Tropospheric Emissions: Monitoring of Pollution (TEMPO) Aerosol Optical Depth (AOD) & Aerosol Layer Height (ALH) Users' Guide

Version 1.1, June 2025

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1. Purpose of this Guide

This Tropospheric Emissions: Monitoring of Pollution (TEMPO) Aerosol Optical Depth (AOD) and Aerosol Layer Height (ALH) User's Guide is intended for users of the AODALH Level 2 (L2) files generated from the UV-visible spectrometer. It provides a general introduction to TEMPO, the AOD and ALH products, and the format and contents of the TEMPO AODALH L2 data files. This guide serves as an introduction to the more technical TEMPO AODALH Algorithm Theoretical Basis Document (ATBD), which as of June 2025 is not yet finalized.

2. Points of Contact

For questions or comments regarding this document, please contact Shobha Kondragunta, Hai Zhang or Amy Huff.

3. Document Definitions

Aerosol optical depth is a measure of extinction of radiation by aerosols due to absorption and scattering. It depends on the chemical composition and size of aerosol particles, and thus varies with the wavelengths of radiation. It also depends on the amount of aerosol in the atmosphere, and as such it is also a measure of aerosol loading. Mathematically, it is defined as the integrated extinction coefficient over a vertical column of unit cross section, and is a unitless quantity.

Aerosol layer height is an estimate of the altitude of vertically localized aerosol layers in the troposphere under cloud-free conditions.

Table 1 lists additional acronyms and abbreviations used in this document.

4. TEMPO Overview

TEMPO is the first space-based instrument to monitor air pollutants on an hourly basis across North America during the daytime. It is an ultraviolet (UV, 290-490 nm)–visible (Vis, 540-740 nm) spectrometer. TEMPO flies onboard Intelsat-40e (IS-40e), a commercial telecommunications satellite centered at 91.0° W longitude.

The spatial resolution of TEMPO is 2.0 km x 4.75 km at the center of its Field of Regard (FOR): 33.7° N latitude and 91.0° W longitude. The FOR extends from Mexico City and the Yucatan Peninsula to the Canadian oil sands in the north-south direction, and from the Atlantic Ocean to the Pacific Ocean in the east-west direction.

TEMPO scans from east to west, covering its FOR in about 1 hour, with shorter scan times in the morning and evening (~40 minutes) and during special high-time-resolution operations. Data collected during each scan are distributed as granules to make individual file sizes manageable. See Section 6 for more information on the TEMPO AODALH L2 data files.

Table 1. List of acronyms and abbreviations used in this document.

Acronym/Abbreviation	Definition
AAI	Absorbing Aerosol Index
ABI	Advanced Baseline Imager
ADP	Aerosol Detection Product
AERONET	AErosol RObotic NETwork
ALH	Aerosol Layer Height
AOD	Aerosol Optical Depth
ATBD	Algorithm Theoretical Basis Document
DLER	Directional Lambertian Equivalent Reflectivity
DSDI	Dust Smoke Discrimination Index
EPIC	Earth Panchromatic Imaging Camera
FOR	Field of Regard
FWHM	Full Width Half Maximum
GFS	Global Forecasting System
GOES	Geostationary Operational Environmental Satellites
IS-40e	Intelsat-40e
JPSS	Joint Polar Satellite Series
L1b	Level 1b
L2	Level 2
LUT	Look-Up Table
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanographic and Atmospheric Administration
STAR	Center for Satellite Applications and Research
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TOA	Top of the Atmosphere
TROPOMI	Tropospheric Monitoring Instrument
UV	Ultraviolet
UV AI	Ultraviolet Aerosol Index
VIIRS	Visible Infrared Imaging Radiometer Suite
Vis	Visible

5. TEMPO AODALH Algorithm Overview

The TEMPO AODALH algorithm is primarily based on the Visible Infrared Imaging Radiometer Suite (VIIRS) AOD retrieval algorithm (Laszlo and Liu, 2022) and the Earth Panchromatic Imaging Camera/Tropospheric Monitoring Instrument (EPIC/TROPOMI) ALH retrieval algorithm (Xu et al. 2017; Chen et al. 2021). Separate algorithms are used to retrieve AOD over land and over ocean.

