First two years of TEMPO Nitrogen Dioxide and Formaldehyde Observations: Algorithm Status and Highlights

Gonzalo González Abad[1,*], Caroline Nowlan[1], Kelly Chance[1], Xiong Liu[1], Heesong Chong[1], Zachary Fasnacht[5], David E. Flittner[3], Masoud Ghahremanloo[1], Barron Henderson[2], Weizhen Hou[1], John Houck[1], Laura Judd[3], K. Emma Knowland[4], Viral Shah[5], Pam Wales[5], Wenhan Qin[5], Luke Valin[2], Huiqun Wang[1], and the TEMPO Team

[1]Center for Astrophysics | Harvard & Smithsonian, [2]Environmental Protection Agency, [3]NASA LaRC, [4]NASA Headquarters, [5]NASA GSFC *ggonzalezabad@cfa.harvard.edu

1. Tropospheric Emissions: Monitoring of Pollution (TEMPO)

TEMPO is a UV/visible spectrometer and the first geostationary satellite instrument designed to measure trace gases over North America.

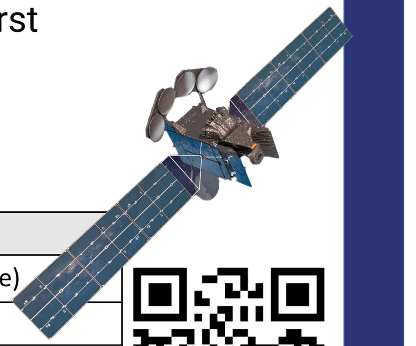

Table 1: TEMPO mission details.

Characteristic	Details
Temporal resolution (nominal)	40 – 60 minutes (daytime)
Spatial resolution	~2 × 4.75 km^2
Launch date	7 April 2023
Data availability	2 August 2023 – present
Data latency (current)	3 – 4.5 hours (standard products) 2 – 3 hours (NRT products)
Baseline trace gas data products	NO_2 (tropospheric & stratospheric), HCHO (total), O_3 (total & profile), cloud fraction & pressure

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2. Trace Gas Algorithm

The TEMPO algorithm has three main steps:

1. Fit a gas slant column density (SCD) for each spectrum.
2. Determine the air mass factor (AMF).
3. NO_2: Apply destriping correction and perform stratosphere-troposphere separation of vertical column densities (VCD); Formaldehyde (HCHO): perform reference background correction on the entire scan.

TEMPO products were updated from version 3 to version 4 on September 17, 2025. Reprocessing of earlier data is ongoing after starting in early 2026.

