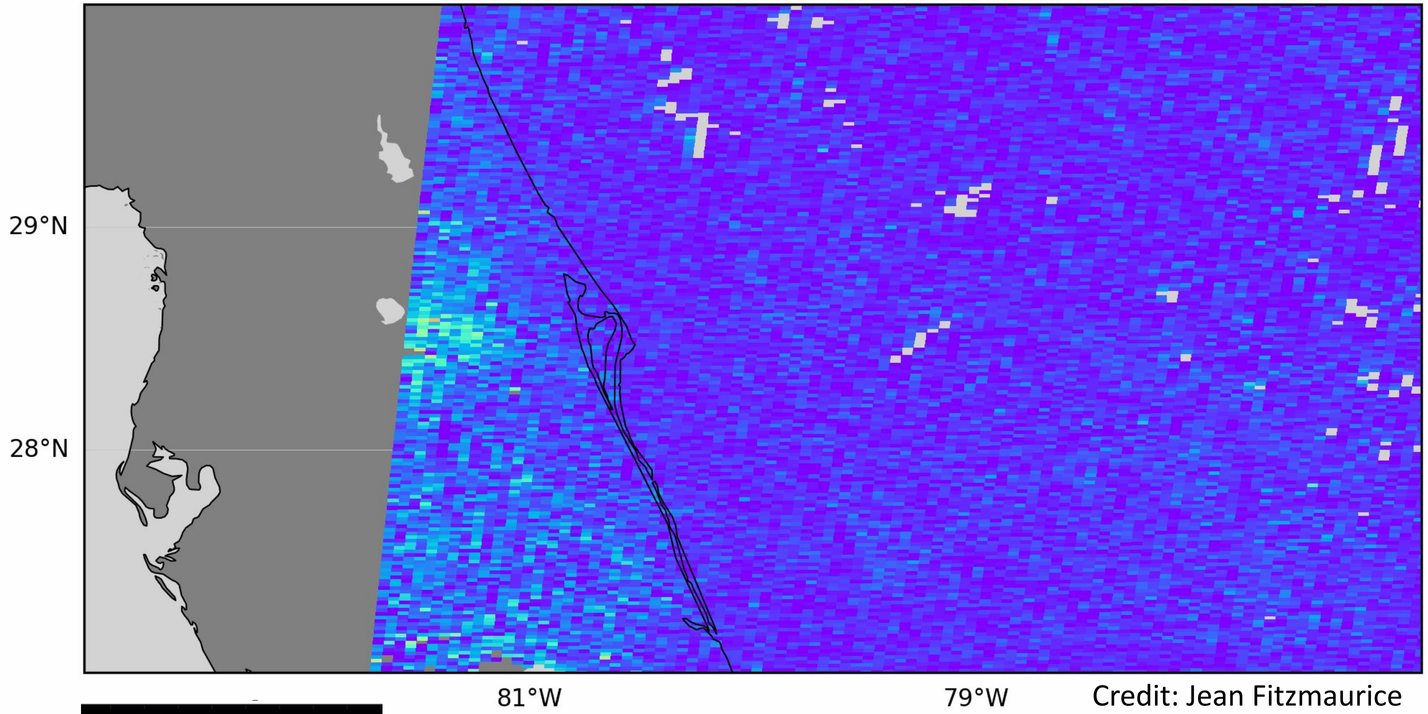
Special observations to support TEMPO

Green Paper & Cal/Val: wildfires, prescribed burning, lightning NOx, CO Front Range field campaigns, Artemis-II Launch, CAL/VAL

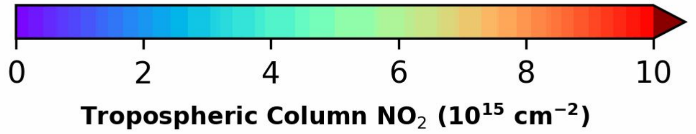
- High-frequency scans (~5-10 mins) over selected regions (alternate hourly scan / 1 hour high-frequency scans)
- Lunar collects (4/9/2025, 9/9/2025, 11/3/2025, 12/10/2025, 2/3/2026, 4/26/2026)
- Railroad Valley (side slither: 6/2024, 6/2025, 10/2025)

Request Special Observations at TEMPO Early Adopter Website

TEMPO Tropospheric Column NO_2 01 Apr 2026 2226 UTC



Credit: Jean Fitzmaurice



Detection of enhanced NO_2 associated with Artemis-II Launch

Credit: Joe Raedle

TEMPO at Night
Bonus Science and Discovery

Earth and Space Science

Research Article | Open Access

TEMPO at Night

James L. Carr, Heesung Chong, Xiong Liu, John C. Houck, Virginia Kalb, Houria Madani, Dong L. Wu, Daniel T. Lindsey, Steven D. Miller, David E. Flittner, Kelly Chance, Raid Suleiman, John E. Davis, Jean Fitzmaurice, Laurel Carpenter ... See fewer authors

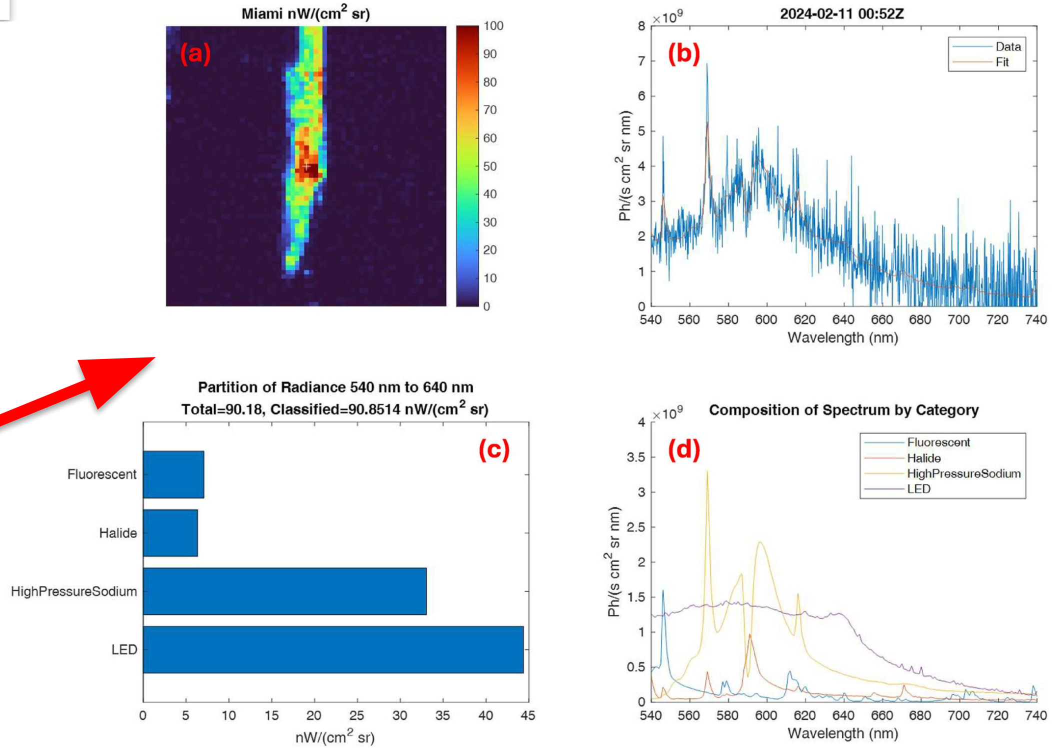
First published: 30 September 2025 | https://doi.org/10.1029/2024EA004157

Twilight (Nighttime) scans

- Performed during darkness (~Aug. 15-Apr. 15)
- City lights, moonlights, Aurora, airglow, gas flaring, fires, lightning,
- Hyperspectral measurements of nighttime lights
- Light pollution, energy use, sleep health, and ecology, etc.

City lights composite 1–12 February 2024

Credit: Jim Carr



Hyperspectral nighttime measurements allow **lighting types** to be identified, including over Miami in this example.

TEMPO

TEMPO Timeline & Status

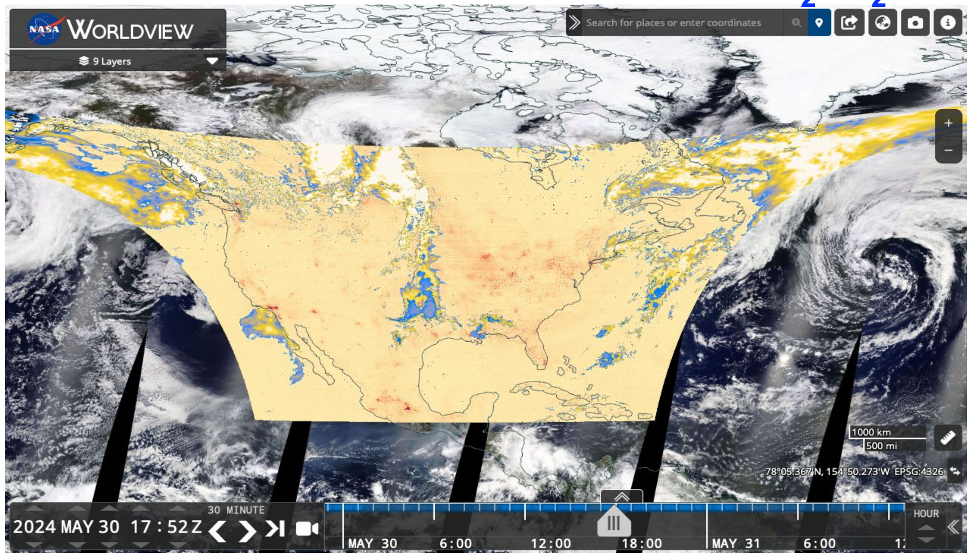
Date	Details
7 April 2023	Launch
June-July 2023	TEMPO power on + dry-out, cool down, etc.
2 August 2023	First light
19 October 2023	**Nominal operations**
18 June 2025	**Baseline mission ended (End-of-Prime Mission Review 12/11/2025)**
September 2026	First extended mission ends, further extension by NASA senior reviews (1st on **April 14, 2026 extending from 10/1/2027-9/30/2029**)

- **The TEMPO instrument (hardware & software): healthy**
  - ✔ Dual solar diffuser system allows for corrections in optical performance
  - ✔ There are no issues with or limitations to the instrument lifetime
- **The IS-40e spacecraft (hardware & software): healthy**
  - ✔ Commercial communications satellite designed for 15+ years of operation

Successful commissioning & nominal operation; Instrument & spacecraft performing very well!

