



Finding your TEMPO: An introduction to the mission, products, and data services for air quality observations over N. America

Caroline Nowlan, Center for Astrophysics

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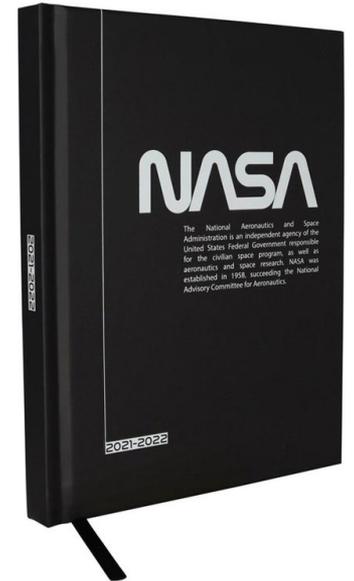
Daniel Kaufman, ASDC

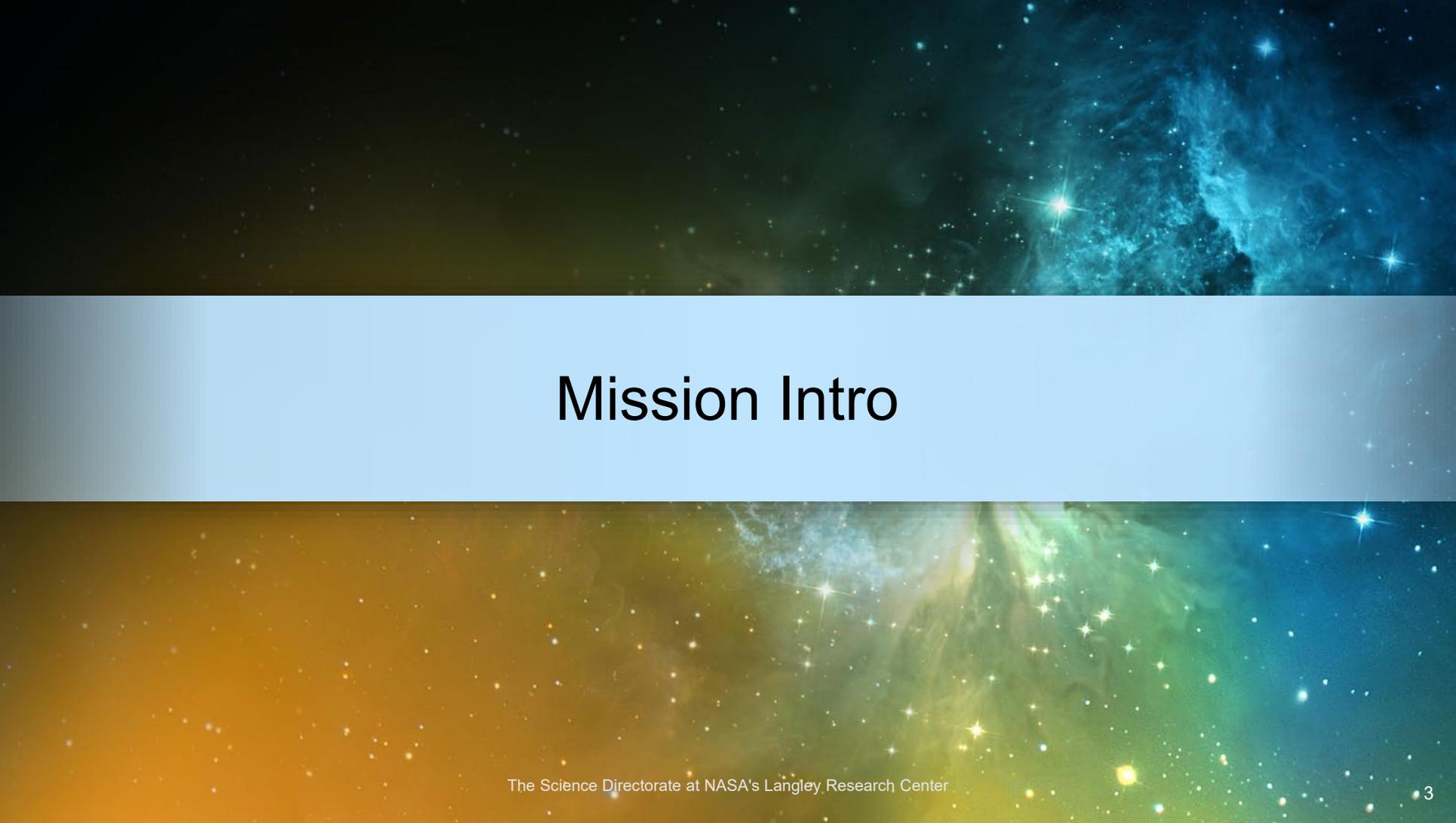
Hazem Mahmoud, ASDC

05/29/2024

Agenda

- Mission introduction
- Data product details
- Accessing TEMPO data on Earthdata Search
 - Finding documentation
 - Searching and filtering
 - Subsetting and concatenating
- Additional TEMPO information resources
- Asking questions on Earthdata Forum
- How to learn more
- Q&A



The background of the slide is a composite of two cosmic images. The top half features a dark blue and black space filled with numerous small white stars and a prominent, bright blue nebula on the right side. The bottom half features a gradient from orange on the left to blue on the right, with a green nebula in the center and many bright yellow and white stars scattered throughout.