The surface Directional Lambertian Equivalent Reflectivity (DLER) over land was built using the accumulated TEMPO L1b data for each calendar month. Bands convolved from TEMPO spectral measurements at 440 nm and 670 nm are used to retrieve AOD over land by assuming there is a fixed ratio between the surface reflectance at these two bands. AOD and surface reflectance are adjusted to find a solution that minimizes the difference between the measured top of the atmosphere (TOA) reflectance and that derived using one of four aerosol models. The four aerosol models are: smoke model 1 (for AOD ≤1.5), smoke model 2 (for AOD >1.5), dust, and generic. The choice of aerosol model is determined by the TEMPO Aerosol Detection Product (ADP), which identifies the presence of smoke and dust in the atmosphere.

The surface reflectance over ocean is derived from the empirical equation by Cox and Munk (1954), which is also used in the VIIRS AOD retrieval over ocean (Laszlo and Liu, 2022). AOD over ocean is derived using the TEMPO measurements at 670 nm in one of the four aerosol models to find the AOD that gives the TOA reflectance at this wavelength. ALH is determined by minimizing differences between the measured and calculated 688/670 nm TOA reflectance ratios.

Ancillary inputs for the AOD and ALH products include the Global Forecasting System (GFS) meteorological fields, surface DLER, Advanced Baseline Imager (ABI) cloud mask, and pre-computed Look-Up Tables (LUTs) based on the US standard atmosphere (1976). The output fields include geolocations, AOD at 550 nm, ALH, quality diagnostic flags, land water mask, and TOA reflectance at seven convolved wavelengths. Not all of these seven wavelengths are used in the current algorithm. More details about the output variables are given in Section 7. Details of the TEMPO AODALH algorithm are described in Appendix 2.

6. TEMPO AODALH Level 2 Data Files

Figure 1 breaks down the file naming convention for TEMPO AODALH L2 data files, which are distributed as granules in netCDF4 (.nc) format. Files are organized in terms of the TEMPO scan number (e.g., S004) and granule number (e.g., G07) for each day. Each TEMPO scan covers a time period of ~60 minutes. Individual granule files contain data for the full FOR in the North-South direction, but only a portion of the East-West direction corresponding to a short time range (~6.7 minutes in nominal operations).

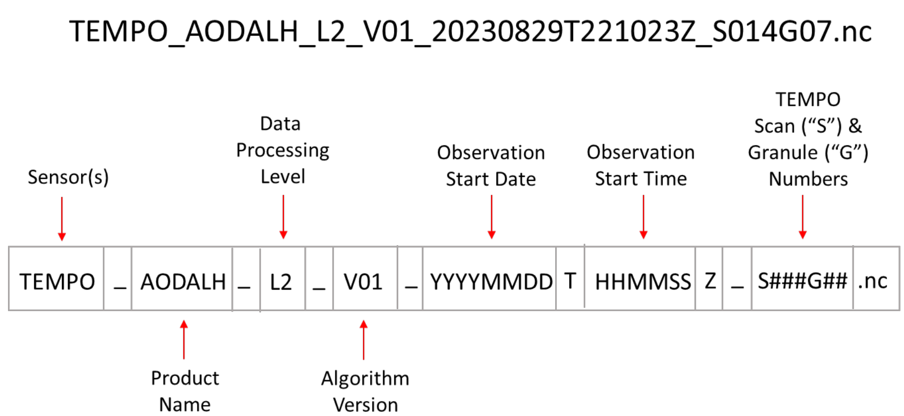

Figure 1. Example of a TEMPO AODALH Level 2 filename and breakdown of the naming convention.

TEMPO AODALH data variables have 2.0 km x 4.75 km spatial resolution at the center of TEMPO's FOR and are contained in ~123 x 2048 arrays, with dimensions corresponding to TEMPO's East-West scanning mirror steps and North-South tracks. Due to the relatively short granule length and the data resolution, users should expect a total of approximately ~150 granule files each day (daytime coverage). The output variables of the TEMPO AODALH data files and their descriptions are shown in Table 1.

The granule number (e.g., G01, G02) does not always correspond to the same geographic location for each scan, but rather to the order in which the granule was collected for the scan. This is because granules will be missing from scans made early and late in the calendar day, corresponding to locations where the sun is below the horizon (before sunrise or after sunset).

Note that the files use UTC time. Some TEMPO scans during daylight hours over North America occur during or after UTC midnight, so files from late in the calendar day will be labeled with the date of the next day.

The "algorithm version" in the filename (e.g., "V01" in Figure 1) refers to the version of or the TEMPO AODALH algorithm, which is also given in global file metadata as the "algorithm_version" attribute.