TEMPO Data Products Public Release NASA's ASDC & EarthData

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, NO_2, H_2CO, total O_3 (provisional)** **V3 O_3 profile (ASDC 6/9/2025, not for the public)**
V04	**9/17/2025**	**Ozone Profile (beta), L1 + other L2/L3 (provisional)** **RADT (1/6/2026), Reprocessing started on (1/29/2026)**
NRT V02	**9/17/2025**	**L1, L2/3 cloud, NO_2, H_2CO (funded by SNWG)**



ASDC TEMPO

- TEMPO data now publicly available at NASA's ASDC/Earthdata (~6 hours latency, NRT with 2-3 hours latency).
- Multiple tools ([enabled] by Earthdata):
  - Earthdata Search, OPeNDAP
  - NASA Worldview: all data products (L2+L3)
  - ArcGIS services (Earthdata & Living Atlas): L3 NO_2 + HCHO + total ozone
  - RSIG (EPA)
  - TEMPO-Lite (CfA CosmicDS): L3 NO_2
  - NASA SPoRT Viewer
  - Google Earth Engine (L3 NO2 & HCHO)
- For more information check out:
  - **User Guides (known issues)**
  - **Daily operation & commissioning logs**
  - Validation reports
  - ATBD (drafts available upon request for L0-1 & O_3 profile, released for total O_3, cloud, NO_2, & HCHO)

TEMPO V3/V4 & NRT V2 download metrics (May 2024-December 2025)

- ✔ **5 PB, 170M files, >1300 unique user IPs**
- ✔ **Worldview: >5300 unique user IPs, 6.2M records**
- ✔ **ArcGIS Trop. NO_2 (Living Atlas): >7800 unique user IPs**

Baseline TEMPO Data Products (V4)

Level	V4 Product	Validation Status
L1	Irradiance	Provisional
	Radiance	Provisional
	Radiance (twilight – city lights)	Provisional
L2	Clouds	Provisional
	NO_2	Provisional
	HCHO	Provisional
	O_3 (total)	Provisional
	O_3 (profile)	Beta->Provisional in 6/2026
L3	L2 gridded to 0.02° × 0.02°	Provisional

Reprocessing started on 1/29/2026, 2-3 days reprocessed in 1 day. Expect to complete in 7-8 mons (Jan. 2027). Trying to finish most data products sooner (excluding O_3 profile)

Work with the Validation Team and PEGASOS team to validate V4 and advance it to Full level (mid. 2027)

**Beta*: "minimally validated", publication "not recommended and highly discouraged"

Provisional: "performance demonstrated", "suitable for scientific publication"

Expand Beyond TEMPO Baseline Products
SNWG NRT + SNWG Enhanced + Research

Level	Product	Developer
L1	Irradiance	SAO
	Radiance NRT	SAO (Chong, ESS, 2026)
	Radiance (twilight – city lights)	SAO (Carr, ESS, 2025)
L2	Cloud NRT	SAO/GSFC (Wang, ESS, 2025)
	NO_2 NRT	SAO (Nowlan, ATBD, 2024)
	H_2CO NRT	SAO (Gonzalez Abad, ATBD,2024)
	O_3 (total)	SAO/GSFC
	O_3 (profile)	SAO
	TEMPO/GOES-R aerosol products NRT	NOAA(released, ASDC, Zhang, JGR,25,26)
	$C_2H_2O_2$	SAO
	H_2O	SAO
	BrO	SAO
	SO_2 NRT	NASA GSFC (Li, 2025, GRL)
	UVAOD	NASA GSFC (under develop.)
	Aerosol Optical Centroid Height	U. Iowa (under develop.)
	UVB	NASA GSFC (under develop.)

Baseline Products: V5 in ~9/2028

Satellite Needs Working Group (SNWG)
Cycle 3 **NRT Products (~2-3 hours)**
Public release (Sep. 17, 2025)

SNWG Cycle 4
TEMPO SO_2 NRT & Enhanced Products
Public release in ~9/2028

Research Products

Ocean color (**Fasnacht, 2025**, ESS, NASA ROSES)
Vegetation (GPP) (Bandel @SSAI/NASA GSFC)
HNO_2 (Theys @BIRA-IASB)
Free tropospheric NO_2 (Dang, 2025, PNAS)
Surface Products (**Ghahremanloo, JGR** & many studies)
Emissions (**Sun, JGR**, **Hsu, submitted** @many studies)
JEDI Data Assimilation (Abdi-Oskouei, 2026)
TEMPO/GOES-R Synergy Radiance (Wang+Carr, ROSES)
Surface albedo/DLER (Zhang, JGR, NOAA)
IO, NO_3, Solar induced fluorescence

Diurnal Variations in Ozone Production


Geophysical Research Letters

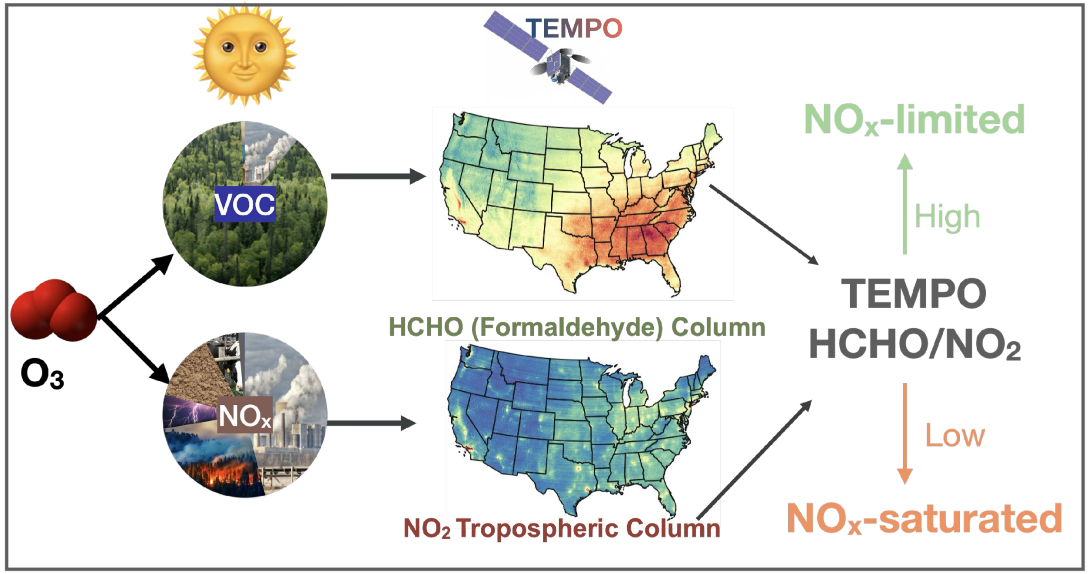
Research Letter | Open Access

Observing the Diurnal Variations of Ozone-NO_x-VOC Chemistry Over the U.S. From the Geostationary TEMPO Instrument

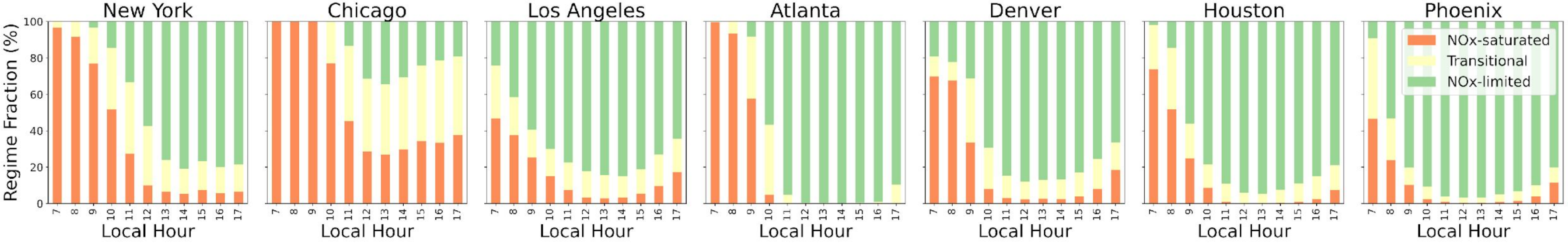
Xiaomeng Jin, Yohan Yang, Gonzalo Gonzalez Abad, Caroline Nowlan, Xiong Liu

First published: 15 July 2025 | https://doi.org/10.1029/2025GL116394

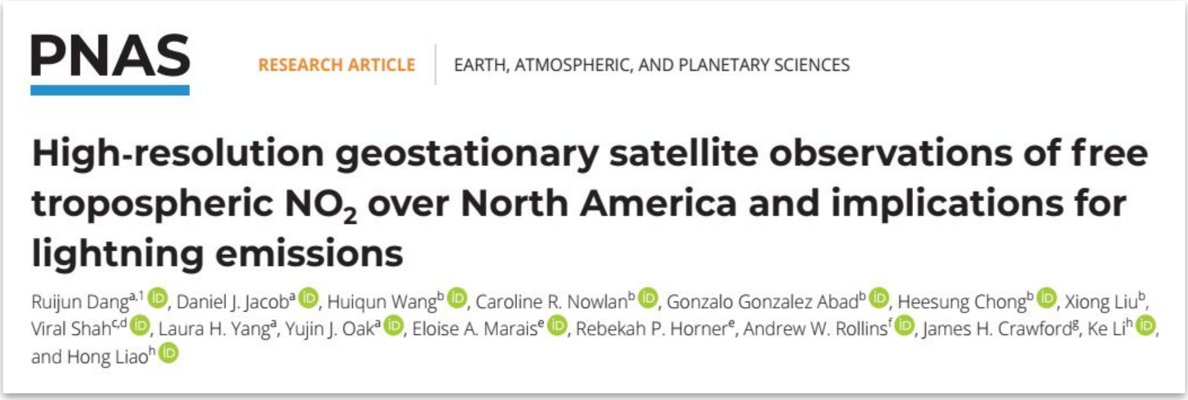
Jin et al. (2025) demonstrate the **potential** of TEMPO-based indicators to track **diurnal changes in ozone chemistry** and to provide a powerful tool to **improve the timing and cost-effectiveness of emission control strategies**.