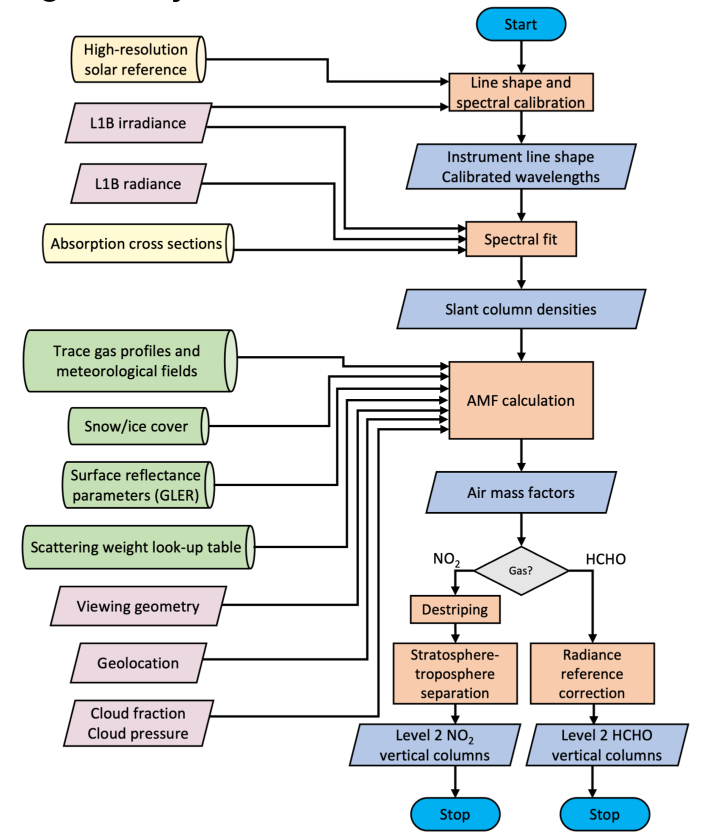

Figure 1: Flow chart of the trace gas retrieval algorithm.

3. Spectral Fitting

Table 2: Details of NO_2 and HCHO spectral fitting.

	NO_2	HCHO
Fitting window	405 - 465 nm	328.5 - 356.5 nm
Baseline and scaling polynomials	4th order	3rd order
Solar reference spectrum	Coddington et al. (2023)	
Raman scattering	Derived using Chance and Spurr (1997)	
Undersampling correction	Derived using Chance et al. (2005)	
Molecules retrieved	O_3, NO_2, O_2-O_2, H_2O, liquid H_2O	O_3, NO_2, O_2-O_2, BrO, HCHO
Reference spectrum	Weekly solar irradiance	Radiance reference

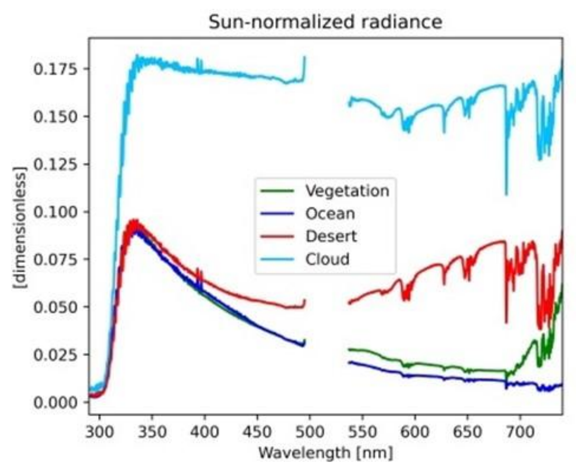

Figure 2: Examples of TEMPO reflectance spectra from first light observations on 2 August 2023.

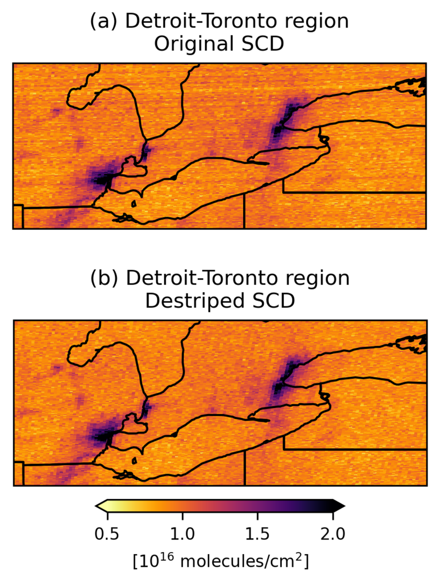

Figure 3: (a) Retrieved fitted slant column densities over Detroit/Toronto region for scan 8 on 16 October 2025 and (b) destriped columns (new in V4).

4. Air Mass Factor

The AMF describes the path of the light through the trace gas of interest, where $VCD = \frac{SCD}{AMF}$, and is a function of vertically-resolved scattering weights and a normalized gas profile shape.