Mission Intro

Tropospheric Emissions: Monitoring of Pollution

- Hourly daytime air pollution measurements over North America
- NASA's first Earth Venture Instrument (EVI), selected in 2012
- **Geostationary orbit** means TEMPO can scan the continent continuously
 - High temporal resolution
 - High spatial resolution
- Baseline data products:
 - Ozone
 - Nitrogen dioxide
 - Formaldehyde



Credit: NASA's Scientific Visualization Studio

Atmospheric Composition Geostationary Constellation

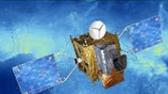
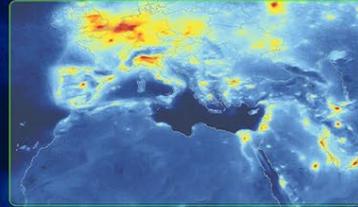
TEMPO (hourly)
Tropospheric Emissions:
Monitoring of Pollution



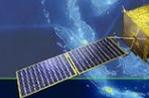
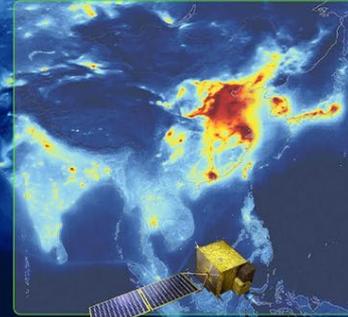
Sentinel-5P (once per day)



Sentinel-4 (hourly)



GEMS (hourly)
Geostationary Environmental
Monitoring Spectrometer



GaoFen-5 (once per day)





PI: Xiong Liu (Smithsonian Astrophysical Observatory)
Founding PI: Kelly Chance



Multiple partners, 600+ early adopters

MAXAR
TECHNOLOGIES
Spacecraft Manufacturer
Palo Alto, CA


Host Acquisition
Los Angeles, CA


Instrument Manufacturer
Boulder, CO


Science Data Archiving
Hampton, VA


Project Management and Engineering
Hampton, VA


Instrument Operations
Cambridge, MA


Science Data Processing
Cambridge, MA


Spacecraft Operator
McLean, VA

TEMPO Timeline

Kick-off	January 2013
Instrument delivered	November 2018
Integrated to Intelsat 40e	June 2022
Launch	7 April 2023
First light	2 August 2023
Nominal operations	October 2023
Radiances and 3 weeks of unvalidated trace gas files released to public	February 2024
Public data release	May 2024
Near real time products	Early 2025



* Baseline mission is 20 months, then up for extensions through NASA Senior Reviews

TEMPO Operations

Nominal scans

- 2048 North/South pixels
- 1181 East/West steps per hour
- 2 x 4.75 km² at center of field of regard

Optimized scans

- Higher temporal resolution AM and PM scans over coasts (40 minutes)

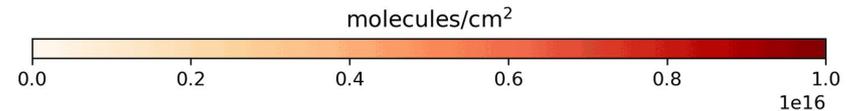
Twilight scans (city lights)

- Performed during darkness, before morning scans

High-time scans

- Frequent scans (5 to 10 minutes) over selected longitudes
- Rare → can be requested but require science team approval

TEMPO tropospheric NO₂ column
01 November 2023
Scan 001 (11:41:47 UTC)



GOME-2

OMI

TROPOMI

TEMPO

Google Earth

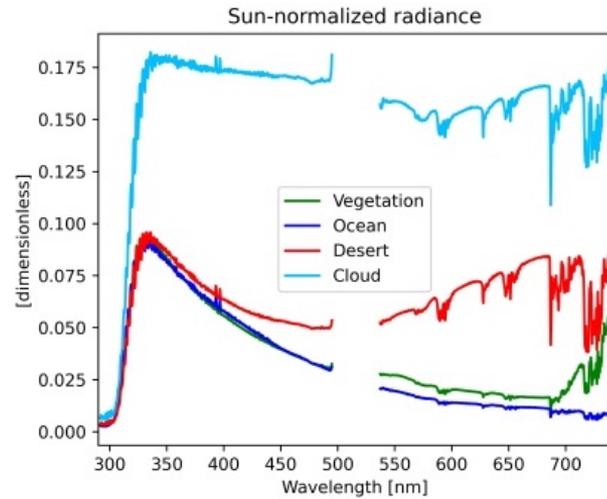
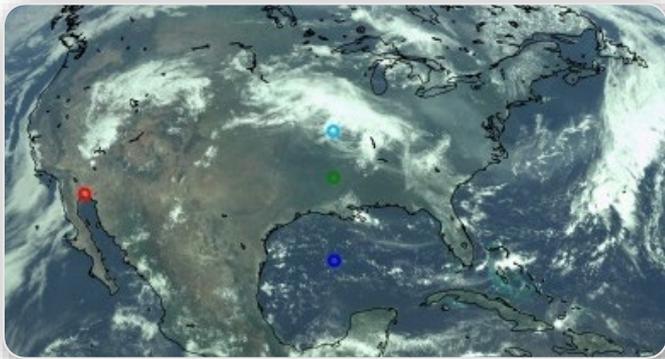
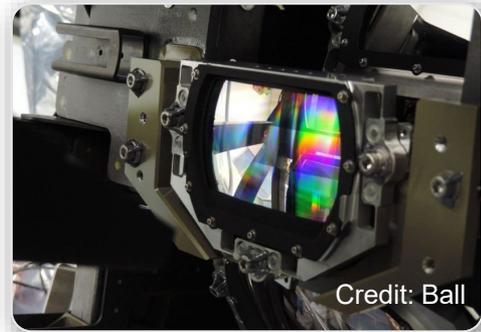
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2023 TerraMetrics