7. Working with TEMPO AODALH Level 2 Data Files

TEMPO AODALH L2 files contain many variables, listed in Table 2. The variables of interest to most users include (group name listed first):

- geolocation/latitude
- geolocation/longitude
- product/aod550
- product/alh
- quality_diagnostic_flags/dqf

Note that ALH (**product/alh**) is retrieved only for pixels with **product/aod550** >0.2, as sufficient aerosols must be present to calculate a layer height.

The **quality_diagnostic_flags/dqf** variable should be used to filter the **product/aod550** variable. For ***quantitative*** applications, use high quality retrievals only (dqf == 0). For ***qualitative*** and ***semi-quantitative*** applications, "top2" qualities (high + medium; dqf <2) may be used. In addition, although the valid range of **product/aod550** extends to 10, residual cloud contamination degrades AOD and ALH pixels with **product/aod550** greater than 5. Users who have a low tolerance for cloud contamination should filter the **product/aod550** and **product/alh** variables using **product/aod550** (aod550 <=5).

For ***quantitative*** applications, use the following variables (**bolded**) in the AODALH data file (group name listed first):

- **geolocation/latitude**
- **geolocation/longitude**
- For ALH:
  - **product/alh**
    - Select pixels with **product/aod550** <=5 to avoid residual cloud contamination
- For AOD:
  - **product/aod550**
    - Select pixels with **product/aod550** <=5 to avoid residual cloud contamination
    - Select pixels with **quality_diagnostic_flags/dqf** == 0 for high quality

Alternatively, for ***qualitative*** or ***semi-quantitative*** applications, use the following variables **bolded**) in the AODALH data file (group name listed first):

- **geolocation/latitude**
- **geolocation/longitude**
- For ALH:
  - **product/alh**
    - Select pixels with **product/aod550** <=5 to avoid residual cloud contamination
- For AOD:
  - **product/aod550**
    - Select pixels with **product/aod550** <=5 to avoid residual cloud contamination
    - Select pixels with **quality_diagnostic_flags/dqf** <2 for high + medium qualities

Example Python code to read and filter the AODALH data is given in Appendix 1, and examples of displaying AOD and ALH data for qualitative applications are given in Figure 2.

8. Known Issues to Date

August 2023 is the first month with operational TEMPO L1b data, so as a result, many individual granules and full scans are missing, sometimes for entire days. These missing upstream L1b data cause corresponding gaps in AODALH L2 granules and scans.

As described in more detail in Appendix 2, both AOD and ALH retrievals are impacted by TEMPO calibration biases and drifts. If TEMPO L1b data are reprocessed by the TEMPO science team in the future to rectify the calibration issues, AODALH L2 data will need to be reprocessed accordingly.

Note also that DLER, derived for each calendar month of data collection, is preliminary – ideally it is derived using a longer record to represent climatology. A new DLER dataset will be derived if

L1b data are reprocessed by the TEMPO science team or when TEMPO has gathered multiple years of data.

9. Data Access

Currently, TEMPO AODALH data files are being generated by NOAA in a research environment. This means that the data are not yet available in near real-time. To allow users to test the TEMPO-ABI Hybrid ADP data, a one-year archive of files for August 1, 2023 to July 31, 2024 is from NOAA.

Moving forward, the primary source for the TEMPO AODALH data files will be NASA Earthdata. Users can register for a free account (needed to download data files) at Earthdata login. Once near real-time TEMPO aerosol files are flowing to Earthdata, the collection short name "TEMPO_AODALH_L2" can be used to search for the AODALH data files.

