TROPOSPHERIC EMISSIONS: MONITORING OF POLLUTION (TEMPO) PROJECT

Near Real-Time Data Products: User Guide and ATBD Supplement

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REVISION HISTORY

Version	Item	Description	Release date
1.0	All	Initial version	September 17, 2025

PRODUCT and SCIENCE DATA PROCESSING CENTER PIPELINE VERSION

Product Version Designation	Science Data Processing Center Pipeline Version	Release
V02	4.7	September 17, 2025; first public release of TEMPO Level 1, 2 and 3 NRT products

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1 Introduction

1.1 The TEMPO mission

Tropospheric Emissions: Monitoring of Pollution (TEMPO) (Zoogman et al., 2017) is a geostationary satellite mission designed to measure air quality over North America during daylight hours at high spatial resolution (2×4.75 km^2 at the center of field of regard) and with a nominal temporal resolution of 40-60 minutes, or more frequently during occasional special operations. Launched on April 7, 2023, TEMPO obtained first light radiances on August 2, 2023 and began nominal operations after passing its post-launch acceptance review in October 2023.

1.2 Purpose of this document

This document is provided as a supplement to the TEMPO user guides and algorithm theoretical basis documents (ATBDs) describing the standard baseline TEMPO products, in order to facilitate use of the TEMPO near real-time (NRT) trace gas data products. This document provides NRT data users with details on the differences between the standard V04 and NRT V02 retrievals, as well as an example of the differences between a standard and NRT scan for each NRT product.

Table 1 lists the standard product user guides and ATBDs relevant to NRT radiance and trace gas products. In all cases, the standard and NRT file formats, usage guidelines and algorithm theory are very similar. As such, users should consult the documentation for the standard data products for most details. As of September 17, 2025, ATBDs are only available for the standard V03 products. This document will be updated once new ATBDs describing standard V04 products become available.

Important: Users should review data usage and filtering recommendations from the standard product user guides, as these also apply to the NRT products.

Table 1. *TEMPO standard product user guides and algorithm theoretical basis documents relevant to NRT products. All documentation is available from the NASA Atmospheric Science Data Center TEMPO project page.*

Product	**User Guide**
Radiances (RAD)	TEMPO Level 1 Data Products: User Guide (Chong, Liu, Houck, Flittner, Carr, Hou, Suleiman, et al., 2025)
Clouds (CLDO4) Nitrogen dioxide (NO2) Formaldehyde (HCHO)	TEMPO Trace Gas and Cloud Level 2 and 3 Data Products: User Guide (González Abad, Nowlan, Wang, et al., 2025)
Product	**Algorithm Theoretical Basis Document**
Radiances (RAD)	Algorithm theoretical basis for Version 3 TEMPO Level 0-1 processor (Chong, Liu, Houck, Flittner, Carr, Hou, Davis, et al., 2025)9/11/2025 1:22:00 PM
Clouds (CLDO4)	Algorithm Theoretical Basis for Version 3 TEMPO O_2-O_2 Cloud Product (Wang et al., 2025)
Nitrogen dioxide (NO2)	TEMPO Nitrogen Dioxide Retrieval Algorithm Theoretical Basis Document (Nowlan et al., 2025)
Formaldehyde (HCHO)	TEMPO Formaldehyde Retrieval Algorithm Theoretical Basis Document (González Abad, Nowlan, Liu, et al., 2025)

1.3 Near real-time data products

TEMPO data products are generated by the Science Data Processing Center (SDPC) at the Smithsonian Astrophysical Observatory (SAO). The TEMPO standard products, once generated at SAO, are pushed to the NASA Atmospheric Science Data Center (ASDC) for public distribution. These include Level 1 (L1) files (calibrated solar irradiance and geolocated Earth radiance spectra), Level 2 (L2) files (cloud and trace gas products at the native ground pixel footprint for the East-West granules which make up part of a TEMPO scan) and Level 3 (L3) files (cloud and trace gas products on a regular grid created from all Level 2 granules constituting an entire East-West scan).