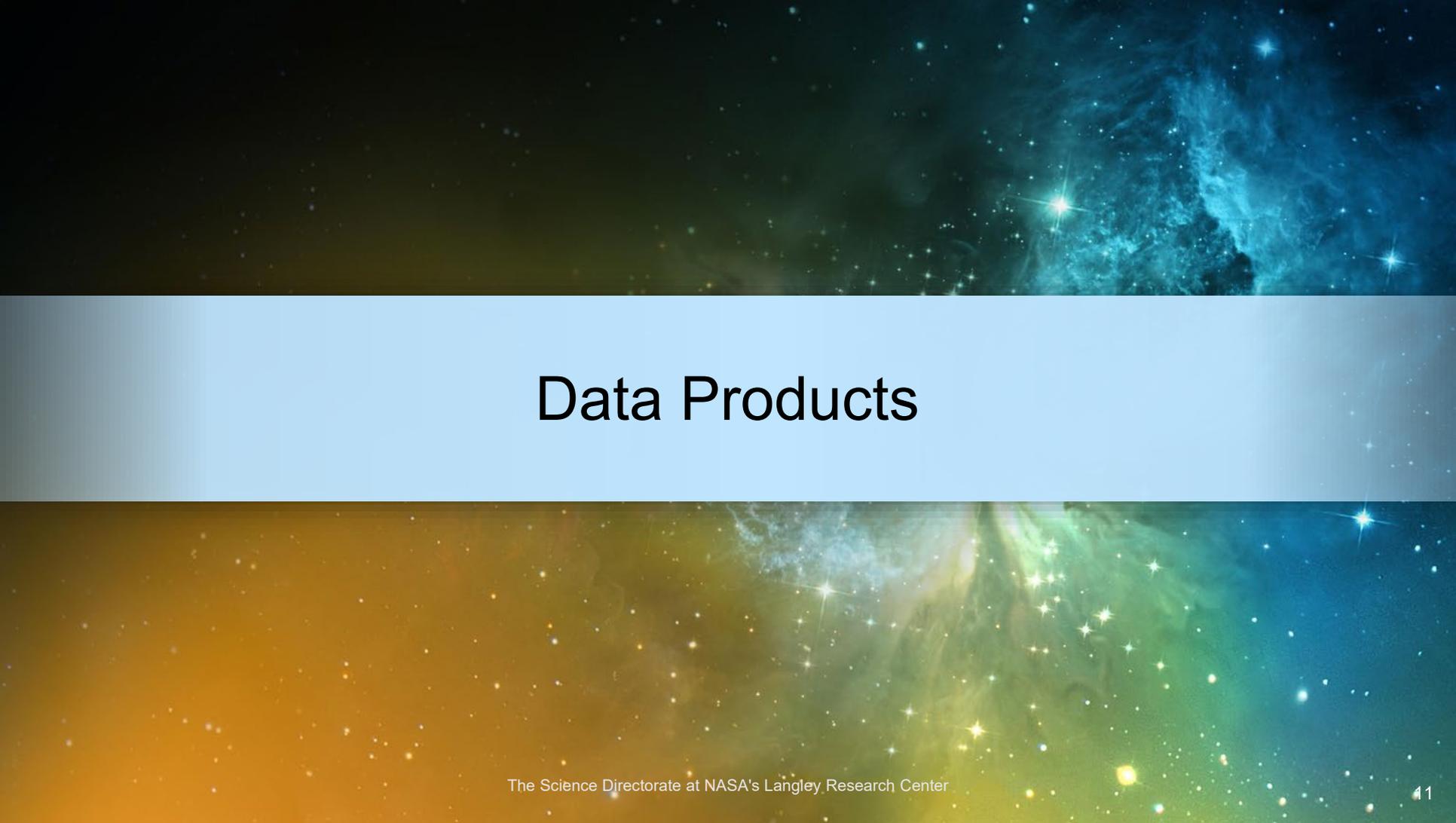
20 km



g

TEMPO Spectra



The background of the slide is a composite of two astronomical images. The top half features a dark blue and black space filled with numerous small stars and a prominent, bright blue nebula on the right side. The bottom half shows a similar starry field but with a color gradient from orange on the left to green on the right, and a bright green nebula on the right side. A light blue horizontal band is centered across the image, containing the title text.

Data Products

TEMPO Level 1 products

Product	Level	Description	Nominal sampling frequency	Maturity level
DRK	1a	Dark exposure	Variable (typically sampled before the beginning of the other types of exposure)	Beta
RAD	1b	Geolocated Earth radiances	Once per hour or more frequent (during daylight hours)	Beta
RADT	1b	Geolocated Earth radiances (twilight)	Variable	Beta
IRR	1b	Solar irradiance (working diffuser)	Once per week	Beta
IRRR	1b	Solar irradiance (reference diffuser)	Once per 3 months	Beta

Beta: “The product is minimally validated but may still contain significant errors;... publication of research based on Beta maturity products is not recommended and highly discouraged”

TEMPO Level 2 & Level 3 products

Product	Level(s)	Description	Most relevant variables in level 2 and level 3 file	Maturity level
NO₂	2 & 3	Nitrogen dioxide total, tropospheric, and stratospheric columns	vertical_column_troposphere, vertical_column_stratosphere	Beta
HCHO	2 & 3	Total formaldehyde columns	vertical_column	Beta
O3TOT	2 & 3	Total ozone columns	column_amount_o3	Beta
CLDO4	2 & 3	Cloud parameters	cloud_fraction, cloud_pressure	Beta

Level 2: Information provided at TEMPO's native resolution (hourly sampling frequency or less; ~10 km²); usually one hour East-West scan is broken in 9 to 10 level 2 files.

Level 3: All level 2 data from a TEMPO East-West scan on a regular grid (0.02° x 0.02°)

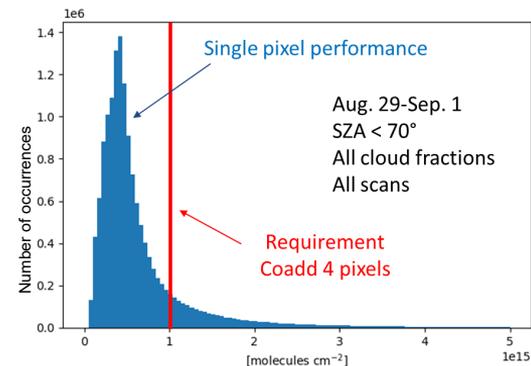
Level 2 product requirements

Product	Required precision	Temporal revisit*
0-2 km O ₃ (selected scenes)	10 ppbv	2 hour
Tropospheric O ₃	10 ppbv	1 hour
Total O ₃	3%	1 hour
Tropospheric NO ₂	1 x 10 ¹⁵ molecules cm ⁻²	1 hour
Tropospheric HCHO	1 x 10 ¹⁶ molecules cm ⁻²	3 hour