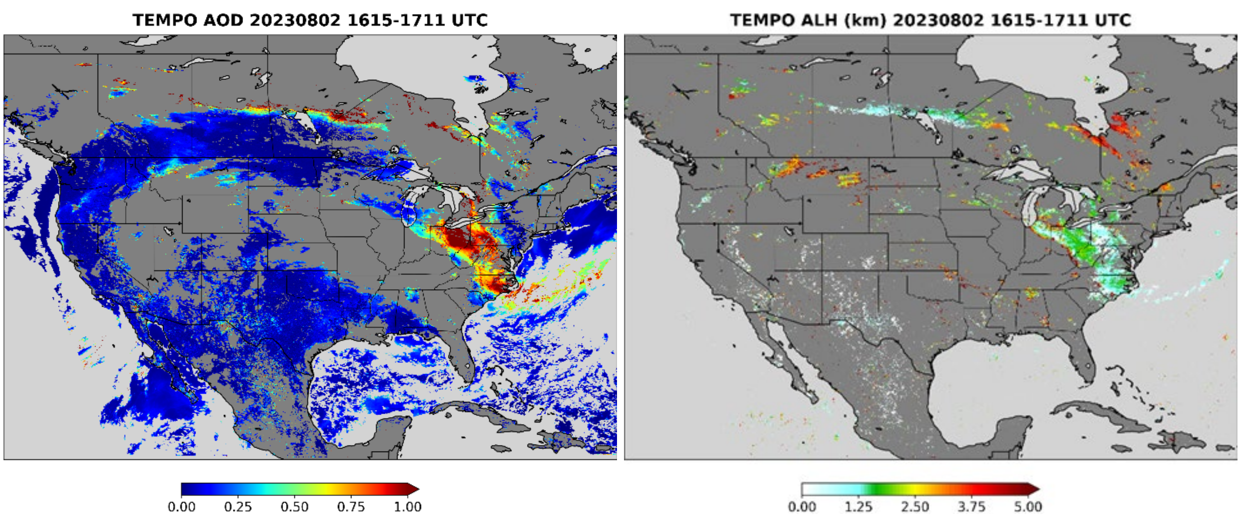

Figure 2. Examples of TEMPO full scan plots of "top 2" qualities (high + medium) AOD (left) and ALH (right) retrievals, suitable for qualitative applications.

Table 2. Output variables from the TEMPO AODALH algorithm. Units of "1" indicate a unitless quantity.

Group	Data Variable	Type	Description	Units	Range
geolocation	longitude	Float	Pixel center longitude	° East	-180, 180
	longitude_bounds	Float	Longitude at pixel corners (SW, SE, NE, NW)	° East	-180, 180
	latitude	Float	Pixel center latitude	° North	-90, 90
	latitude_bounds	Float	Latitude at pixel corners (SW, SE, NE, NW)	° North	-90, 90
product	aod550	Float	Aerosol Optical Depth at 550nm	1	-0.05, 10
	alh	Float	Aerosol Layer Height	km	0, 15
	aermodel	Integer	Aerosol Model • 0: smoke model 1 • 1: smoke model 2 • 2: dust • 3: generic	1	0, 3
quality_diagonostic_flags	lwmask	Integer	Land water mask • 0: water • 1: land • 2: coastal or shallow water, etc.	1	0, 2
	qctest	Byte	Product quality information diagnostic flag • bit 0: ABI cloudy • bit 1: ABI probably cloudy • bit 2: internal test cloudy • bit 3: cloud adjacent • bit 4: high sza or vza • bit 5: sunglint over water • bit 6: snow ice	1	-127, 128
	dqf	Byte	AOD/ALH data quality flag • 0: high quality • 1: medium quality • 2: low quality • 3: no retrieval	1	0, 3
support_data	refl	Float	TOA reflectance at convolved bands 354, 388, 416,440, 494, 670, and 687.75 nm	1	0, 1

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Appendix 1. Helpful Tools for Working with TEMPO AODALH L2 Files

A. NetCDF Data Model

For users unaccustomed to working with NetCDF4 formatted files, please visit the website https://docs.unidata.ucar.edu/netcdf-c/current/netcdf_data_model.html for information.

B. Panoply Data Viewer

The Panoply NetCDF, HDF and GRIB Data Viewer developed by NASS GISS is a convenient tool for visualization of the EPS ADP outputs. Please visit the website https://www.giss.nasa.gov/tools/panoply/ for more information about this software.

C. IDL Tools

IDL has a built-in library of commands for NetCDF4 files. Documentation can be found online at https://www.harrisgeospatial.com/docs/NCDF_Overview.html or using IDL Help.

Michael Galloy has written a particularly helpful IDL program to read HDF5 (also works for NetCDF4) arrays into IDL, available at http://docs.idldev.com/idllib/hdf5/mg_h5_getdata-code.html.