Observations of major components, directly or by proxy, of the diurnal tropospheric O_3 chemistry cycle.



Diurnal Variation of Free Tropospheric NO_2


PNAS

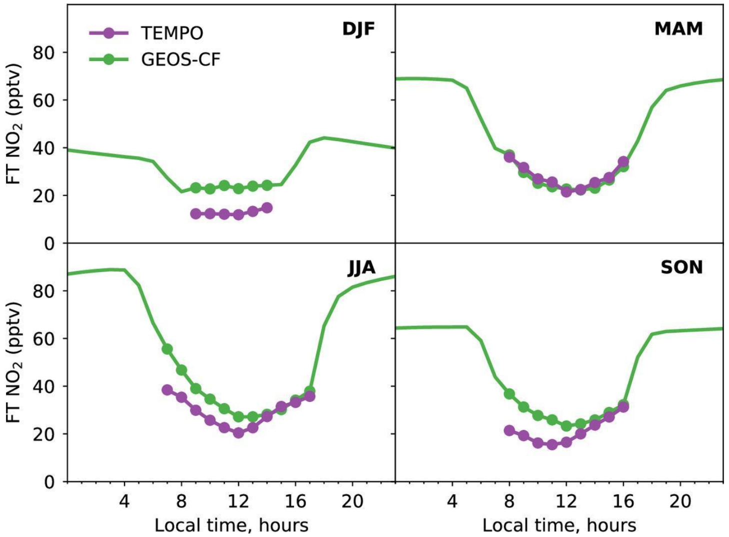
RESEARCH ARTICLE | EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

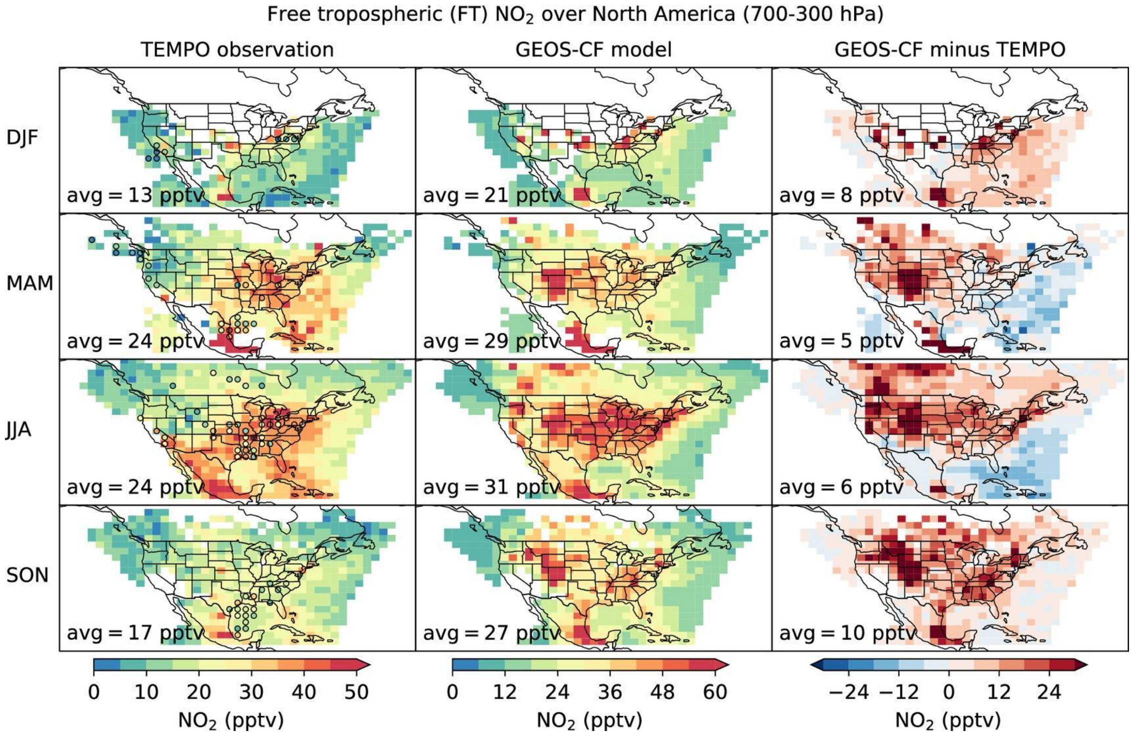
High-resolution geostationary satellite observations of free tropospheric NO_2 over North America and implications for lightning emissions

Ruijun Dang[a,1], Daniel J. Jacob[a], Huiqun Wang[b], Caroline R. Nowlan[b], Gonzalo Gonzalez Abad[b], Heesung Chong[b], Xiong Liu[b], Viral Shah[c,d], Laura H. Yang[a], Yujin J. Oak[a], Eloise A. Marais[e], Rebekah P. Horner[e], Andrew W. Rollins[f], James H. Crawford[g], Ke Li[h], and Hong Liao[h]

Dang et al. (2025) use a **cloud slicing technique** to estimate free tropospheric (FT) NO_2 from TEMPO. Comparisons with the Global Lightning Mapper (GLM) suggest **lightning NO_x is the dominant source of free tropospheric NO_2 in non-winter months**.