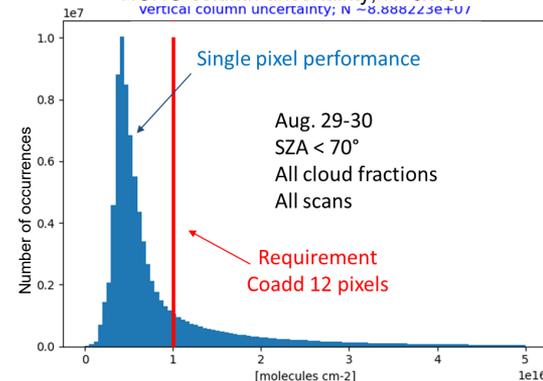
* number of hourly measurements to be averaged to achieve required precision

There are ongoing efforts to expand the suite of TEMPO operational products with aerosol information (AOD, layer height, UVAI) and traces gases (SO₂, CHOCHO, BrO, H₂O and HONO) in the near future.

NO₂ tropospheric column uncertainty; N~2x10⁷



HCHO column uncertainty; N~8x10⁷
vertical column uncertainty; N ~8.888223e+U

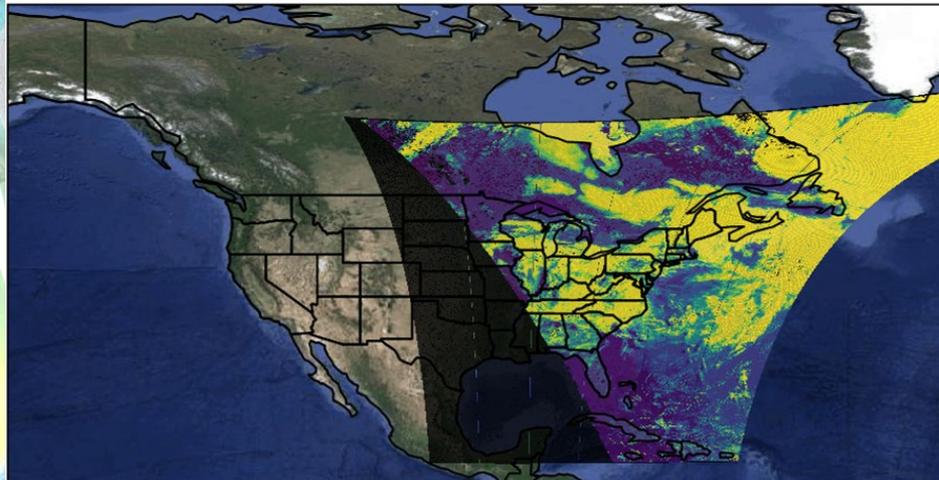


One day of HCHO retrievals: filtering data

To perform qualitative studies it is essential to perform quality control on the data; multiple variables in the level 2 and level 3 files (main_data_quality_flag, cloud_fraction, vertical_column_uncertainty, snow_ice_fraction...) provide suitable information to filter data depending on the user's application.

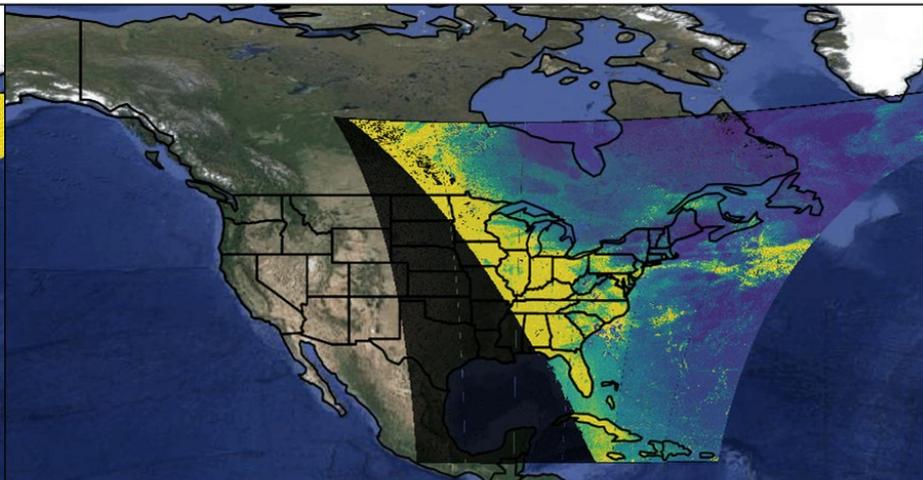
2024-05-09 10:41:07 to 2024-05-09 11:14:16; SCAN S001

2024-05-09 10:41:07 to 2024-05-09 11:14:16; SCAN S001



Basemap Google (c)