D. Example Code of Python Code for Processing TEMPO AODALH L2 Files using Xarray

Python configuration:
python=3.11
 - numpy=2.0.2
 - netcdf4=1.7.2
 - dask=2024.12.1
 - xarray=2025.3.1

```
# Module to set filesystem paths for user's operating system
from pathlib import Path
```

```
# Library to work with labeled multi-dimensional arrays
import xarray as xr

# Library to perform array operations
import numpy as np


# User: enter directory & file name of TEMPO data file
file_path = Path('D://Data/2023/20230802')  # Directory where .nc file is located
file_name = 'TEMPO_AODALH_L2_V01_20230802T163359Z_S002G04.nc'

# User: enter AOD data quality
quality = 'top2'  # 'high' (high quality only) or 'top2' (high + medium quality)


# Process TEMPO AOD
def process_tempo_aod(dt, quality):

   # Screen AOD following recommendations from the Science Team
   # 'high' is high quality AOD only (recommended for quantitative applications)
   # 'top2' is high + medium quality AOD (recommended for qualitative applications)
   # Exclude pixels with aod550 > 5 to avoid cloud contamination
   if quality == 'high':
      screen = ((dt['quality_diagnostic_flags/dqf'] == 0) & (dt['product/aod550'] <= 5.0))
   elif quality == 'top2':
      screen = ((dt['quality_diagnostic_flags/dqf'] <= 1) & (dt['product/aod550'] <= 5.0))

   aod = dt['product/aod550'].where(screen)

   return aod
```

```
# Main function
if __name__ == "__main__":

    # Set full path for TEMPO data file
    file_id = file_path / file_name

    # Open file using xarray (automatically closes file when done)
    with xr.open_datatree(file_id, engine='netcdf4') as dt:

        # Filter AOD data using data quality flag
        aod = process_tempo_aod(dt, quality)

        # Read in & screen ALH data (following recommendation from the Science Team)
        # Exclude pixels with aod550 > 5 to avoid cloud contamination
        alh = dt['product/alh'].where(dt['product/aod550'] <= 5.0)

        # Read in latitude and longitude
        # Fill missing lat/lon pixels so matplotlib.pyplot.pcolormesh plots AOD/ALH data
        if np.isnan(np.sum(dt['/geolocation/latitude'].values)):
            latitude = dt['/geolocation/latitude'].fillna(-999.99)
            longitude = dt['/geolocation/longitude'].fillna(-999.99)
        else:
            latitude = dt['/geolocation/latitude']
            longitude = dt['/geolocation/longitude']
```

Appendix 2. Details of the TEMPO AODALH Algorithm

A2.1 Convolution to Bands

The hyperspectral TEMPO data were convolved to the bands 354, 388, 416, 440, 494, 670, 687.75 nm. The selection of the bands other than the O_2B band (687.75 nm) is based on the KNMI directionally dependent Lambertian equivalent reflectance (DLER) bands, the bands used by the VIIRS AOD retrieval algorithm over land, and the bands used for retrieving the ultraviolet aerosol index (UVAI).

A triangle function is used as a weight function to convolve the L1b data (KNMI TROPOMI DLER ATBD, Tilstra 2022):

$$w_i^j = \begin{cases} 1 - \frac{\left|\lambda_i - \lambda_j^c\right|}{\omega_j} & for \left|\lambda_i - \lambda_j^c\right| \leq \omega_j \\ 0 & for \left|\lambda_i - \lambda_j^c\right| > \omega_j \end{cases} \quad (A.1)$$

where λ_i is the original wavelength of L1b data, λ_j^c is the central wavelength of the bands to be convolved to, and $2\omega_j$ is the width, set as $2\omega_j$ = 1nm. The shape of the weight function is illustrated in Figure A.1 (Figure 3 in KNMI TROPOMI DLER ATBD).

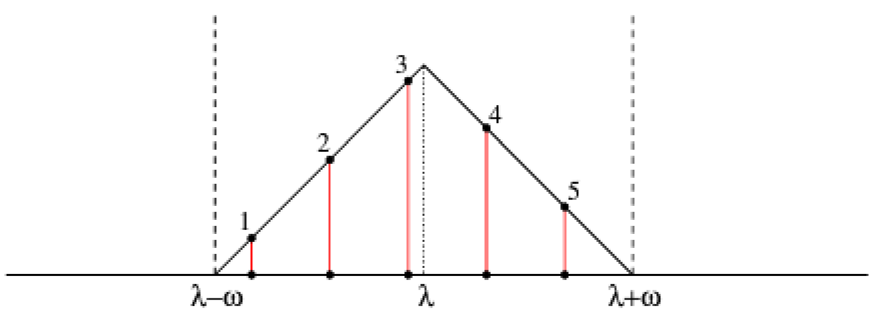

Figure A.1. The triangle weight function used to convolve the bands (Figure 3 in KNMI TROPOMI DLER ATBD).