The 2020 Cycle 3 Satellite Needs Working Group (SNWG) survey identified near real-time (NRT) low-latency (< 3 hours) Earth radiance, cloud, nitrogen dioxide, formaldehyde and aerosol products as high priorities for stakeholders and users in federal agencies. In response, the SAO is now providing NRT radiance, cloud, nitrogen dioxide and formaldehyde products through NASA after upload to NASA's Earth Observing System Data and Information System (EOSDIS) Cumulus cloud. Aerosol products are additionally under separate development by NOAA using the TEMPO L1 NRT radiances.

Table 2 describes the publicly available SAO TEMPO standard data products and their corresponding NRT products. Note that the solar irradiance from the working diffuser (IRR) is

also used in cloud and trace gas retrievals, but as this is collected weekly and processed quickly, the same IRR product (TEMPO_IRR_L1) is used in both standard and NRT production.

Table 2. *TEMPO standard products with corresponding NRT products*

Standard Product Short Name	NRT Product Short Name	Description	Spatial Resolution and Coverage	NRT Latency (Average)
TEMPO_RAD_L1	TEMPO_RAD_L1_NRT	Geolocated Earth radiances	Native TEMPO ground pixel, one granule	~1-1.5 hours after TEMPO observation time
TEMPO_CLDO4_L2	TEMPO_CLDO4_L2_NRT	Effective cloud fraction (ECF) and cloud optical centroid pressure (OCP)	Native TEMPO ground pixel, one granule	~1.5-2 hours after TEMPO observation time
TEMPO_CLDO4_L3	TEMPO_CLDO4_L3_NRT	ECF and OCP on regular grid	All Level 2 granules merged for a single scan, on a 0.02°×0.02° regular grid	<30 minutes after processing is complete for the related L2 scan
TEMPO_NO2_L2	TEMPO_NO2_L2_NRT	Nitrogen dioxide tropospheric and stratospheric vertical columns	Native TEMPO ground pixel, one granule	2-3 hours after TEMPO observation time
TEMPO_NO2_L3	TEMPO_NO2_L3_NRT	Nitrogen dioxide tropospheric and stratospheric vertical columns on regular grid	All Level 2 granules merged for a single scan, on 0.02°×0.02° regular grid	<30 minutes after processing is complete for the related L2 scan
TEMPO_HCHO_L2	TEMPO_HCHO_L2_NRT	Formaldehyde vertical columns	Native TEMPO ground pixel, one granule	2-3 hours after TEMPO observation time
TEMPO_HCHO_L3	TEMPO_HCHO_L3_NRT	Formaldehyde vertical columns on regular grid	All Level 2 granules merged for a single scan, on 0.02°×0.02° regular grid	<30 minutes after processing is complete for the related L2 scan

1.4 Data versioning and release history

Updates to the SDPC operational pipeline result in periodic new data releases. When this occurs, a new collection is created that includes all data products. The collection version number can be found in the data filename and has format VXX, where XX denotes the collection version.

The version 1 (V01) NRT production began on May 6, 2025, and these products were made available to a small group of stakeholders for testing. The NRT V01 products were produced in parallel with the standard V03 products. The NRT V02 products are the first TEMPO NRT data made available to the public. Their production began on September 17, 2025 (except for HCHO which began on September 18, 2025), and they are produced in parallel with the standard V04 collection.

2 Near real-time product description

2.1 Processing pipeline overview

The NRT products are produced using almost the same algorithm as the standard products, but with several steps optimized for production speed, and pipeline options controlled by configuration files. The NRT reconfiguration consists of two types of modifications to the standard pipeline:

- Reorganization of pipeline steps, including image navigation and registration and Level 2 cloud production, which do not significantly affect results between standard and NRT products.
- Changes to the radiance calibration and trace gas retrieval for processing speed, which do introduce differences between standard and NRT products.