First observations of FT NO_2 diurnal variability

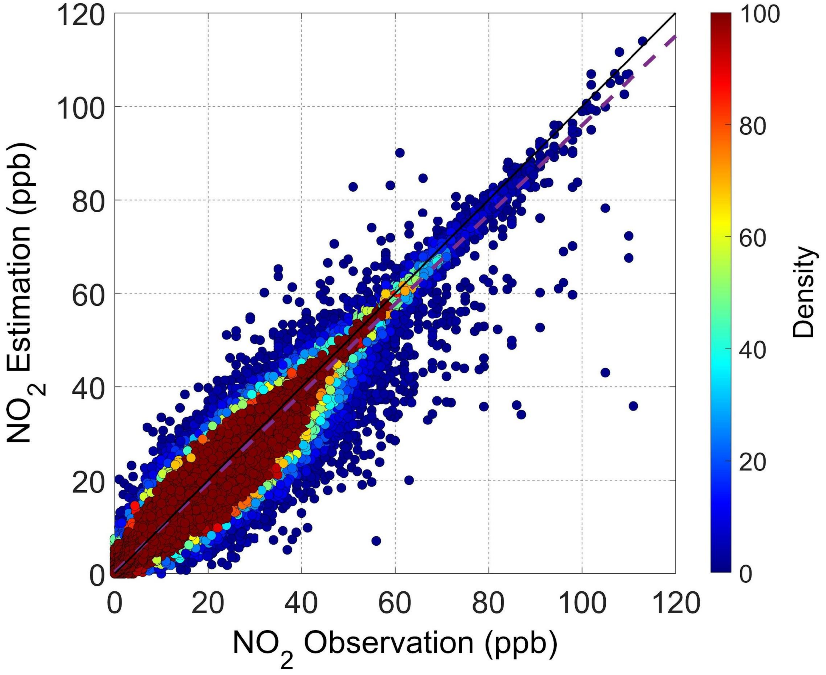


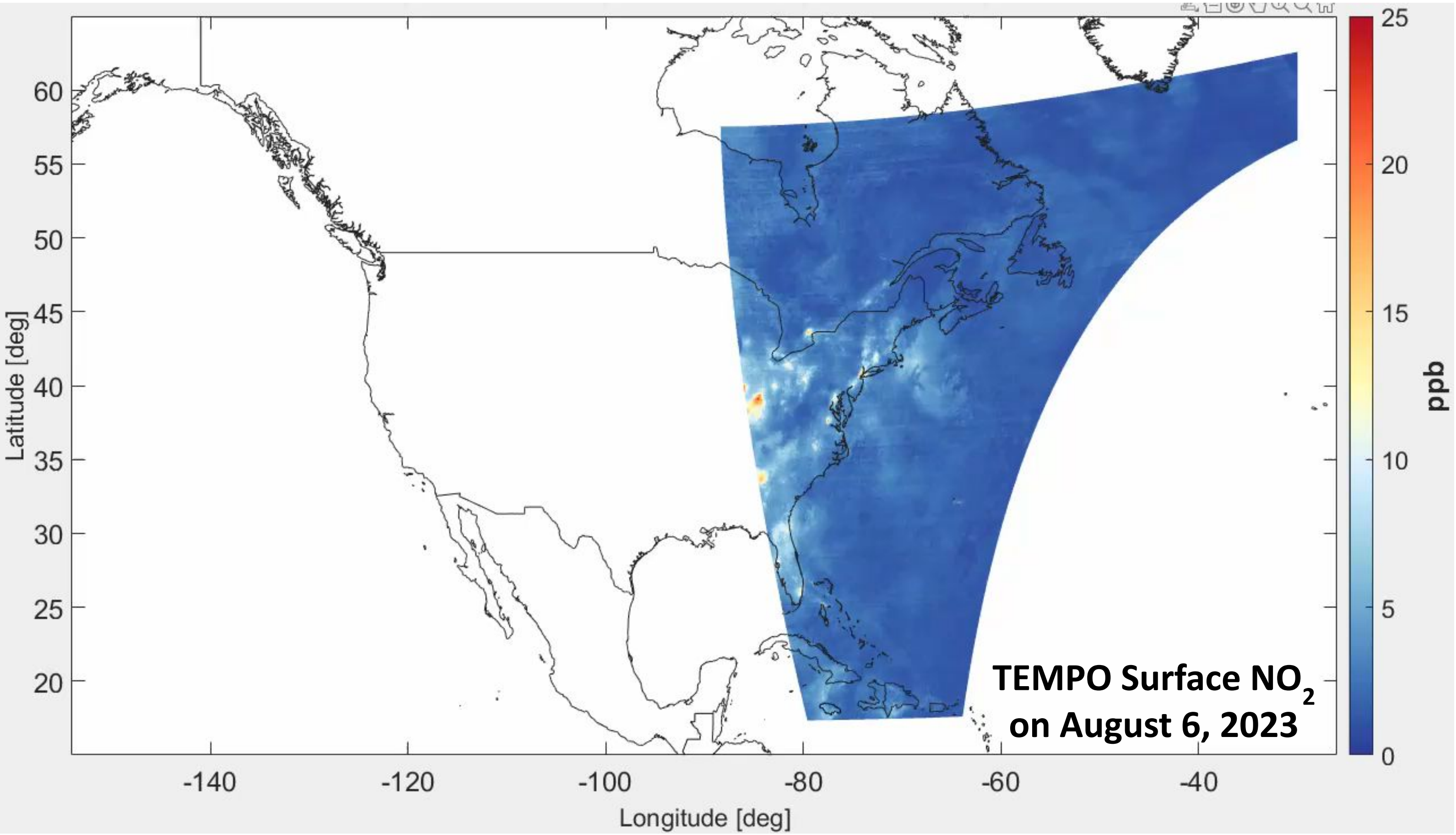


Large discrepancies are seen between TEMPO and modeled spatial distributions of free tropospheric NO_2, **indicating a commonly used parameterization of this source in atmospheric chemistry models has large errors**. A follow-up study is using TEMPO to quantify lightning NO_x production, and estimates ~150 mol N flash^{-1} [Dang et al., in preparation].

AI-Derived TEMPO Surface NO_2 Product

- **A new 2023-2024 record of hourly gap-free surface NO_2 is now available from TEMPO**
  - ✔ Produced using a deep learning model trained on 750 US, Canadian and Mexican surface monitors.
  - ✔ Cross-validation using different methods (ten-fold, spatial, rural-vs-urban, gap-filled) shows excellent performance (R=0.93-0.98, MAB ~1 ppb, MB ~0 ppb).





Ghahremanloo et al., submitted to *RSE.* Preprint at SSRN

Surface NO2 data (8/2/2023-12/31/2024) available at Harvard Dataverse

Summary and Outlook

- Revolutionizing air quality monitoring from space with widespread data adoption
- Successful commissioning and nominal operations
- Instrument and spacecraft performing very well
- Successfully completed baseline mission. 1st extension to Sep. 2026 + NASA Senior Reviews
- Special observations capability to support TEMPO Green Paper & CAL/VAL
- TEMPO at night capability provides bonus science and discovery
- Released significantly improved V4 data products including ozone profile (reprocessing ongoing) and V2 NRT products on September 17, 2025.
- Continue to improve data products (next version in ~9/2028)
- Develop new data products (funded under SNWG, public release in ~9/2028)
- Expand the wide usage of TEMPO data for science and applications

Acknowledgements: **Funding from NASA (TEMPO, NNL13AA09C; SNWG TEMPO NRT, 80MSFC24CA004)**

Thank you!

NASA

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Ball

MAXAR

INTELSAT

SPACEX

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE NOAA

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

THE UNIVERSITY OF CALIFORNIA 1868

UAH THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

HARVARD UNIVERSITY ATMOSPHERIC CHEMISTRY MODELING GROUP

YONSEI UNIVERSITY 1885 연세대학교

SAINT LOUIS UNIVERSITY

WASHINGTON UNIVERSITY IN ST. LOUIS 1853

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

UNIVERSITY OF MARYLAND BALTIMORE COUNTY UMBC 1966

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

THE UNIVERSITY OF IOWA

YORK UNIVERSITÉ UNIVERSITY

INECC INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

INSMET

THE UNIVERSITY OF EDINBURGH

FINNISH METEOROLOGICAL INSTITUTE

CARR ASTRONAUTICS Science at work

RTS

NCAR

Environment and Climate Change Canada

Environnement et Changement climatique Canada

KNMI

TEMPO

Geostationary + LEO Air Quality Constellation

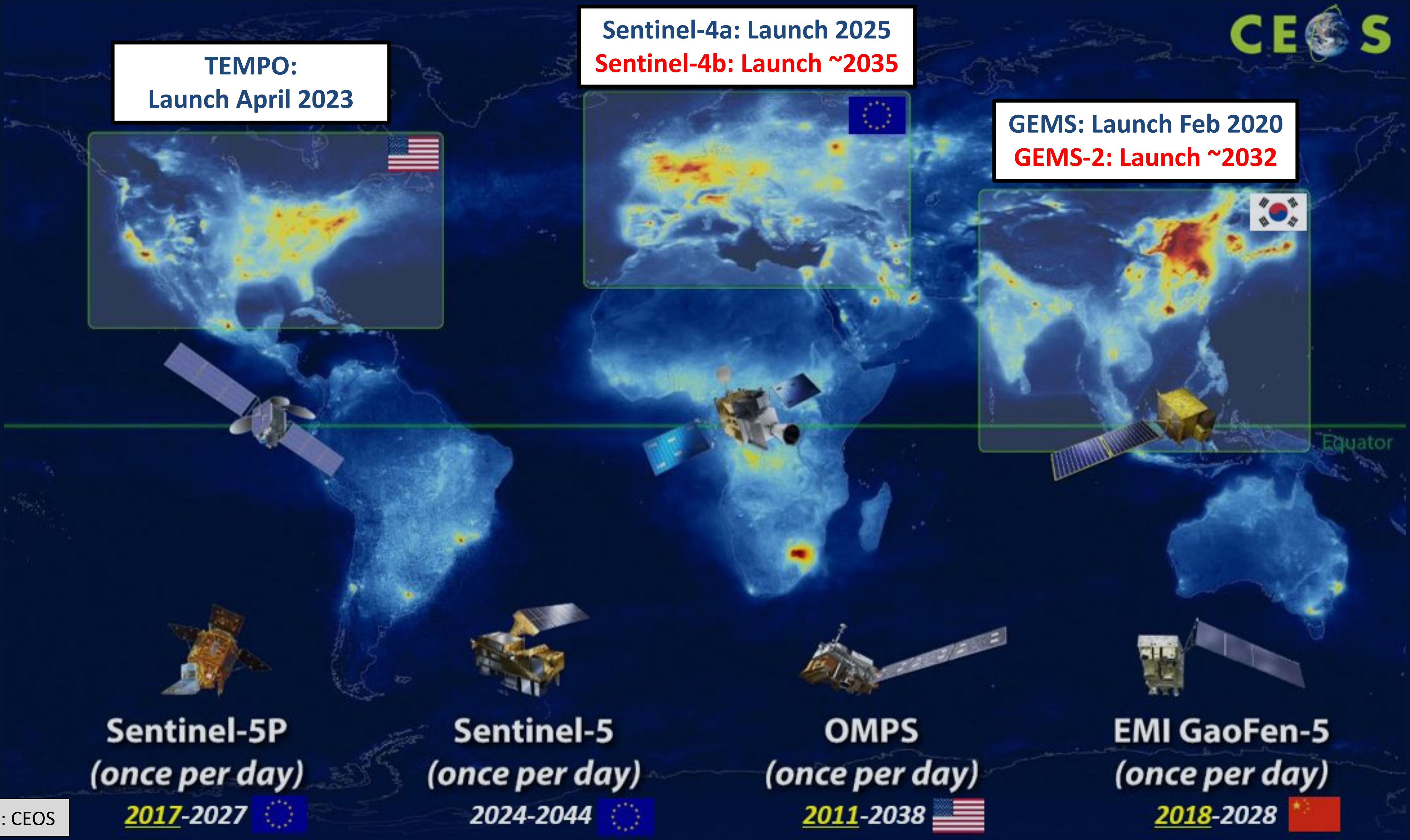


Image Credit: CEOS

TEMPO Science Questions and Objectives

TEMPO's original community-derived science questions and objectives are central to the mission given the variability of atmospheric composition, emissions and air quality.