The convolved TOA reflectance is calculated using the following equation:

$$\rho^j = \frac{\sum_i w_i^j \rho_i}{\sum_i w_i^j} \quad (A.2)$$

A2.2 Look-Up Table (LUT)

The look-up table (LUT) was developed using the UNL-VRTM radiative transfer model developed by Jun Wang's group (Xu and Wang, 2019; Wang et al., 2014). The main component of the model is the VLIDORT radiative transfer model (Spurr 2006). The US Standard Atmosphere 1976 was used for the atmospheric profiles. The LUT was made using two smoke models, provided by Xi Chen at the University of Iowa, a generic model, and a dust model, which were adopted from the VIIRS aerosol retrieval algorithm. The parameters of the smoke models are listed in Table A.1, and those for the generic and the dust models are listed in Table A.2.

Table A.1. Parameters for smoke models (τ is for 680 nm).

		r_{eff}	v_{eff}	Fmf_v	m_r (443nm)	m_i (443nm)	m_r (680nm)	m_i (680nm)	m_r (780nm)	m_i (780nm)
Smoke model 1 (for AOD > 1.5; Chen et al. 2021)	Fine mode	0.017τ +0.178	1.26	0.162τ +0.532	1.54	0.0106	0.026τ +1.513	0.00857	0.025τ +1.513	0.00855
	Coarse mode	0.579τ +2.477	0.278							
Smoke model 2 (for AOD<=1.5)	Fine mode	0.032τ +0.172	1.3	0.201τ +0.513	m_r=1.55 m_i= 0.002τ+0.003					
	Coarse mode	0.749τ +2.205	0.262							

Table A.2. Dust model and generic model (from Laszlo and Liu 2022). The properties (r_v, σ and refractive index) of the generic aerosol model are defined for τ<2.0, and τ=2.0 is used in calculations when τ>2.0. Likewise, parameters of the dust aerosol model are defined for τ<1.0, and τ=1.0 is applied for higher τ.

		Volume median radius r_v	Standard Deviation σ	Volume Concentration C_v ($\mu m^3/\ \mu m^2$)	Complex Refractive index
Dust model	Fine mode	$0.1416\ \tau_{550}^{-0.0519}$	$0.7561\ \tau_{550}^{0.148}$	$0.087\ \tau_{550}^{1.026}$	$1.48\ \tau_{550}^{-0.021}$-$0.0025\ \tau_{550}^{0.132}$ i at 470 nm $1.48\ \tau_{550}^{-0.021}$-0.002 i at 550 nm $1.48\ \tau_{550}^{-0.021}$-$0.0018\ \tau_{550}^{0.08}$ i at 660 nm $1.46\ \tau_{550}^{-0.040}$-$0.0018\ \tau_{550}^{0.30}$ i at 2120 nm
	Coarse mode	2.20	$0.554\ \tau_{550}^{-0.0519}$	$0.6786\ \tau_{550}^{1.0569}$	
Generic model	Fine mode	$0.145+0.0203\ \tau_{550}$	$0.3738+0.1365\ \tau_{550}$	$0.1642\ \tau_{550}^{0.7747}$	$1.43-(0.008-0.002\ \tau_{550})$ i
	Coarse mode	$3.1007+0.3364\ \tau_{550}$	$0.7292+0.098\ \tau_{550}$	$0.1482\ \tau_{550}^{0.6846}$	

For the bands other than the O_2B band, the TOA reflectance is calculated using a Gaussian shape function with FWHM of 1.0 nm. For the O_2B bands, the TOA reflectance is calculated by first calculating the lines of TOA reflectance at intervals of 0.01 nm and FWHM 0.02 nm that cover the whole triangle convolution bandwidth (Equation A.1), and then convolving the TOA reflectances of the lines using the triangle weighting function and TEMPO's slit function.

The LUT contains the TOA reflectance of the bands for different values of AOD (at 550 nm), ALH, surface reflectance, surface pressure, and Sun-satellite geometry. The details of the parameters are listed in Table A.3.

Table A.3. Parameters in the LUT.

Parameters	Values
AOD (unitless)	0,0.05,0.2,0.4,0.8,1.2,1.6,2.0,2.5,4.0,5.0,7.5,10.0
ALH (km)	0.,1.0,2.0,3.5,5.0,8.0,11,15
Surface reflectance	0.0,0.02,0.05,0.1,0.15,0.2,0.25,0.3,0.4
Surface pressure (mb)	1013,900,800,700
Solar zenith angle (degrees)	0,6,12,18,24,30,36,42,48,54,60,66,72, 78
View zenith angle (degrees)	0,8,16,24,32,40,48,56,64,72
Relative azimuth angle (degrees)	0,15,30,45,60,75,90,105,120,135,150,165,180