Cloud fraction

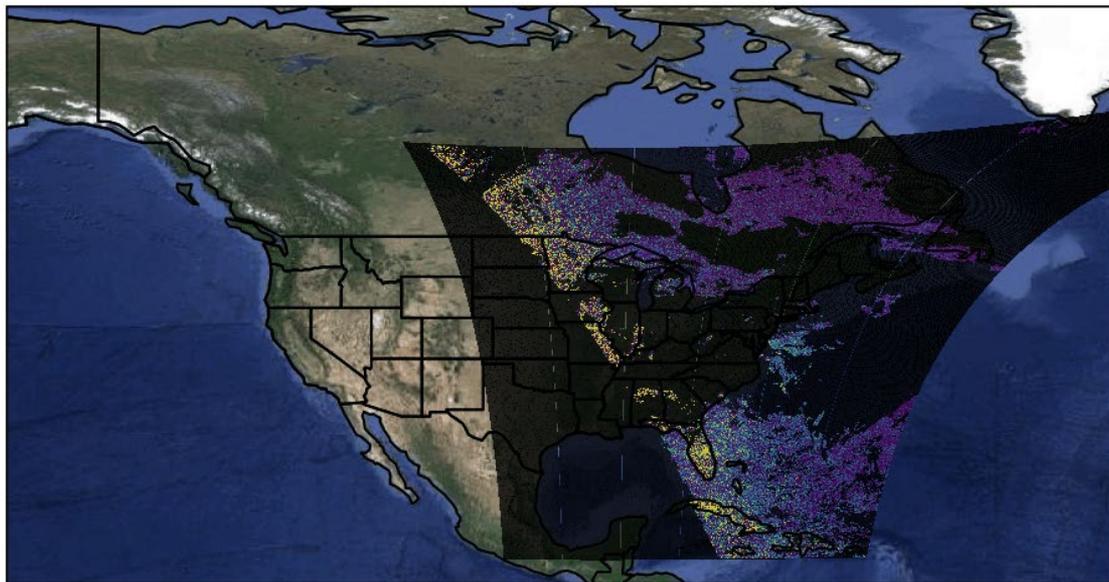


Basemap Google (c)

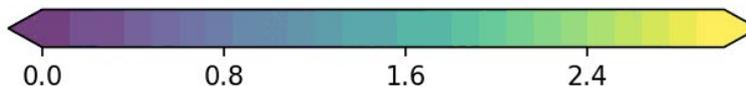
Vertical column uncertainty

One day of HCHO retrievals showing data only with cloud fraction < 0.25

2024-05-09 10:41:07 to 2024-05-09 11:14:16; SCAN S001



Basemap Google (c)



0.0

0.8

1.6

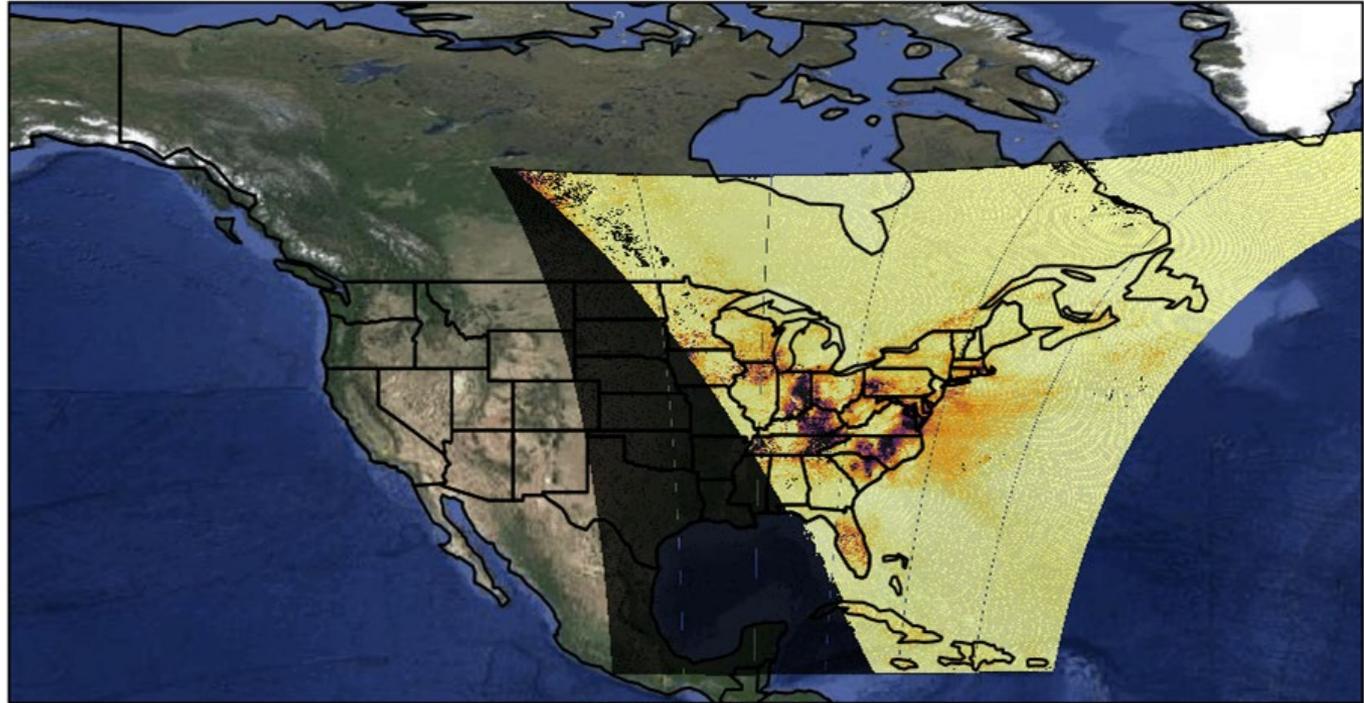
2.4

HCHO vertical column [molecules cm^{-2}]