The reorganization of the pipeline consists of the following significant change:

1. **The L2 cloud O_2-O_2 slant column density retrieval proceeds after one pass of the image navigation and registration (INR) for pointing geolocation.** In the standard baseline pipeline, the INR consists of two passes. The first INR pass provides an initial estimate of the INR for a single granule, while a second pass refines the INR, but uses all granules and requires completion of a full scan. In the NRT pipeline, the O_2-O_2 slant column density retrieval is allowed to proceed after completion of the first-pass INR, before completion of the full scan and in parallel with the second-pass INR. At full INR completion, the geolocation variables are overwritten in the L1 radiance and L2 O_2-O_2 cloud files. As the O_2-O_2 algorithm only proceeds when solar zenith angles (SZA) < 90°

and these values could have small changes with respect to second-pass INR results, there can be some differences in which ground pixels are processed at the very far extreme solar zenith angles. In addition, as the Main Data Quality Flag (MDQF) from the O_2-O_2 fitting has a dependence on SZA in addition to other criteria, the MDQF of those pixels assigned by the fitting could also be affected. However, those high-SZA pixels usually do not yield reliable cloud retrievals in either the standard or the NRT cloud product, and thus the impact on useful cloud retrievals is minimal.

The changes to the NRT pipeline that produce differences with the standard products are:

1. **The Level 1 Earth radiances are provided without pixel-by-pixel wavelength calibration.** The baseline pipeline corrects the nominal wavelengths (provided by wavelength calibration of the latest solar irradiance measurement (Chong, Liu, Houck, Flittner, Carr, Hou, Davis, et al., 2025)) by a shift determined by fitting each radiance to a modeled radiance spectrum. In the NRT product, this step is skipped and a correction of the first-guess nominal wavelength is not provided.
2. **The formaldehyde trace gas retrieval uses a radiance reference derived from a previous day, instead of a reference derived from the current scan.** The standard formaldehyde retrieval uses a reference derived from observations collected from the current scan, but the NRT pipeline proceeds with a radiance reference determined from a previous day, rather than waiting for the completion of the current scan to calculate a reference required for the slant column density retrieval.
3. **O_2-O_2 slant columns for clouds are not corrected for stripes in the NRT product.** The O_2-O_2 slant columns used for the cloud pressure derivation in the standard retrieval are corrected for stripes oriented in the East-West scan direction, while the NRT slant columns are not destriped.

2.2 Level 1 Earth radiances

The production of Level 1 standard product Earth radiances is described in detail in the Level 1 ATBD (Chong, Liu, Houck, Flittner, Carr, Hou, Davis, et al., 2025), with file format and usage recommendations described in the Level 1 user guide (Chong, Liu, Houck, Flittner, Carr, Hou, Suleiman, et al., 2025). The NRT radiance production follows the same procedure as that of the standard baseline production described in the ATBD, with the exception that radiance wavelength calibration is disabled in the NRT production.

As a result, the NRT files are missing the variable *wavecal_params*, which stores a single wavelength shift covering the entire spectral range of each CCD (either UV or VIS array) for each observation. The variables *wavecal_niter*, *wavecal_opt_status* and *wavecal_par*, which are output from the L1 radiance calibration but are not used downstream, are also missing in NRT files. In standard L2 cloud and trace gas retrievals, the shift values in *wavecal_params* are added to the *nominal_wavelength* variable to produce updated calibrated wavelengths. Therefore, the

absence of radiance wavelength calibration in the NRT means that the unadjusted nominal wavelength (determined from wavelength calibration of the most recent solar irradiance) will be used by L2 processors.

Figure 1 shows the wavelength difference between the standard and NRT products for a scan on July 12, 2025 for both the UV (293 – 494 nm) and VIS (538 – 741 nm) bands. The shift is generally on the order of ±0.01 nm for most pixels in the UV band and slightly larger in the VIS band. The influence of this wavelength calibration change on the clouds and trace gas retrievals will be discussed in the following sections, but is usually minimized by the fact that the slant column density spectral fitting algorithm used by O_2-O_2 (clouds), NO_2 and HCHO performs its own wavelength calibration and so can account for small wavelength shifts within the retrieval windows.