A2.3 Directional Lambertian Equivalent Reflectance (DLER)

A surface reflectance database was constructed using accumulated TEMPO Level 1b data. The surface reflectance, known as the directional Lambertian effective reflectivity (DLER, Tilstra, 2022; Tilstra et al., 2024), depends on sun-satellite geometry. Monthly DLER is derived from a time series of atmospheric-corrected reflectance, using a standard atmosphere and an assumed background AOD of 0.025 over North America, based on analysis of AERONET AOD climatology (Zhang et al., 2016). The convolved TEMPO L1b data undergo atmospheric correction with the background AOD and are then regridded to a 0.05-degree spatial resolution latitude-longitude grid over the CONUS. The monthly atmospheric-corrected reflectances are binned by UTC time for each observation hour, as DLER is considered a function of UTC time. For each bin, the lowest value in the 440 nm band is identified. The minimum aerosol loading is assumed to match the background AOD for that time step, and the corrected reflectance in other bands is selected accordingly. These selected corrected reflectances are then set as the DLER values. A similar approach was used to build a surface reflectance ratio database for VIIRS, which is employed in the VIIRS operational algorithm for AOD retrieval at NOAA (Zhang et al., 2016; VIIRS AOD ATBD), for which the surface reflectance varies with view angle.

A2.4 AODALH Retrieval Algorithm

The flowchart of the TEMPO AODALH algorithm is shown in Figure A.2. The GOES-16 ABI full disk sector cloud mask (Heidinger, 2020) is used to mask cloudy pixels. This mask is regridded using the nearest pixel method to match the TEMPO grid and input into the algorithm. Additionally, an internal cloud mask is applied to further remove cloudy pixels. The criteria for the internal test are outlined in Table A.4: a land pixel is considered cloudy if the standard deviation of the TOA reflectance at 440 nm across a 3x3 pixel window exceeds $0.0105/\mu_0$ or if the TOA reflectance at 440 nm exceeds $0.28/\mu_0$, and a water pixel is considered cloudy if the standard deviation of the TOA reflectance at 670 nm across a 3x3 pixel window exceeds $0.0056/\mu_0$, where μ_0 is the solar zenith angle. These thresholds depend on the solar zenith angle to account for the tendency of reflectance to be higher at lower solar zenith angles. Since the algorithm cannot retrieve aerosol properties in the presence of clouds, cloudy pixels are removed prior to further processing.