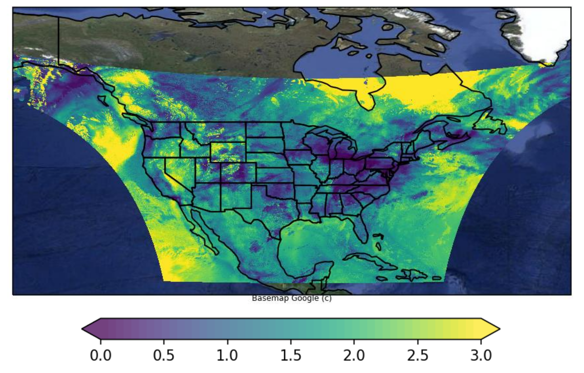

Figure 4: TEMPO tropospheric NO_2 air mass factor derived for scan 6 on 9 May 2024.

Table 3: Ancillary data used in TEMPO V4 AMF calculations.

Input	Source
Clouds	TEMPO O_2-O_2 cloud fraction and pressure
Trace gas profiles Meteorological variables (T, $p_{surface}$, $p_{tropopause}$, wind)	• GEOS-CF hourly analysis (reprocessed) or forecast (forward processed from 17 September 2025) (25-km resolution). • Defaults to monthly 1-hour climatology derived from GEOS-CF if analysis or forecast is unavailable.
Vertical layers	72 layers on GEOS-CF vertical grid
Surface albedo	• GLER over land (Qin et al., 2019): derived from MODIS BRDF, extended to shorter wavelengths • GLER over water (Fasnacht et al., 2019): Cox-Munk
Snow/ice fraction	IMS snow and ice (1-km resolution)
Terrain height correction	Corrected using GMTED2010 (30 arcsec) DEM
Aerosols	Not applied (considered implicitly in cloud retrieval)

5. NO_2 Stratosphere-Troposphere Separation

After the SCD and AMFs have been derived for all granules in the full scan, they are used to estimate the stratospheric contribution to the NO_2 measurement and determine the tropospheric column following Geddes et al. (2018).

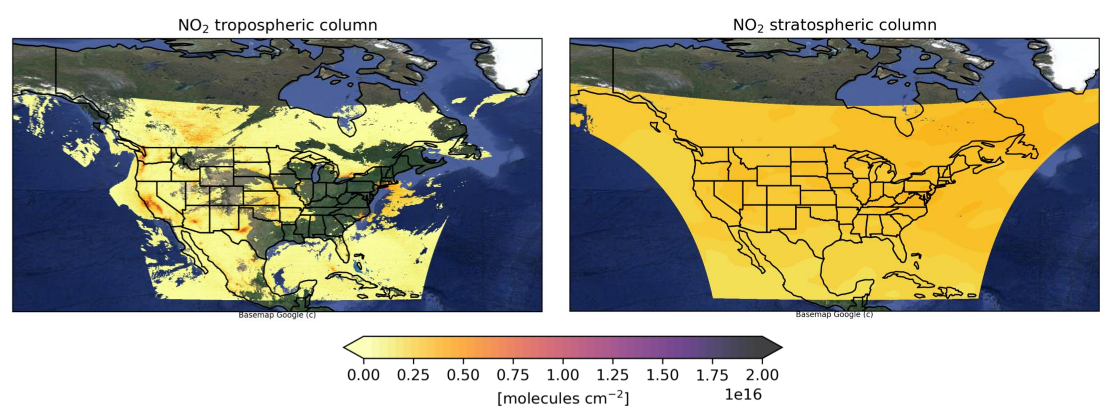

Figure 5: Tropospheric NO_2 (cloud fractions < 0.5) and stratospheric NO_2 vertical columns after stratosphere-troposphere separation, for scan 6 on 9 May 2024.

6. Formaldehyde Background Reference Correction

The use of a radiance reference requires the correction of the HCHO columns to account for the presence of HCHO spectral signatures in the radiance reference.