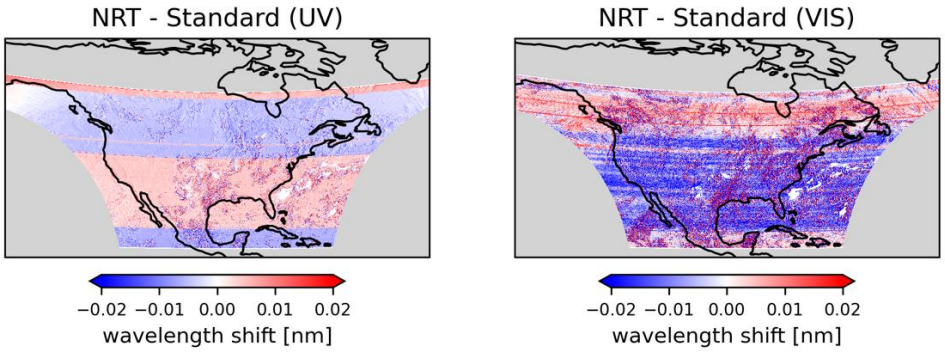

Figure 1. *Shift in detector pixel to wavelength registration in the UV and VIS bands for NRT radiances relative to standard product radiances for scan 7 on July 12, 2025.*

2.3 Level 2 clouds

The cloud fraction is derived from the top of atmosphere radiance / irradiance at 466 nm. The cloud pressure retrieval uses the slant column density of O_2-O_2 retrieved from an absorption feature near 477 nm.

Figures 2 and 3 show the differences between the standard and NRT cloud fractions for a single scan on July 12, 2025. Figures 4 and 5 show the comparison of derived cloud pressures for the same scan. Differences in both cloud products are very small and well within uncertainties introduced by other potential sources of error in the cloud retrievals (Wang et al., 2025).

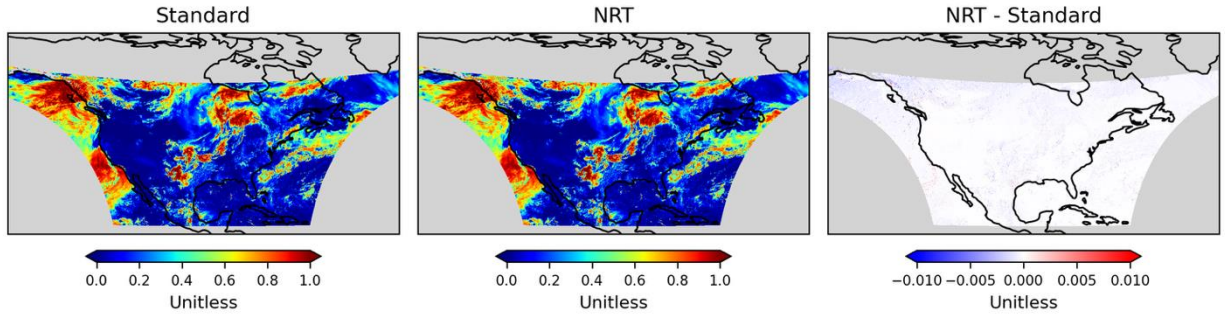

Figure 2. *Standard (left), NRT (middle) and their difference (right) for TEMPO effective cloud fractions retrieved from scan 7 on July 12, 2025. The differences between the standard and NRT columns are almost negligible; small differences do occur in partly cloudy scenes due to differences in wavelength calibration.*

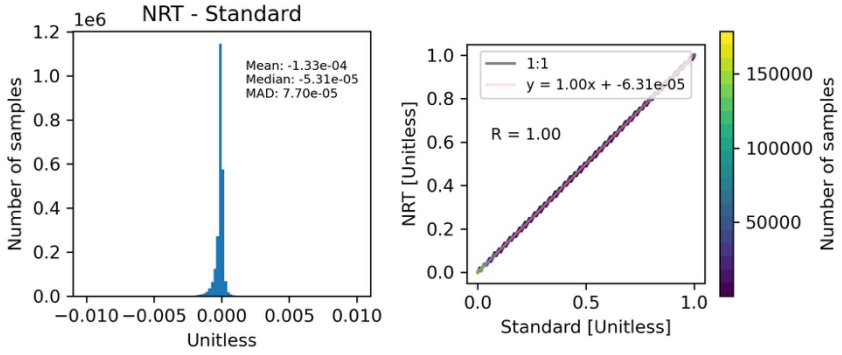

Figure 3. *Histogram (left) and scatter plot (right) showing a comparison between the standard and NRT cloud fractions from Figure 2. For visual clarity, the scatter plot only includes bins with >50 samples.*