Science Questions	Science Objectives
Q1. What are the temporal and spatial variations of **emissions** of gases and aerosols important for air quality and climate?	**High temporal resolution** measurements to capture changes in pollutant **gas** distributions. [Q1, Q2, Q3, Q4, Q5, Q6]
Q2. How do physical, chemical, and dynamical **processes** determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally?	**High spatial resolution** measurements that sense urban scale pollutant **gases** across Greater North America and surrounding areas. [Q1, Q2, Q3, Q5, Q6]
Q3. How do **episodic events** affect atmospheric composition and air quality?	Measurements of **major elements in tropospheric O_3 chemistry cycle**, including multispectral measurements to improve sensing of lower-tropospheric O_3, with precision to clearly **distinguish pollutants from background** levels. [Q1, Q2, Q4, Q5, Q6]
Q4. How does **air quality** drive **climate** forcing and climate change affect air quality on a continental scale?	Observe **aerosol** optical properties with **high temporal and spatial resolution** for quantifying and tracking evolution of aerosol loading. [Q1, Q2, Q3, Q4, Q5, Q6]
Q5. How can observations from space improve **air quality forecasts and assessments** for societal benefit?	Determine the instantaneous radiative **forcings** associated with **O_3 and aerosols** on the continental scale. [Q3, Q4, Q5]
Q6. How does trans-boundary **transport** affect air quality?	**Integrate observations** from TEMPO and other platforms into **models** to improve representation of **processes** in the models and construct an **enhanced observing system**. [Q1, Q2, Q3, Q5, Q6]
	Quantify the **flow of pollutants** across boundaries (physical & political); **Join a global observing system**. [Q2, Q3, Q4, Q5, Q6]

TEMPO Science Traceability Matrix

Science Questions	Science Objective	Science Measurement Requirement: Observables	Investigation Requirements
Q1. What are the temporal and spatial variations of emissions of gases and aerosols important for AQ and climate? **Q2.** How do physical, chemical, and dynamical processes determine tropospheric composition and AQ over scales ranging from urban to continental, diurnally to seasonally? **Q3.** How do episodic events affect atmospheric composition and AQ? **Q4.** How does AQ drive climate forcing and climate change affect AQ on a continental scale? **Q5.** How can observations from space improve AQ forecasts and assessments for societal benefit? **Q6.** How does trans-boundary transport affect AQ?	**A.** High temporal resolution measurements to capture changes in pollutant gas distributions. [Q1, Q2, Q3, Q4, Q5, Q6] **B.** High spatial resolution measurements that sense urban scale pollutant gases across GNA and surrounding areas. [Q1, Q2, Q3, Q5, Q6] **C.** Measurement of major elements in tropospheric O_3 chemistry cycle, including multispectral measurements to improve sensing of lower-tropospheric O_3, with precision to clearly distinguish pollutants from background levels. [Q1, Q2, Q4, Q5, Q6] **D.** Observe aerosol optical properties with high temporal and spatial resolution for quantifying and tracking evolution of aerosol loading. [Q1, Q2, Q3, Q4, Q5, Q6] **E.** Determine the instantaneous radiative forcings associated with O_3 and aerosols on the continental scale. [Q3, Q4, Q6] **F.** Integrate observations from TEMPO and other platforms into models to improve representation of processes in the models and construct an enhanced observing system. [Q1, Q2, Q3, Q5, Q6] **G.** Quantify the flow of pollutants across boundaries (physical & political); Join a global observing system. [Q2, Q3, Q4, Q5, Q6]	Spatially imaged & spectrally resolved, solar backscattered earth radiance, spanning spectral windows suitable for retrievals of O_3, NO_2, H_2CO, SO_2 and $C_2H_2O_2$. [A, B, C, E, F, G] Measurements at spatial scales comparable to regional atmospheric chemistry models. [A, B, C, D, F, G] Multispectral data in suitable O_3 absorption bands to provide vertical distribution information. [A, B, C, E, F, G] Spectral radiance measurements with suitable quality (SNR) to provide multiple measurements over daylight hours (solar zenith angle < 70°) at precisions to distinguish pollutants from background levels. [A to G] Spatially imaged, wavelength dependence of atmospheric reflectance spectrum for solar zenith angles <70°. [B, D, E, F, G]	Mission lifetime: 1-yr (Threshold), 20-mon (Baseline), 10-yr (Goal) Orbit Longitude °W: 90-110 (Preferred), 75-137 (Acceptable) GEO Bus Pointing: Control <0.1° Knowledge <0.04° On-orbit Calibration, Validation, Verification FOR encompasses CONUS and adjacent areas Provide near-real-time products to user communities within 2.5-hr to enable assimilation into chemical models (NOAA & EPA) and use by smart-phone applications Distribute and archive TEMPO science data products

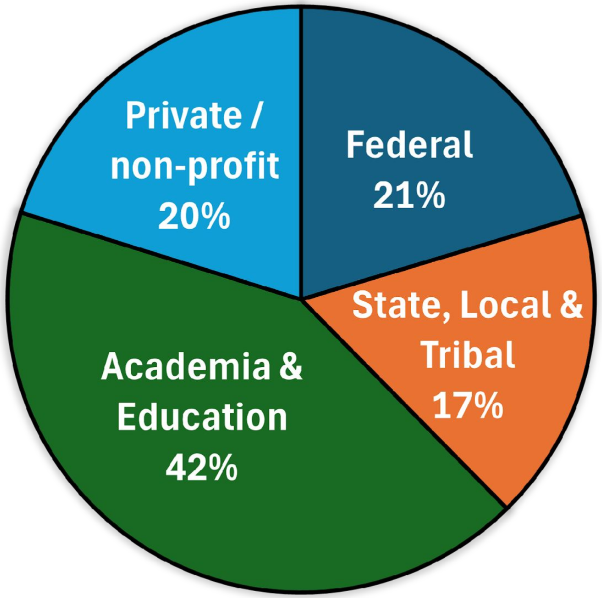
Science Measurement Requirement: Physical Parameters		Instrument Function Requirements: Parameter	Required	Predicted
Baseline#* Trace gas column densities (10^{15} cm^{-2}) hourly @ 8.9 km x 5.2 km				
Species	Precision	Band	Signal to Noise	
O_3: 0-2 km	10 ppbv	O_3: Vis (540-650 nm)	≥1413	1765
O_3: FT	10 ppbv	O_3: UV (290-345 nm)	≥1032	1247
O_3: SOC	5%			
O_3: Total	3%			
NO_2	1.00	423-451 nm	≥781	2604
H_2CO	17.3	327-354 nm	≥742	2266
SO_2	17.3	305-330 nm	≥1100	1328
$C_2H_2O_2$	0.70	433-465 nm	≥1972	2670
Baseline#* Aerosol/Cloud properties hourly @ 8.9 km x 5.2 km				
Property	Precision	Band	Signal to Noise	
AOD	0.10	354, 388 nm	≥1414	2158
AAOD	0.06			
AI	0.2			
CF	0.05	346-354 nm	≥1200	2222
COCP	100 mb			
Spectral Imaging Requirements				
Relevant absorption bands for trace gases & windows for aerosols		Spectral Range (nm)	290-490, 540-740	290-490, 540-740
		Spectral Resolution (nm)	≤0.6	0.6
		Spectral Sampling (nm)	< 0.22	0.2
Radiometric Requirements				
Solar irradiance and Earth backscattered radiance spectrally resolved over spectral range		Wavelength-dependent Albedo Calibration Uncert. (%)	≤1	0.8
		Wavelength-independent Albedo Calibration Uncert. (%)	≤2	2.0
		Spectral Uncertainty (nm)	< 0.02	< 0.02
		Polarization Factor (%)	<5 UV, <20 Vis	≤4 UV, <20 Vis
Spatial Imaging Requirements				
Observations at relevant urban to synoptic scales and multiple times during daytime		Revisit Time (hr)	≤1	1
		FOR	CONUS	GNA
		Geolocation Uncertainty (km)	<4.0	2.8
		IFOV*: N/S × E/W (km)	≤2.2 × ≤5.2	2.2 × 5.2
		E/W Oversampling (%)	7.5 ± 2.5	7.5
		MTF of IFOV*: N/S × E/W	≥0.16 × ≥0.30	0.16 × 0.36

TEMPO Requirements and Science Questions are leveraged from the GEO-CAPE Science Traceability Matrix.

Due to the cost-capped nature of the mission, aerosols, SO_2 and $C_2H_2O_2$ products were de-scoped during development. These have since been funded by the Satellite Needs Working Group and are planned to become operational in 2028.

TEMPO Early Adopter Program for Science and Applications

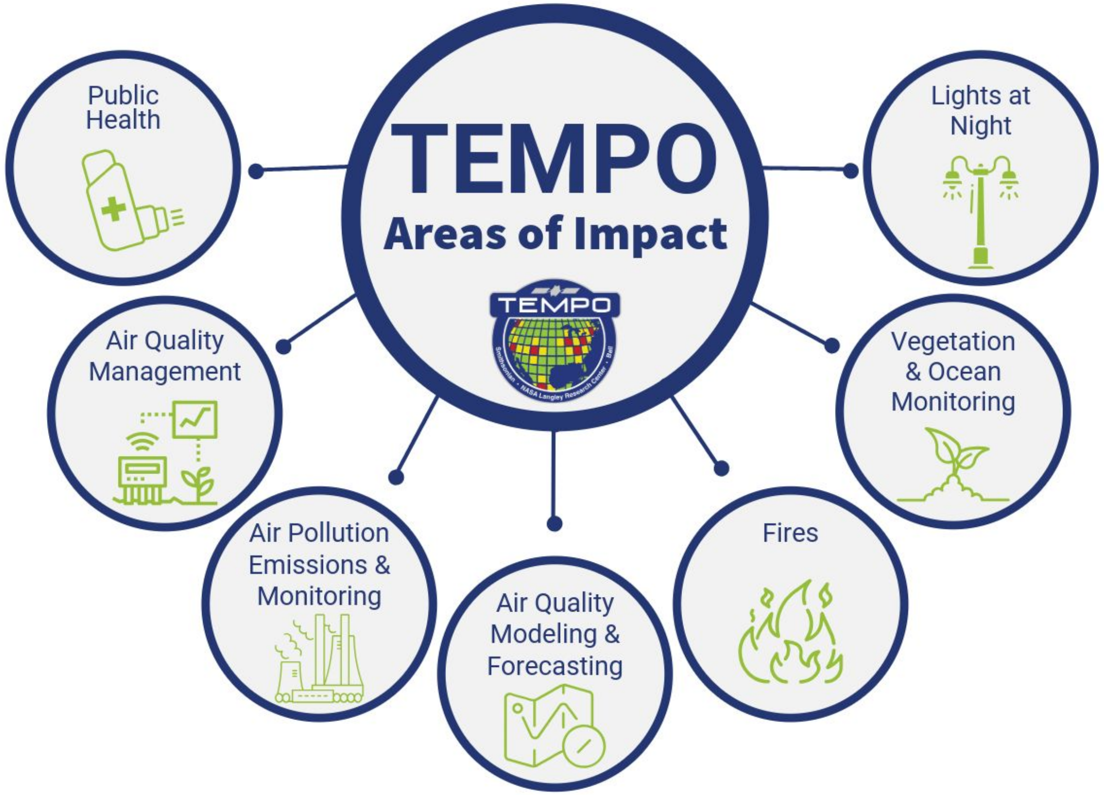
The <u>TEMPO Early Adopters/Practitioners</u> program was established in 2019 to facilitate the use of TEMPO and build connections between science and stakeholders.