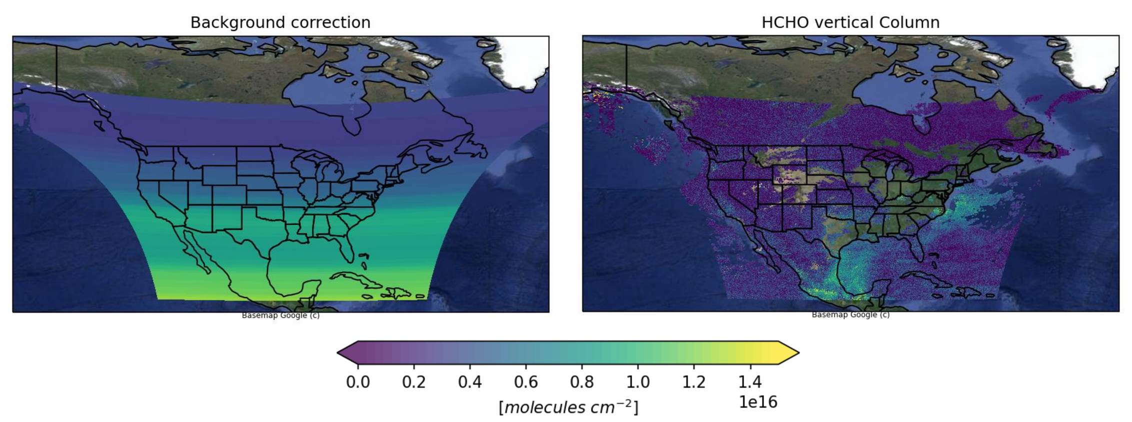

Figure 6: Background correction and final HCHO vertical columns (cloud fractions < 0.5) for scan 6 on 9 May 2024.

7. Version 4 Updates

Several significant updates were included for the September 2025 Version 4 release:

- A high bias in cloud fractions is reduced after correction of a ~10% high bias in radiances.
- Stray light correction reduces high bias in HCHO over clouds.
- Update of GEOS-CF model from v1 to v2.
- Improved surface reflectance over land.
- Surface pressure and cloudy scattering weights improvements.
- Destriping correction for NO_2.

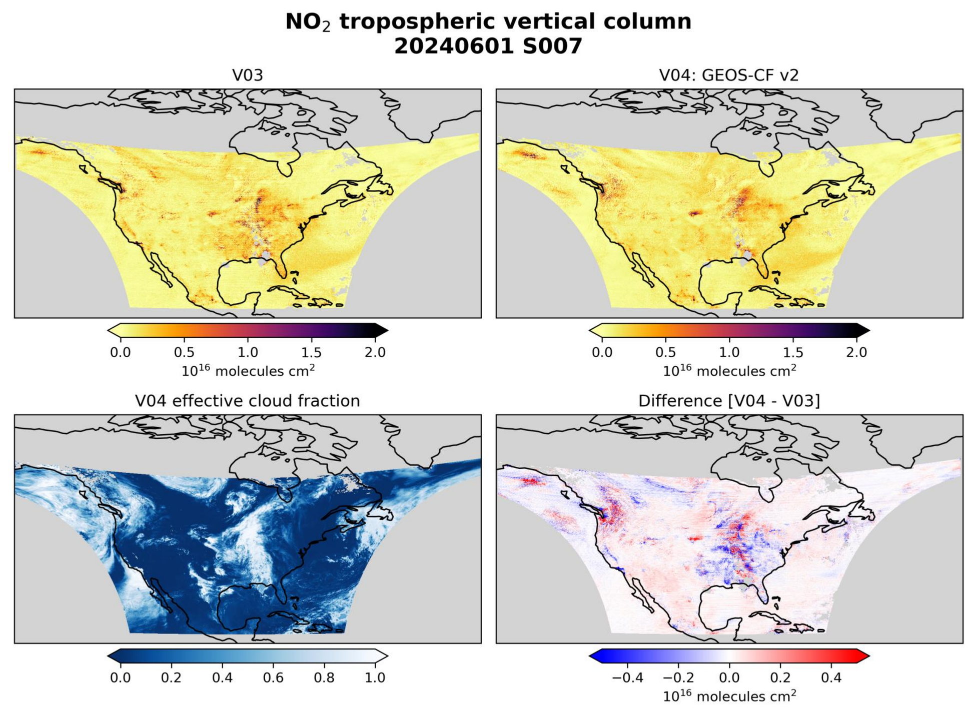

Figure 7: TEMPO NO_2 tropospheric column from versions 3 and 4 on 6 June 2025, and their differences. Differences vary geographically and with cloud cover. V4 uses the GEOS-CF analysis, while V3 uses the forecast.