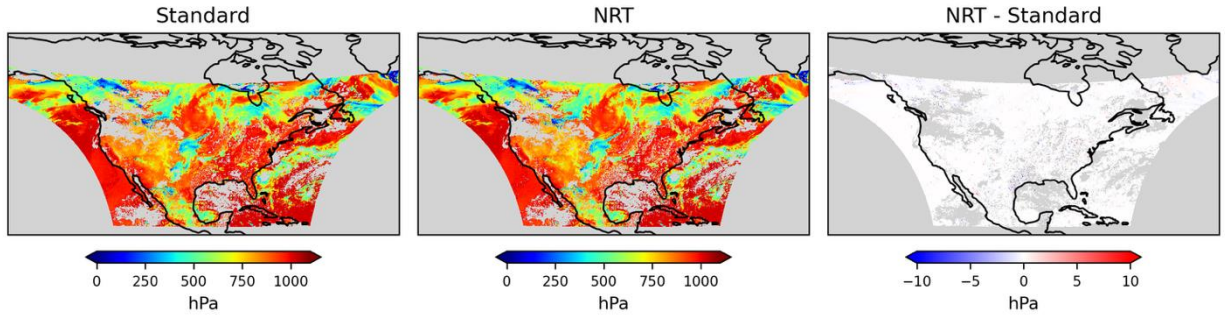

Figure 4. *Standard (left), NRT (middle) and their difference (right) for TEMPO cloud pressures retrieved from scan 7 on July 12, 2025. The differences between the standard and NRT cloud pressures are effectively negligible.*

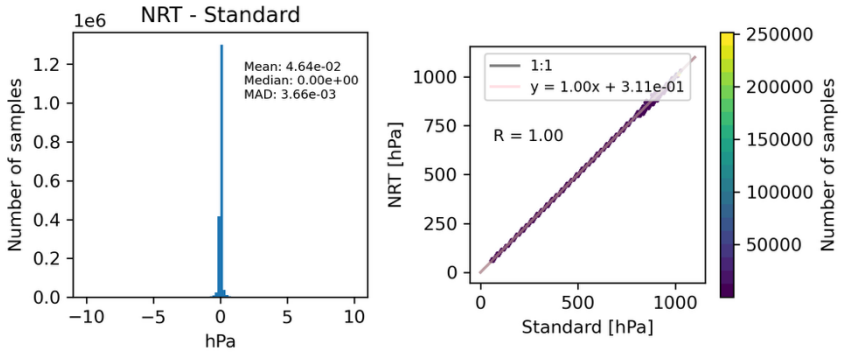

Figure 5. *Histogram (left) and scatter plot (right) showing a comparison between the standard and NRT cloud pressures from Figure 4. For visual clarity, the scatter plot only includes bins with >50 samples.*

2.4 Level 2 nitrogen dioxide

NO_2 vertical columns in the troposphere and stratosphere are derived using slant columns retrieved through spectral fitting, air mass factor calculations and an algorithm to separate the tropospheric and stratospheric contributions.

Figures 6 and 7 show the differences in tropospheric NO_2 vertical column densities between the standard and NRT products, while Figures 8 and 9 show differences in stratospheric NO_2. The differences between NO_2 products primarily result from differences in the NO_2 slant column densities derived through spectral fitting due to the omission of the radiance wavelength calibration in the L1 NRT processing. The largest differences in retrieved slant columns occur over ground pixels where the instrument slit is filled in an inhomogeneous way. This effect usually occurs over a partly cloudy scene or sometimes from a sharp change in albedo within a scene (for instance, at a coastline), resulting in a skewed slit function and an apparent larger shift in the wavelength registration. This is a known issue that affects both the standard and NRT products, and the current recommendation is for users to avoid using trace gas observations with effective cloud fractions greater than 0.1 (González Abad, Nowlan, Wang, et al., 2025).