~650 registered participants from diverse sectors
~200 considered highly engaged users

Regular tutorials and ARSET trainings engage new end users. This training in August 2025, organized by the Western States Air Resources Council, had 30 participants from western state and local air quality agencies. Only 2 had previously used TEMPO data.

TEMPO observations enable transformations in critical applications areas:

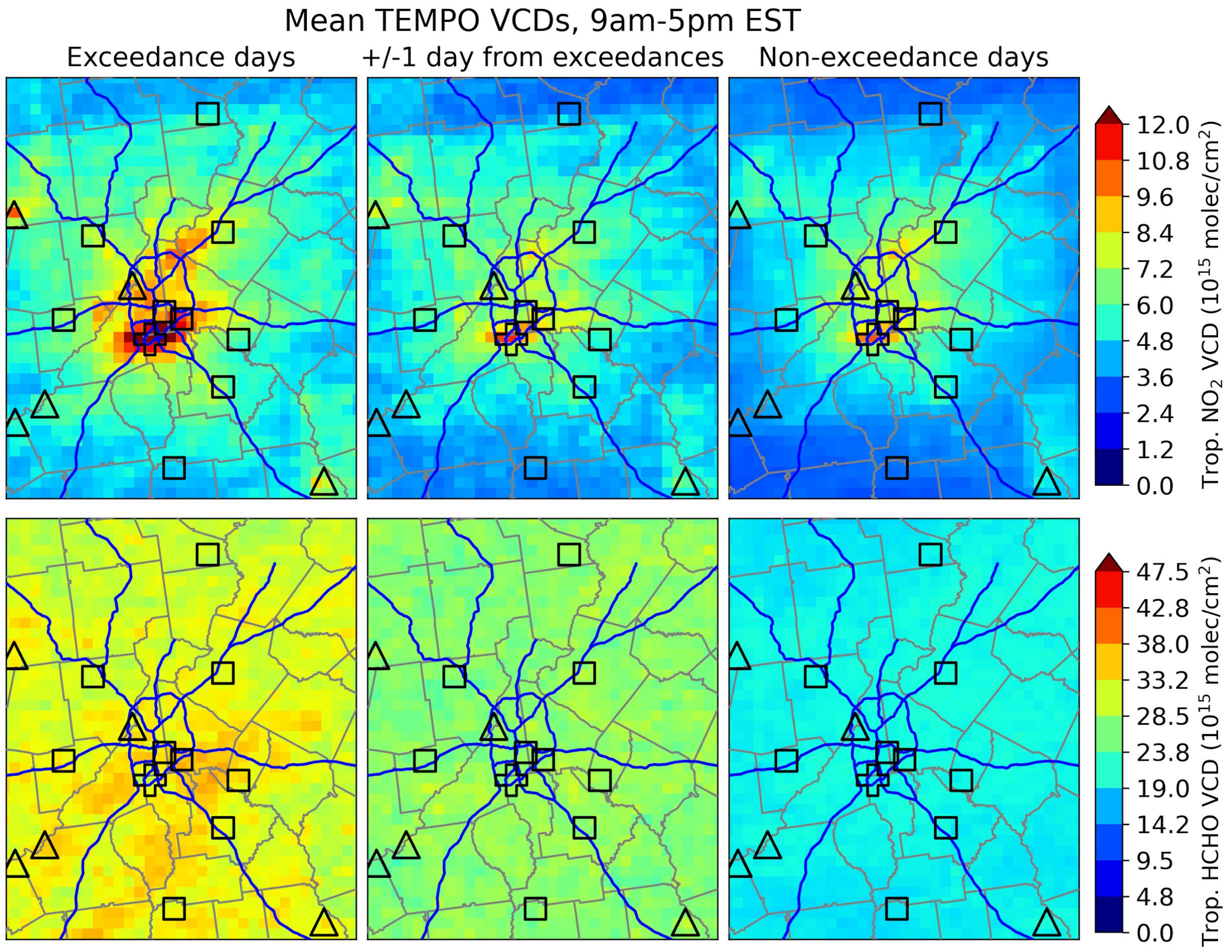


Applied and Operational Uses: Georgia EPD

The State of Georgia's Environmental Protection Division (EPD) uses TEMPO vertical columns as proxies for concentrations in National Ambient Air Quality Standards (NAAQS) **Exceedance Reports** and **Exceptional Event Demonstrations**.

- These reports are the foundation of Georgia EPD's control strategy development for State Implementation Plans required by the Clean Air Act.

Tropospheric NO_2 and HCHO (a VOC proxy) are involved in ozone production. June-August 2024 TEMPO mean columns over Atlanta show clear enhancements of these precursors on days with ozone exceedances.



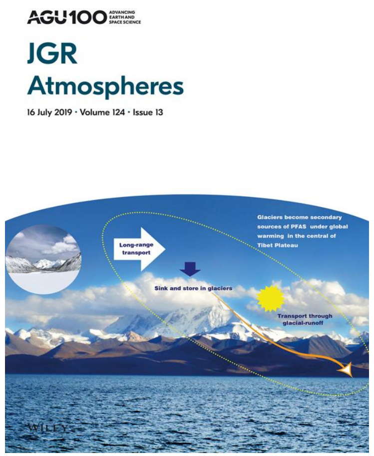
[Credit: Byeong Kim, Georgia EPD]

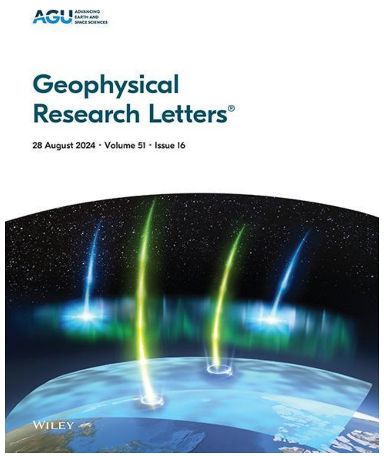
Publications & AGU Special Collection

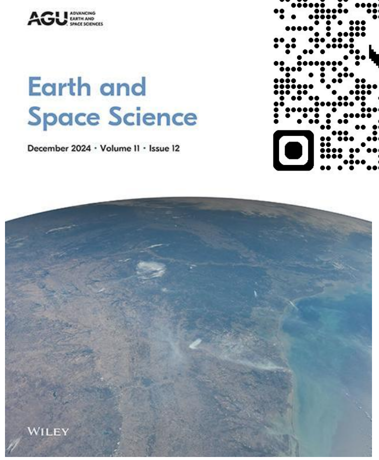
Enthusiastic community uptake has translated into a high number of publications.

- **More than 30 refereed publications** since mid-2025
- Publications span diverse areas:
  - **Air quality:** Urban air quality, diurnal patterns, wildfires
  - **New cross-disciplinary products:** Ocean color and nighttime lights
  - **Technical & foundational:** Algorithms and validation

TEMPO AGU Special Collection
TEMPO Data Products, Science, and Applications







29 papers submitted, 26 papers published/accepted
Open until 31 December 2026

SciX TEMPO Library https://scixplorer.org/public-libraries/7Fzv13x4TSe-mmt3SQqiYQ

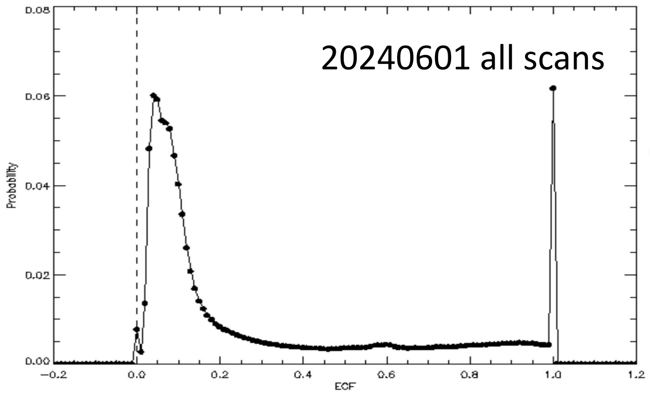
https://tempo.si.edu

Algorithm Updates for TEMPO V4 (& NRT V2)

- **GEOS-CF (meteorology / a priori): V1 □ V2**
- **L1b: Improve absolute calibration (~10% overestimation in normalized radiance)**
  - ✔ Update BTDF by ~cos(30°) and scattering angle dependence, update to radiometric calibration coefficients based on ABI/VIIRS comparison
  - ✔ Improve straylight correction (**over correction in V3**): improve PSF + background correction + reconstruct saturated pixels
  - ✔ Improve wavelength calibration, and wavelength grid for rad. cal. coefficients
  - ✔ Improve INR (geolocation)
- **Trace gases and clouds**
  - ✔ Greatly Improved GLER surface albedo climatology over land/snow (fix RAA clipping & BRDF clipping)
  - ✔ NO_2 / O_2-O_2 cloud de-striping
  - ✔ Fix surface pressure anomaly (index shift by 1 in GEOS-CF surface pressure)
  - ✔ Include clear-sky AMF & scattering weights for NO_2/HCHO