TEMPO vs. GCAS Tropospheric NO_2

Table 4: TEMPO vs. GCAS comparison statistics

	V3 y=mx+b	V4 y=mx+b	V3 r^2	V4 r^2	V3 N	V4 N
Chicago	y=1.13-1e15	y=0.87x-4e14	0.57	0.66	2873	2599
Toronto	y=0.86x-8e14	y=0.85x-7e14	0.36	0.43	545	590
NYC	y=1.10x-8e14	y=0.97x-9e14	0.40	0.59	2930	2659
Los Angeles	y=1.59x-3.8e15	y=0.90x+9e14	0.76	0.89	15284	13703

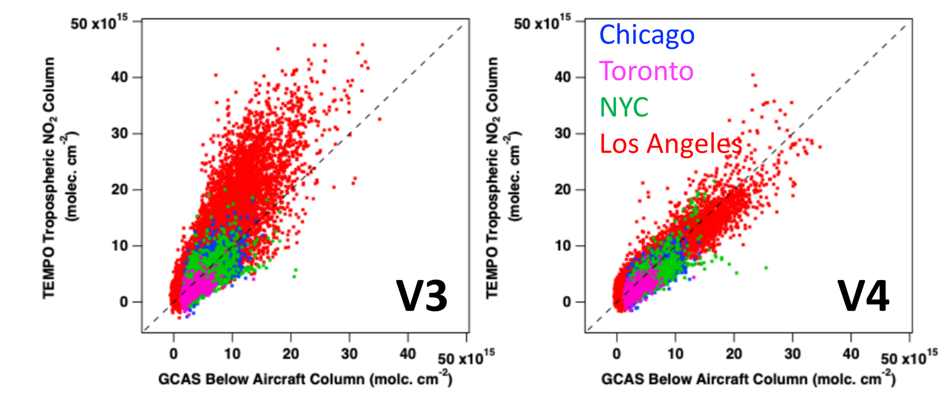

Figure 8: Comparison of TEMPO V3 and V4 tropospheric NO_2 vertical columns with GCAS observations collected during the August 2023 STAQS campaign. V4 shows significant improvements over V3 in all regions.

8. Near Real-Time Products

TEMPO near real-time (NRT) radiances and NO_2 and HCHO trace gas products (2 – 3 hours latency) were released in September 2025, supported by the Satellite Needs Working Group.