In Figure 6, regional-scale differences in the tropospheric vertical columns result from differences in the stratospheric estimates shown in Figure 8. The stratospheric vertical column is determined by applying a spatial filtering approach across a full scan in a stratosphere-troposphere separation algorithm (Nowlan et al., 2025). Spatial variations in slant column density and number of available samples (e.g., due to detector saturation over bright clouds or NO_2 enhancements) propagate through the interpolation and smoothing steps. As a result, differences in the slant column inputs between the standard and NRT products can introduce characteristic blocking artifacts in the stratospheric NO_2 estimates which then propagate to the tropospheric NO_2 vertical column. Still, in most areas the uncertainties are far smaller than the estimated uncertainty of the standard NO_2 stratospheric column, which is on the order of 2×10^{14} molecules cm^{-2} (Nowlan et al., 2025).

Overall, the standard and NRT NO_2 products are highly consistent and well within the typical TEMPO single pixel tropospheric NO_2 precision of ~6×10^{14} molecules cm^{-2}. For context, TEMPO NO_2 already far exceeds the design requirement of 1×10^{15} molecules cm^{-2} for four co-added ground pixels.

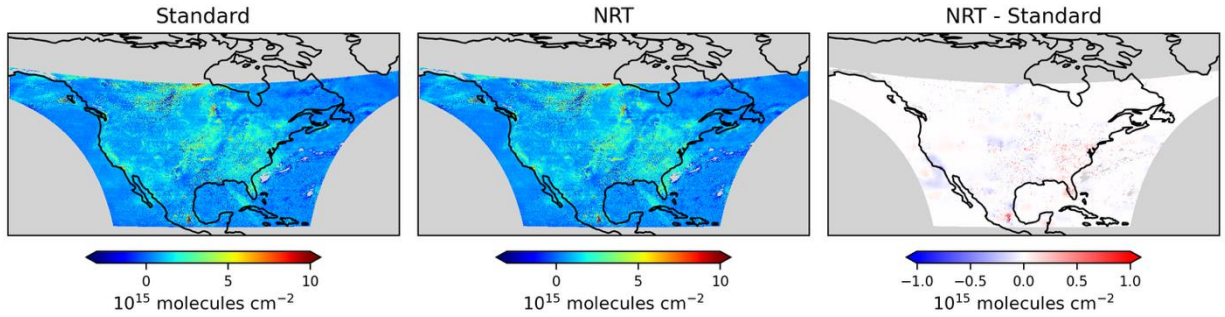

Figure 6. *Standard (left), NRT (middle) and their difference (right) for TEMPO tropospheric NO_2 vertical columns retrieved from scan 7 on July 12, 2025. The differences between the standard and NRT columns occur over partly cloudy pixels due to different radiance wavelength calibrations, and in small regional areas due to the stratospheric NO_2 estimates shown in Figure 8.*

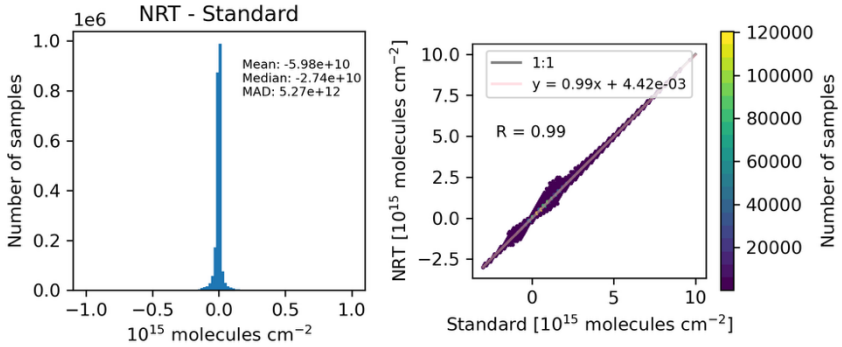

Figure 7. *Histogram (left) and scatter plot (right) showing a comparison between the standard and NRT tropospheric NO_2 vertical columns from Figure 6. For visual clarity, the scatter plot only includes bins with >50 samples.*