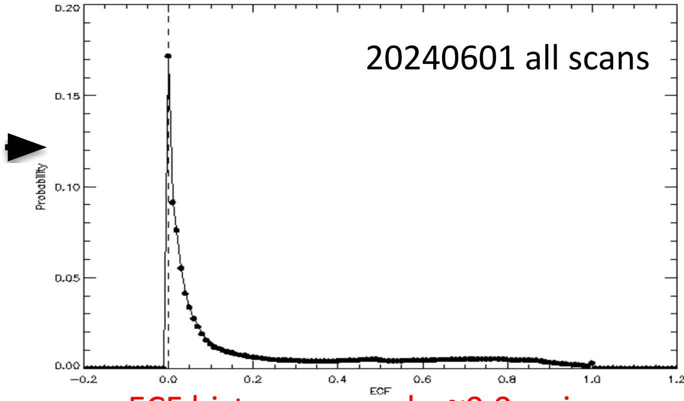
Histogram of Effective Cloud Fraction (ECF)

TEMPO V3 in NASA ASDC

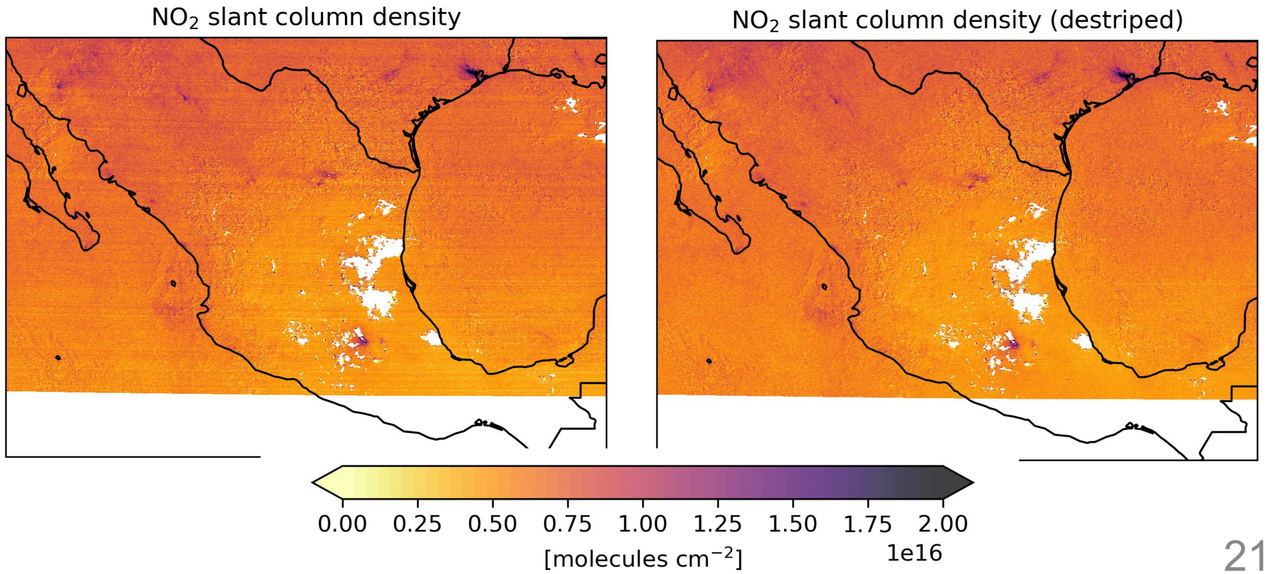


histogram peaks at ECF ~ 0.05, suggesting an overestimate.

TEMPO V4*

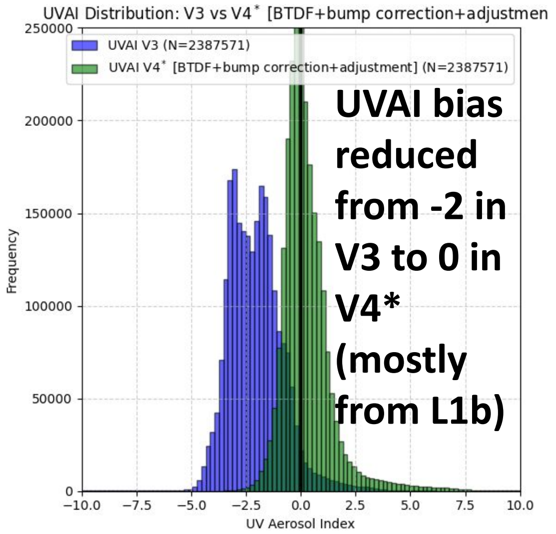


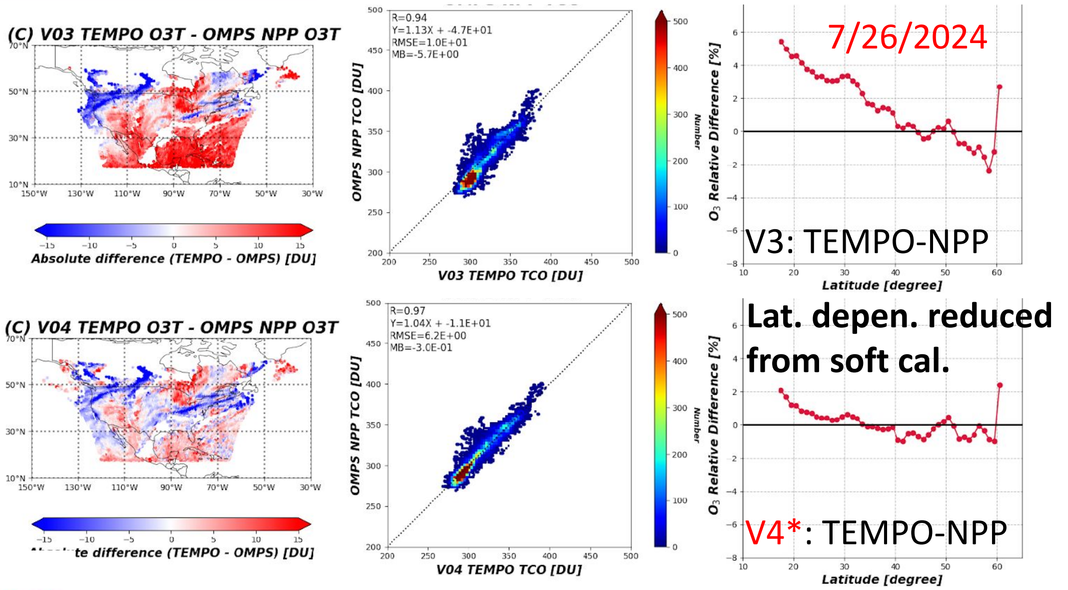
ECF histogram peaks ~0.0, primary due to L1b update & GLER