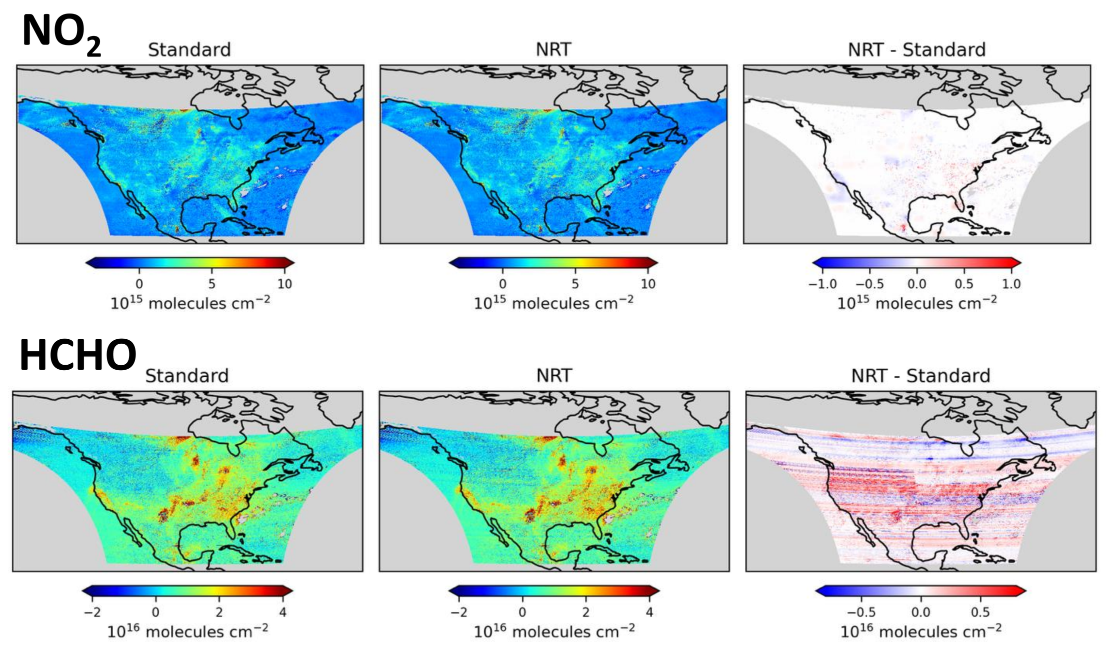

Figure 9: TEMPO NO_2 tropospheric (top) and HCHO total (bottom) vertical column densities from the standard and NRT products for scan 7 on 12 July 2025, and their differences. The standard and NRT products are highly correlated (NO_2: r = 0.99; HCHO: r = 0.90). Larger differences occur in HCHO due to the use of a radiance reference from the previous day but remain within expected HCHO uncertainties.

9. Nitric Acid Leak Detection

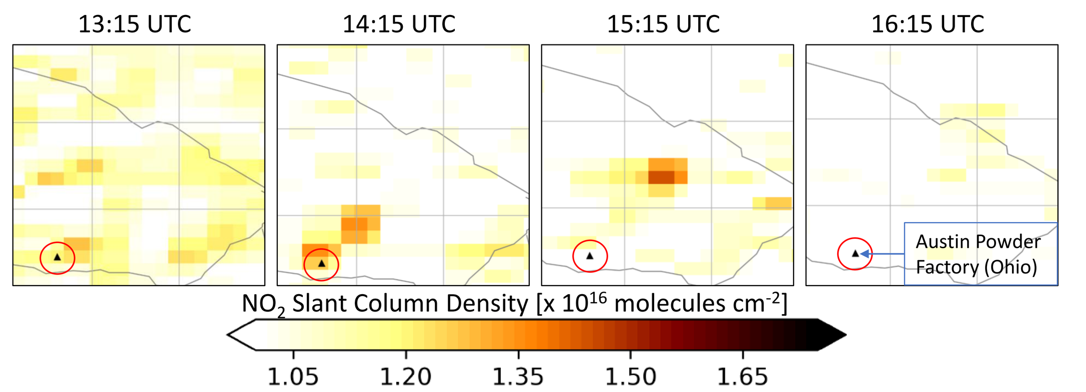

Figure 10: TEMPO NO_2 detected the NO_2 plume caused by a leak of nitric acid at the Austin Powder Plant in Vinton County (Ohio) on June 11, 2025. Four successive TEMPO observations tracked the transport and dispersion of the plume.

Learn more about TEMPO

Visit the NASA Atmospheric Science Data Center (ASDC) TEMPO project webpage for TEMPO data links, tools and up-to-date documentation.

Read the User Guide at this site to get the latest on known issues and data usage recommendations.

References

Gonzalez Abad et al. (2025), TEMPO Formaldehyde Retrieval Algorithm Theoretical Basis Document, NASA Algorithm Publication Tool.

Fasnacht et al. (2019), A geometry-dependent surface Lambertian-equivalent reflectivity product for UV-Vis retrievals - Part 2: Evaluation over open ocean, *AMT*, 12, 6749-6769.

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