10^{16}

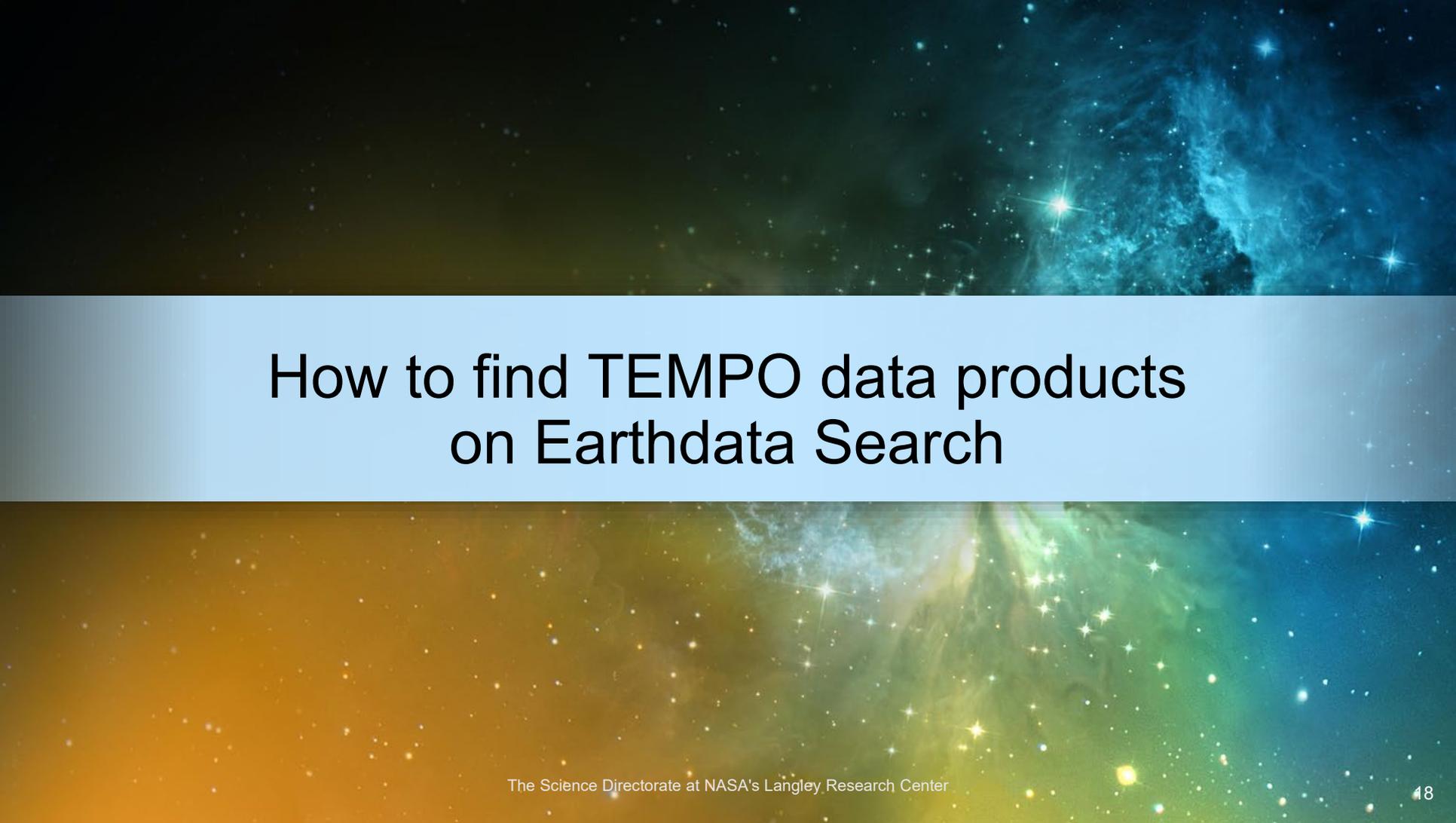
One day of NO₂ retrievals (unfiltered)

2024-05-09 10:41:07 to 2024-05-09 11:14:16; SCAN S001



Basemap Google (c)

As mentioned previously it is important to filter data using the criteria described in the user guides



How to find TEMPO data products on Earthdata Search

Summary

Navigate to Earthdata Search

The screenshot shows the Earthdata Search interface with a search bar at the top. Below the search bar, there are several filter collections on the left side, including 'Browse Panels', 'Filter Collections', 'Features', 'Available in Earthdata Cloud', 'Customizable', 'Map Imagery', 'Keywords', 'Platforms', 'Instruments', 'Organizations', 'Projects', 'Processing Levels', 'Data Format', 'Tiling System', 'Horizontal Data Resolution', 'Latency', and 'Additional Filters'. The main area displays search results for 'ATLASCESM-2 L1A Global Geostationary Photon Data V006' with details like '426,292 Granules' and '2016-10-13 imagery'. A map of the globe is visible in the background.

search.earthdata.nasa.gov/

Dataset details

The screenshot shows the 'Dataset details' page for 'TEMPO gridded NO2 tropospheric and stratospheric column V03 (BETA)'. The page includes a search bar, a list of granules with columns for 'Granule ID', 'Start Time', 'End Time', and 'Status'. A map of the globe is shown in the background, and there are sections for 'About this dataset' and 'For Developers'.

Log in

The screenshot shows the Earthdata Login page. It features a 'Username' field, a 'Password' field, and 'LOG IN' and 'REGISTER' buttons. A 'Remember me' checkbox is also present. A sidebar on the right contains the text: 'Why must I register? The Earthdata Login provides a single mechanism for user registration and profile management for all EOSDIS system components (DAACs, Tools, Services). Your Earthdata Login also helps the EOSDIS program better understand the usage of EOSDIS services to improve user experience through customization of tools and improvements of services. EOSDIS data are openly available to all and free of charge except where governed by international agreements.' At the bottom, there is a link: 'Get single sign-on access to all your favorite EOSDIS sites' and a 'REGISTER FOR A PROFILE' button.

Search and filter

The screenshot shows the filter sidebar on the Earthdata Search page. It includes a 'Filter Collections' section with a search bar and a 'INST. TEMPO' button. Below this, there are sections for 'Features', 'Keywords', 'Platforms', 'Instruments' (with a '1 Selected' badge), 'Organizations', 'Projects', 'Processing Levels', and 'Data Format'. Each section has a list of filter options with checkboxes and counts.

Customizing the download or access

The screenshot shows the 'Download options' dialog box in Earthdata Search. It has two main sections: '1 Choose how you want to download your data' and '2 Select a service and customize options'. The first section has radio buttons for 'Customize with Harmony' (selected), 'Download all data', and 'Direct download of all selected data'. The second section has a 'Service' dropdown menu. At the bottom, there is a 'Select a data access method for each collection in your request before downloading.' section with a 'Download All' button and a 'Cancel' button.