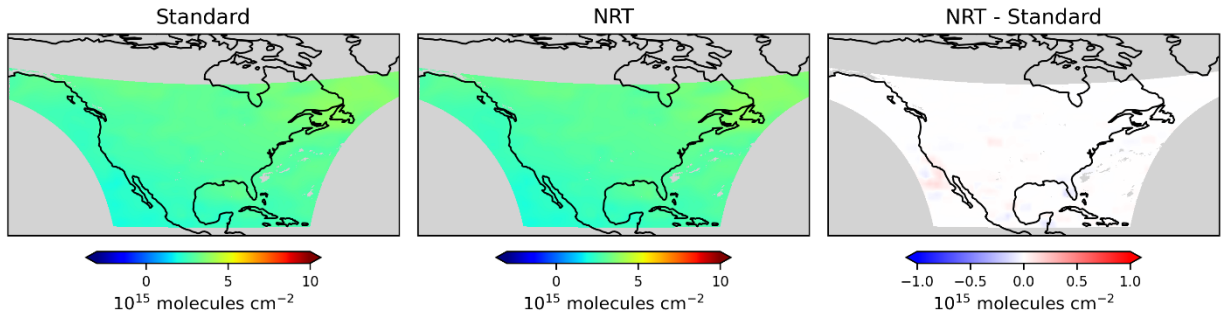

Figure 8. *Standard (left), NRT (middle) and their difference (right) for TEMPO stratospheric NO_2 vertical columns retrieved from scan 7 on July 12, 2025. The differences between the standard and NRT columns occur in regional areas due to differences in the slant column densities input to the stratospheric calculation.*

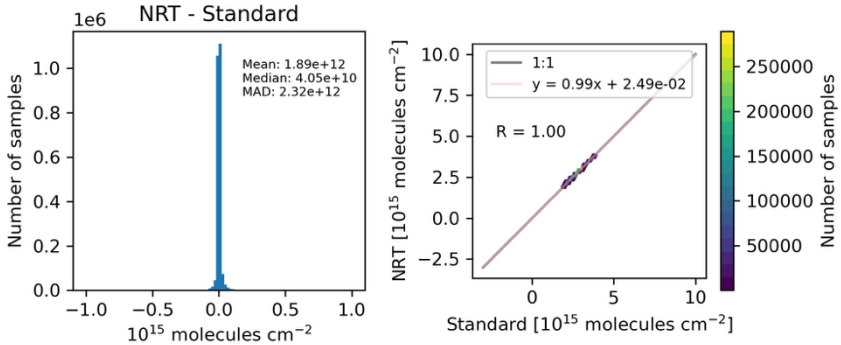

Figure 9. *Histogram (left) and scatter plot (right) showing a comparison between the standard and NRT stratospheric NO_2 vertical columns from Figure 8. For visual clarity, the scatter plot only includes bins with >50 samples.*

2.5 Level 2 formaldehyde

Formaldehyde vertical columns are derived using slant columns retrieved through spectral fitting, air mass factor calculations and a background correction that adds a background HCHO column from the radiance reference.

Figures 10 and 11 show the differences in formaldehyde vertical column densities between the standard and NRT products. These differences result from differences in the differential HCHO slant column densities derived through spectral fitting due to (1) the use of a different radiance reference and (2) the omission of the radiance wavelength calibration in the L1 NRT processing.

Details about the calculation of the radiance reference are provided in the TEMPO HCHO ATBD (González Abad et al., 2025). The difference between the standard and NRT product use of the radiance reference resides in its selection within the processing pipeline. Without NRT

constraints, the standard baseline pipeline can wait for a full TEMPO scan to be recorded to proceed with the calculation of a radiance reference and use it with the granules of the same scan. In the NRT pipeline this is not an option due to latency requirements. Instead, the NRT pipeline selects the radiance reference closest to the time of day, calculated with observations from previous days. The use of a different radiance reference results in the East-West stripe pattern shown in the rightmost panel in Figure 10. These differences are for the most part below TEMPO's HCHO uncertainty, and follow a Gaussian distribution as seen in Figure 11. Differences introduced by the omission of radiance wavelength calibration in the L1 NRT processing are small relative to those introduced by the radiance reference.