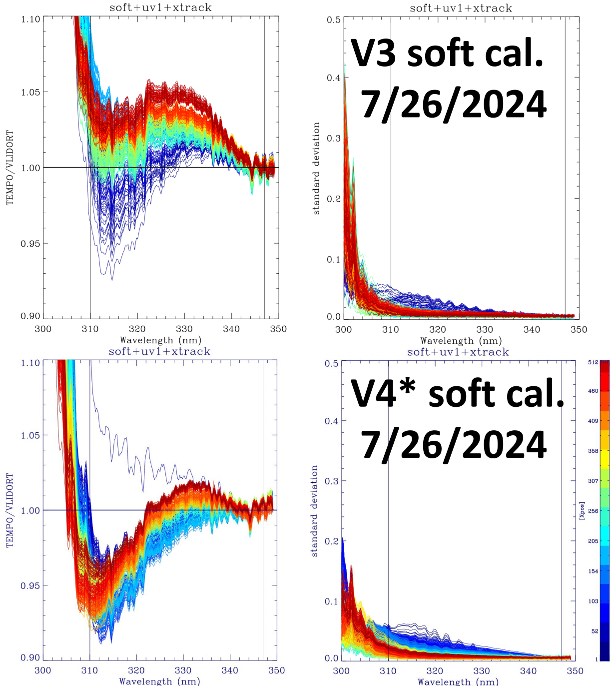


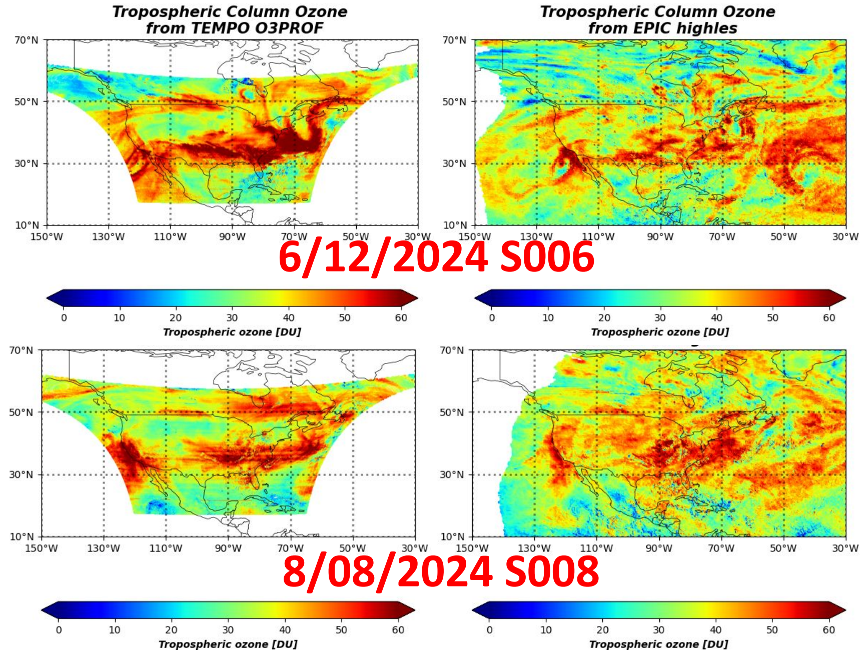
Algorithm Updates for TEMPO V4

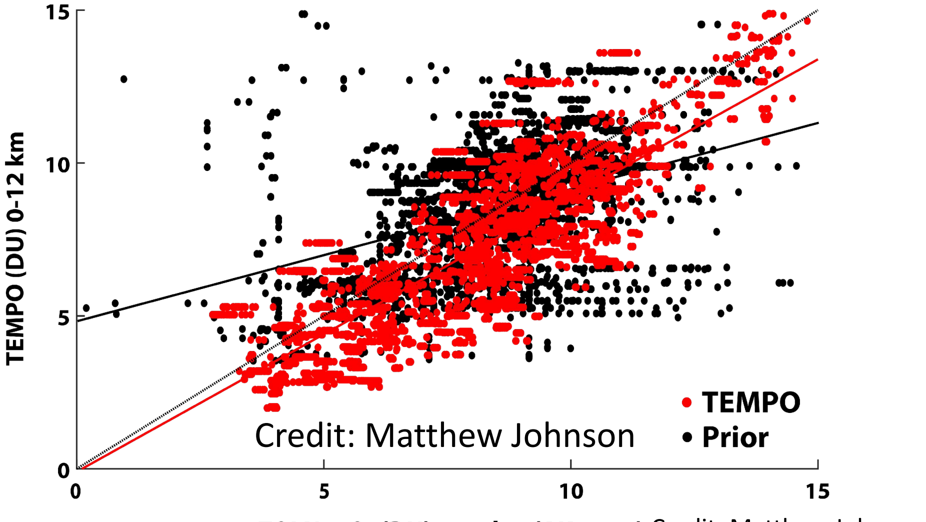
- Total O_3: L1b improvement and
  - ✔ Update LUTs with average on-orbit slit functions
  - ✔ Perform additional soft calibrations using NPP OMPS data
  - ✔ Quality flag updates.
- Profile O_3: L1b improvement and
  - ✔ Additional soft calibration
  - ✔ Optimization in a priori, surface albedo, and measurement error constraint











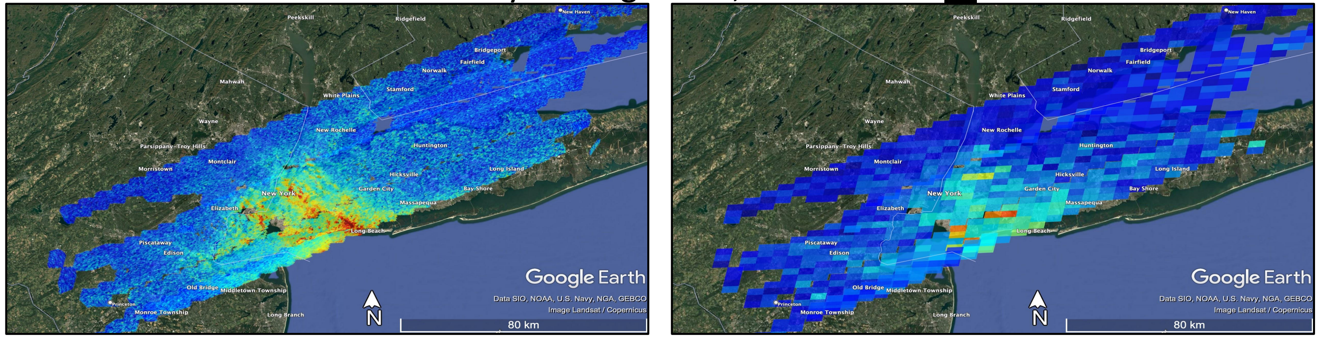
Credit: Matthew Johnson

V4: This version is subject to change before public release of V4.*

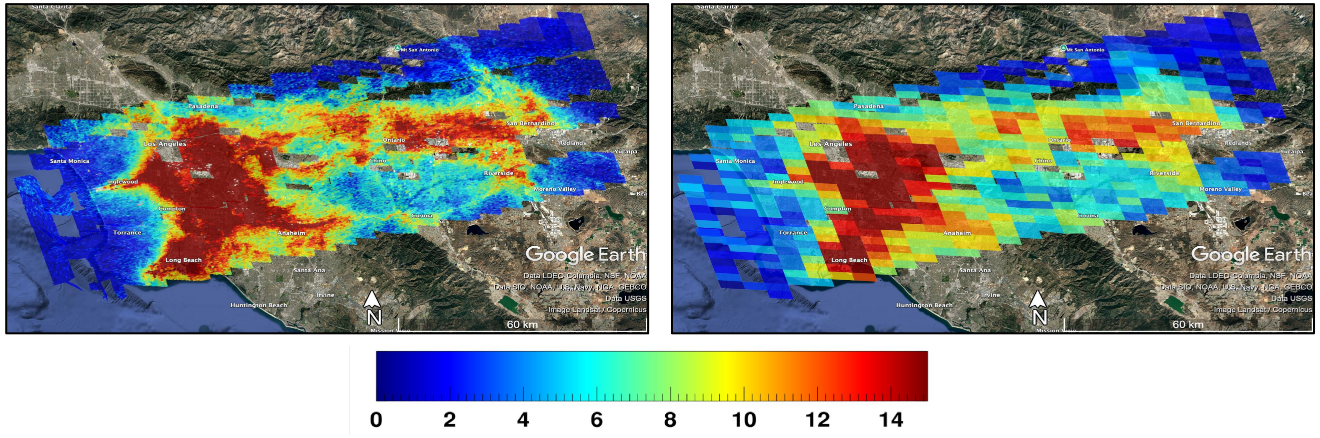
TEMPO V4 L2 Validation

GCAS **TEMPO**

New York City on August 9th, 2023: Scans



Los Angeles on August 22nd, 2023: Scans 9,



All GCAS data is collected within 30 minutes of the TEMPO scan

y=0.95x+2E14
r^2=0.85
Median % difference: -1.7%
Median difference: -6E13

V4 shows a huge improvement over V3 in all regions measured during STAQS

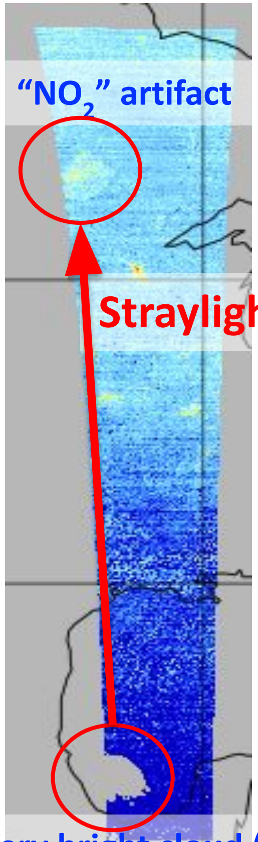
Credit: Laura Judd

r^2 improved from 0.73 → 0.85 for all sites
0.49 → 0.62 for East Cost

Algorithm Improvements for V5

The core algorithm team will continue routine maintenance of the operational pipeline and will implement several updates during mission extension to further mature TEMPO standard product algorithms.

Planned Update	Benefit
Calibration and Level 1B	
Improve straylight correction	Spectral fitting improvements, remove artifacts in NO_2 from internal reflection
Perform dynamic degradation correction	Level 2 improvements, especially products derived with absolute radiances (O_3 and clouds)
Improve radiometric calibration	
Improve pixel quality flagging	Perform Level 2 retrievals with only reliable pixels
Perform polarization correction	Lower fitting residuals in Level 2 retrievals
Refine spectral calibration	Total O_3 retrieval improvement
Refine image processing	Improve detection of small signals
Clouds	
Improve scene albedo and pressure retrieval	Reduce trace gas biases over snow
Update look-up table with on-orbit slit function	Improve cloud pressure accuracy

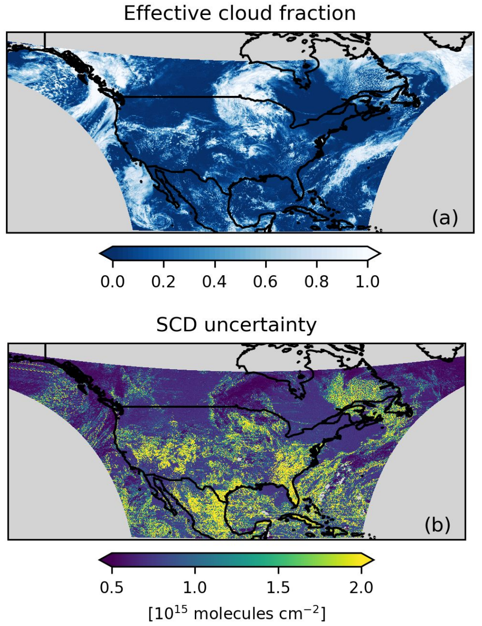


On rare occasions, artifacts from very bright clouds appear as NO_2 signal due to internal reflection.

Algorithm Improvements for V5

Planned Update	Benefit
NO_2 and HCHO	
Improve fitting over partial clouds with scene inhomogeneity using PCAs	Reduce measurement uncertainty over partial clouds; ~25% increase in high-quality observations
Use cloud scene albedo over snow	Reduce trace gas biases over snow [Griffin et al., 2026]
Refine HCHO radiance reference	Reduce background bias in HCHO [Rawat et al., 2026]
Implement aerosol correction	Improve products over fires and urban regions
Total Ozone and Ozone Profile	
[Both] Minimize inconsistency in ancillary data	Reduce inter-product discrepancy in total O_3
[Both] Use cloud scene albedo and pressure	Enhance retrieval accuracy over snow and ice
[Both] Update soft calibration	Reduce striping; reduce regional and systematic biases
[O_3 total] Optimize λ pair and profile shape switch	Reduce regional and systematic biases [Zhao et al, 2025]
[O_3 profile] Optimize the UV-only retrieval	Improve accuracy in stratospheric and tropospheric O_3

Additional tasks include offline testing, feature additions, bug fixes, pipeline integration, evaluation, live testing, documentation; continuation of ASDC DAAC collaboration for data distribution.



NO_2 slant column densities (SCD) currently show higher fitting uncertainties over partial clouds due to inhomogeneous filling of the instrument slit.