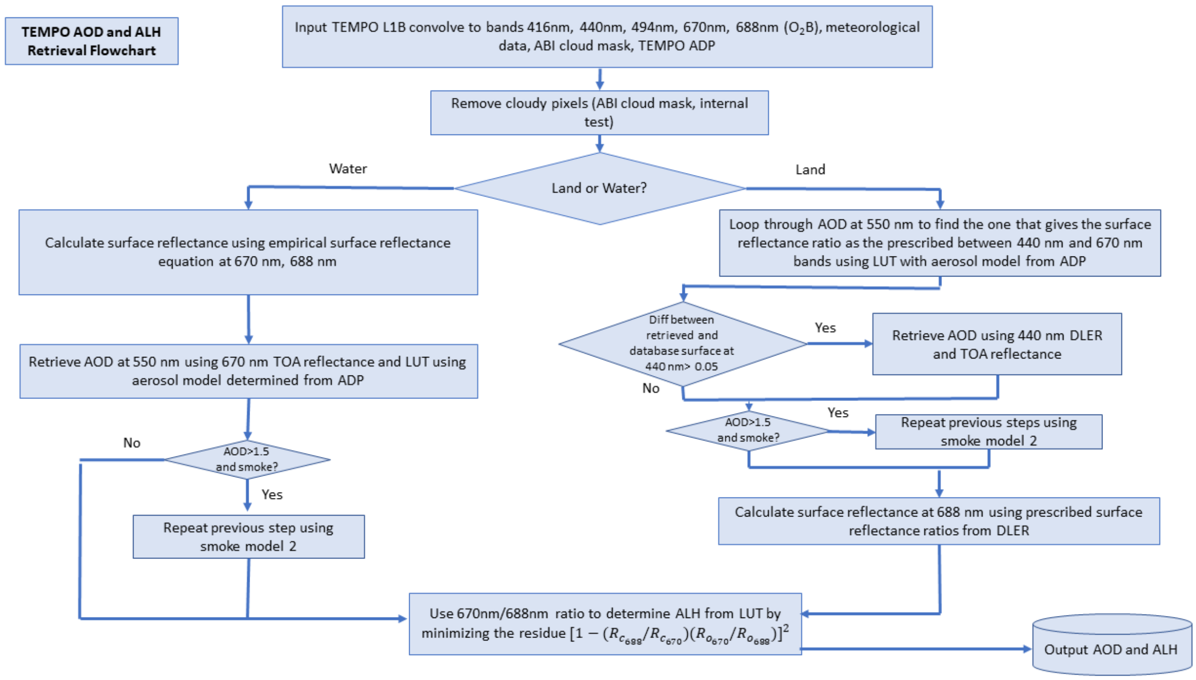

Figure A.2. TEMPO AODALH retrieval algorithm flowchart.

Table A.4. Internal test for cloud mask criteria.

Surface type	Criteria (if any one criterium is satisfied, the pixel is set as cloud)
Land	$\sigma_{440} > 0.0105/\mu_0$ $\rho_{440} > 0.28/\mu_0$
Water	$\sigma_{670} > 0.0056/\mu_0$

Surface pressure and wind data from the Global Forecast System (GFS) are also input into the algorithm. The Interactive Multi-sensor Snow and Ice Mapping System (IMS) is used to identify clear-sky snow/ice-free pixels. The land water mask is used to select the appropriate (land or water) algorithm for AOD retrieval. The coastal mask, shallow inland water mask, and shallow ocean mask are also obtained from the land water mask. Pixels that are identified as shallow water are flagged and removed due to the difficulty in modeling the surface reflectance.

Another key input is the TEMPO Aerosol Detection Product (ADP), which combines TEMPO and ABI Level 1b data to detect aerosol types. ADP provides a mask that classifies aerosols in each cloud-free pixel as smoke, dust, or no detection. ADP uses deep blue (412nm), blue (440nm), and shortwave IR (2130nm) wavelengths to generate an Absorption Aerosol Index (AAI) and Dust Smoke Discrimination

Index (DSDI) to determine whether there are smoke or dust aerosols in a pixel (VIIRS ADP ATBD, 2018; Ciren and Kondragunta, 2014; Ciren and Kondragunta, 2022). This dust-smoke mask is used in the TEMPO AOD retrieval algorithm to select the appropriate aerosol model: if ADP indicates smoke or dust, the corresponding aerosol model is applied; otherwise, the generic model is used. Two smoke models are employed: a low-absorption model for AOD values less than 1.5, and a higher-absorption model for AOD values greater than 1.5.

The ALH retrieval method leverages the absorption characteristics of the O_2B band (686–695 nm) and the fact that O_2 is well-mixed in the atmosphere (Xu et al., 2019). Aerosol layers scatter sunlight, and the satellite sensor measures the scattered photons. Due to aerosol scattering, the layer beneath the aerosol has fewer photons, resulting in reduced O_2 absorption for those layers. When the aerosol layer is higher in the atmosphere, the air mass below it is larger, leading to less O_2 absorption compared to a lower aerosol layer. Therefore, for the same aerosol amount in the total column, the satellite sensor is expected to receive more photons from a higher aerosol layer than from a lower one. The retrieval of ALH uses the ratio of TOA reflectances between 670 nm and 688 nm and looks for the ALH that can minimize the differences between the observed and calculated ratio, i.e. that minimizes the following quantity:

$$\left[1 - \left(\frac{R_{c688}}{R_{c670}}\right)\left(\frac{R_{o670}}{R_{o688}}\right)\right]^2 \qquad \text{(A.3)}$$

where R_{c670} and R_{c688} represent the calculated TOA reflectances at the two bands and R_{o670} and R_{o688} represent the observed TOA reflectances at the two bands. ALH is only retrieved for the pixels with AOD greater than 0.2.

A2.5 Soft Calibration

We found that the TEMPO L1b TOA reflectances have positive biases. To correct these biases, a soft calibration was developed by comparing calculated TOA reflectance with measured TOA reflectance over the ocean. In particular, TEMPO granules and ABI granules are matched up at the pixel level, and the pixels with low ABI AOD are selected over the ocean. TOA reflectances are then calculated for the convolved TEMPO bands using the ABI AOD values and prescribed parameters, such as surface reflectance, sun-satellite geometries, etc. Regression relationships are derived by comparing the calculated and measured TOA reflectances, and these relationships are then used to correct the TOA reflectance for all TEMPO pixels. The monthly DLER database is constructed using the soft-calibrated TOA reflectances, and used in the algorithm described in the previous section to retrieve AOD and ALH.