Demonstration

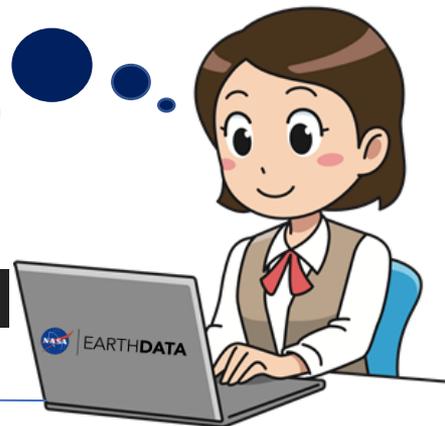
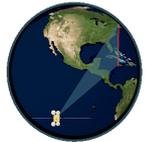
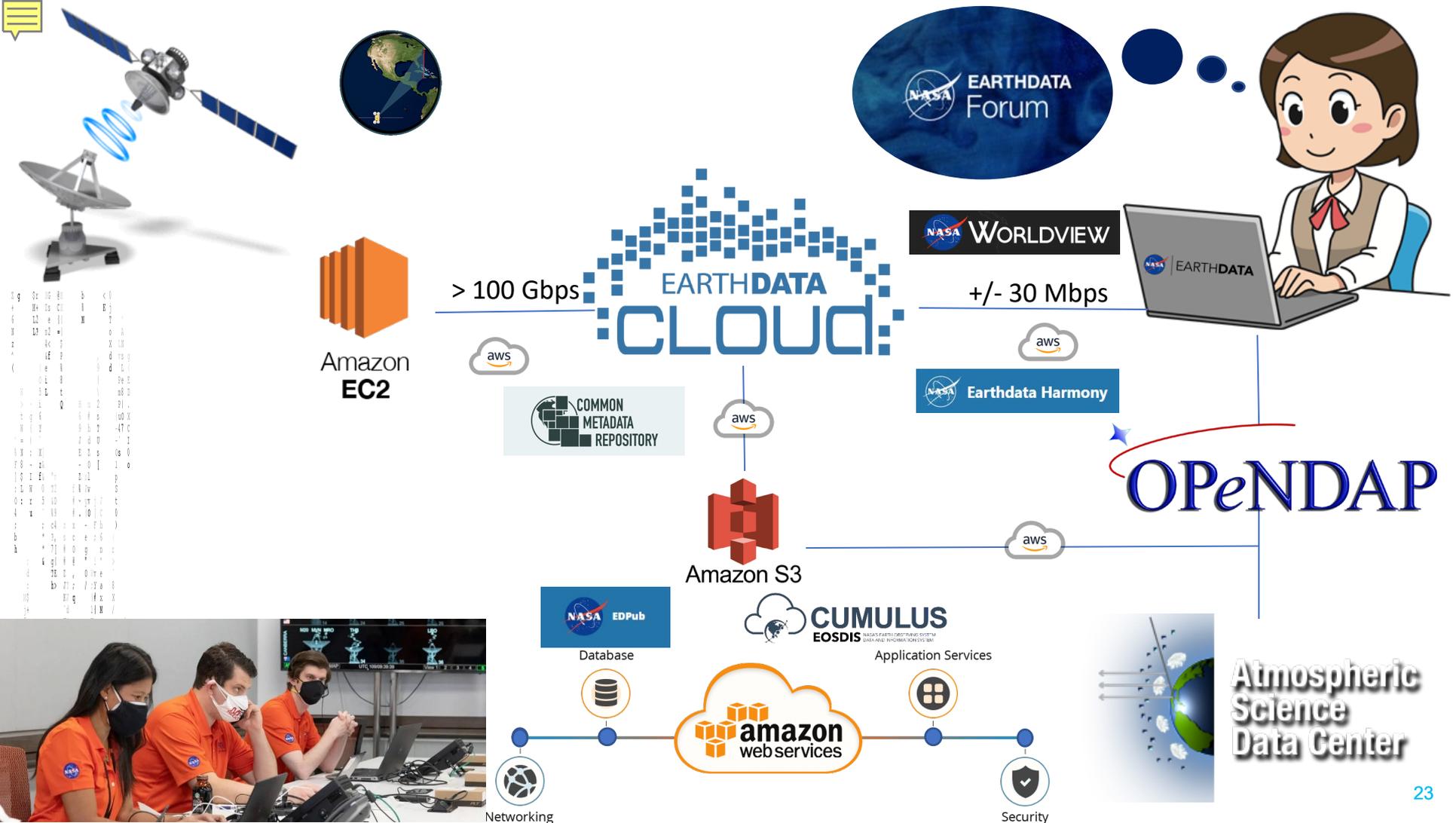


Demonstration Links - for reference

- **Earthdata Search:** <https://search.earthdata.nasa.gov>
- **TEMPO Project landing page:** <https://asdc.larc.nasa.gov/project/TEMPO>
- **NASA Earthdata Cloud information:** <https://www.earthdata.nasa.gov/eosdis/cloud-evolution>
- **NASA CMR STAC API tutorial:** https://nasa-openscapes.github.io/2021-Cloud-Hackathon/tutorials/02_Data_Discovery_CMR-STAC_API.html
- **Panoply**
<https://www.giss.nasa.gov/tools/panoply/>



TEMPO Resources at ASDC



> 100 Gbps

EARTHDATA
CLOUD



+/- 30 Mbps



OPeNDAP



Amazon S3



Database



Application Services



Networking



Security



**Atmospheric
Science
Data Center**



Earthdata Forum

Science Data Users can seamlessly search for information even if they do not know which DAAC the data belongs to.

Scientists & Data Providers can effectively assist their user community in more accurately using their products.

DAACs & Subject Matter Experts (SMEs) can quickly link users to existing resources.