In summary, most regions see small differences in the HCHO vertical column, which can be $> 5\times10^{15}$ molecules cm^{-2} in some areas. Most differences lie within the estimated uncertainty of the standard HCHO vertical column, which is on the order of 5×10^{15} molecules cm^{-2} (González Abad, Nowlan, Liu, et al., 2025). For context, this single-pixel performance already exceeds the TEMPO design precision requirement of 1×10^{16} molecules cm^{-2} for twelve co-added ground pixels.

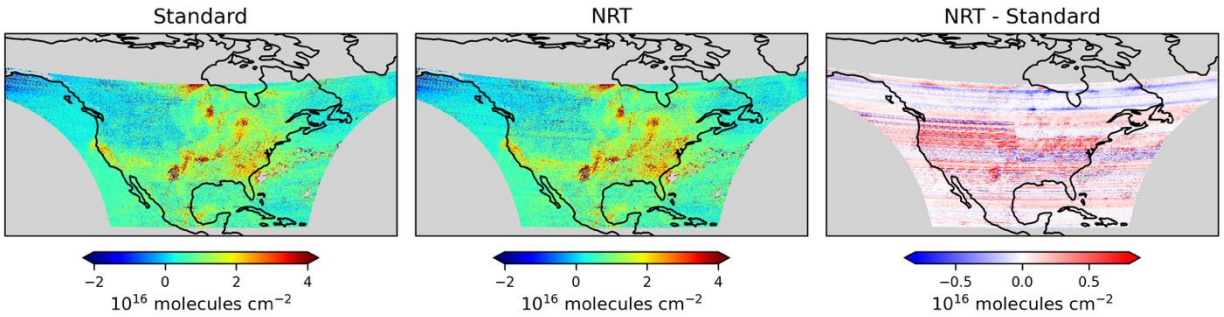

Figure 10. *Standard (left), NRT (middle) and their difference (right) for TEMPO HCHO vertical columns retrieved from scan 7 on July 12, 2025. The difference between the standard and NRT columns depicts the East-West striping pattern characteristic of using different radiance references in the standard and NRT as the source term in the spectral fitting.*

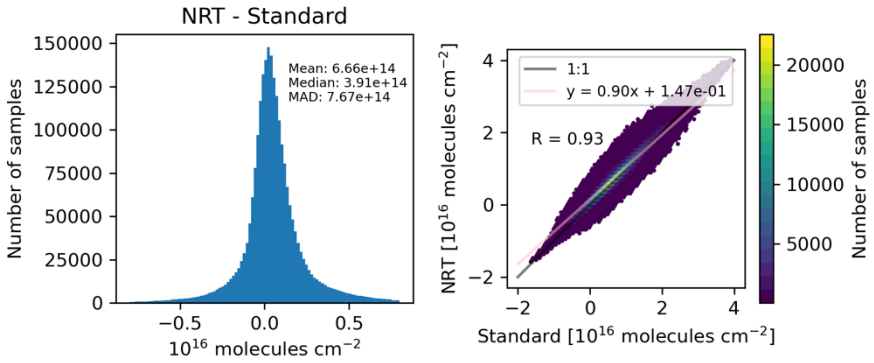

Figure 11. *Histogram (left) and scatter plot (right) showing a comparison between the standard and NRT HCHO vertical columns from Figure 10. For visual clarity, the scatter plot only includes bins with >50 samples.*

2.6 Level 3 gridded products

Both the baseline and NRT pipelines use the same algorithm to produce Level 3 gridded products. Differences in Level 3 data products result from differences in their source Level 2 inputs, and the previous assessments of L2 differences also apply to Level 3 data.

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Appendix A: List of acronyms

Table A1. List of acronyms

Acronym	Meaning
ASDC	Atmospheric Science Data Center
ATBD	Algorithm Theoretical Basis Document
CCD	Charge-Coupled Device
ECF	Effective cloud fraction
EOSDIS	Earth Observing System Data and Information System
L1	Level 1
L2	Level 2
L3	Level 3
INR	Image Navigation and Registration
MDQF	Main data quality flag
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
NRT	Near Real-Time
OCP	Optical centroid pressure
SAO	Smithsonian Astrophysical Observatory
SDPC	Science Data Processing Center
SNWG	Satellite Needs Working Group
SZA	Solar zenith angle
TEMPO	Tropospheric Emissions: Monitoring of Pollution