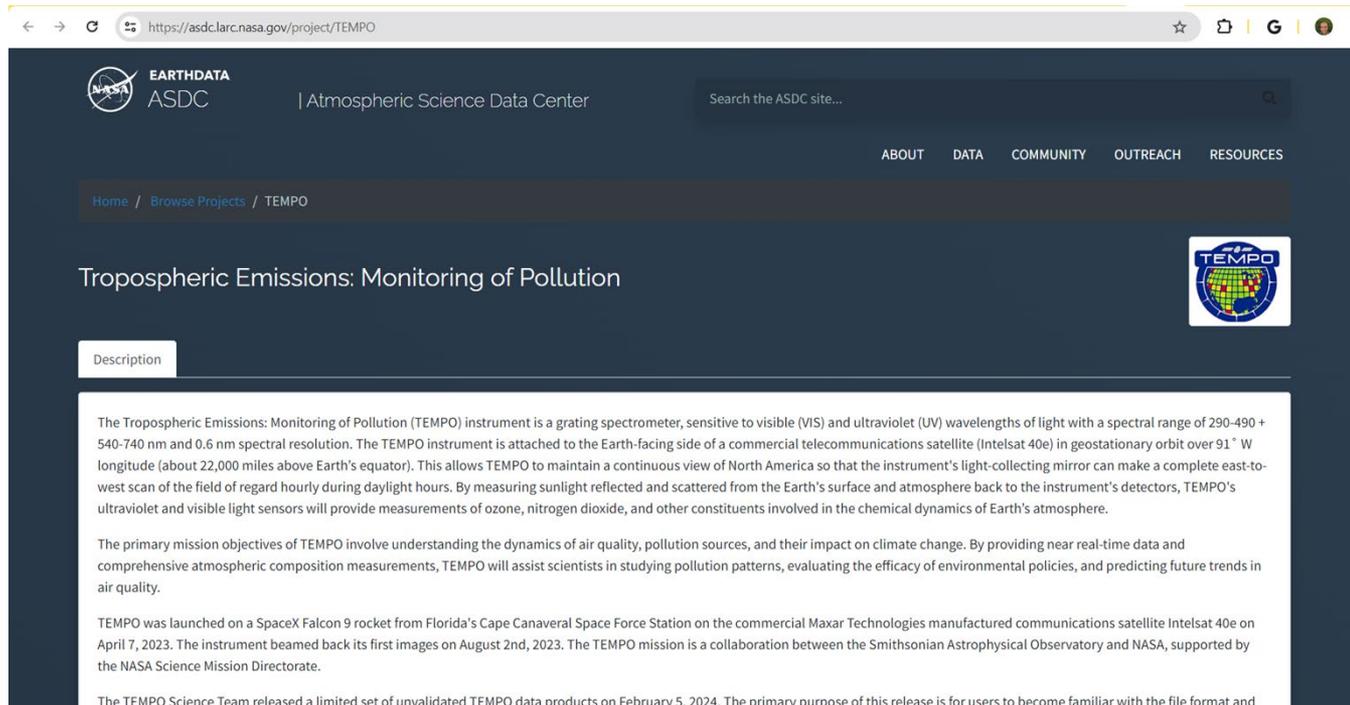
DAAC User Services can swiftly provide inquirers with an authoritative source related to DAAC data products & services.

The screenshot shows the Earthdata Forum website. At the top, there is a navigation bar with the EarthData logo, a search bar for DAACs, and a feedback icon. Below the navigation bar is a header section with the NASA logo and the text "EARTHDATA Forum BETA". A welcome message follows: "Welcome to the Earthdata User Forum! Here, subject matter experts from several NASA Distributed Active Archive Centers (DAAC) can discuss general questions, research needs and data applications. Users can query how to access, view and interpret the data." Below this is a secondary navigation bar with links for "Quick links", "FAQ", "Data Recipes", and a "Login" button. A "Home" link is also present. The main content area shows the current date and time: "It is currently Fri Feb 21, 2020 1:51 pm America/New_York". There is a "Post a New Question" button. Below that is a "SEARCH" section with a search input field and an "Advanced Search" link. An "OR" separator follows. The "SEARCH BY TAGS" section contains four dropdown menus for "Discipline", "DAAC", "Major Projects", and "Services/Usage", each with a "Select" option, and a "Submit" button. A link "What do these tags mean?" is at the bottom right of this section. Another "OR" separator follows. The "FORUM" section is a table with columns for "FORUM", "QUESTIONS", "POSTS", and "LAST POST".

FORUM	QUESTIONS	POSTS	LAST POST
 All Questions/Comments Please enter here to ask a question about any NASA Science related topics!	215	452	Where can I find more FAQs fr... by GES DISC - zliu  Fri Feb 21, 2020 10:18 am America/New_York

<https://forum.earthdata.nasa.gov/>

ASDC Webpage



The screenshot shows a web browser window with the URL <https://asdc.larc.nasa.gov/project/TEMPO>. The page header includes the NASA EarthData ASDC logo and the text "Atmospheric Science Data Center". A search bar is located in the top right corner. A navigation menu contains links for "ABOUT", "DATA", "COMMUNITY", "OUTREACH", and "RESOURCES". The breadcrumb trail reads "Home / Browse Projects / TEMPO". The main heading is "Tropospheric Emissions: Monitoring of Pollution", accompanied by the TEMPO logo. A "Description" tab is active, displaying the following text:

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument is a grating spectrometer, sensitive to visible (VIS) and ultraviolet (UV) wavelengths of light with a spectral range of 290-490 + 540-740 nm and 0.6 nm spectral resolution. The TEMPO instrument is attached to the Earth-facing side of a commercial telecommunications satellite (Intelsat 40e) in geostationary orbit over 91° W longitude (about 22,000 miles above Earth's equator). This allows TEMPO to maintain a continuous view of North America so that the instrument's light-collecting mirror can make a complete east-to-west scan of the field of regard hourly during daylight hours. By measuring sunlight reflected and scattered from the Earth's surface and atmosphere back to the instrument's detectors, TEMPO's ultraviolet and visible light sensors will provide measurements of ozone, nitrogen dioxide, and other constituents involved in the chemical dynamics of Earth's atmosphere.

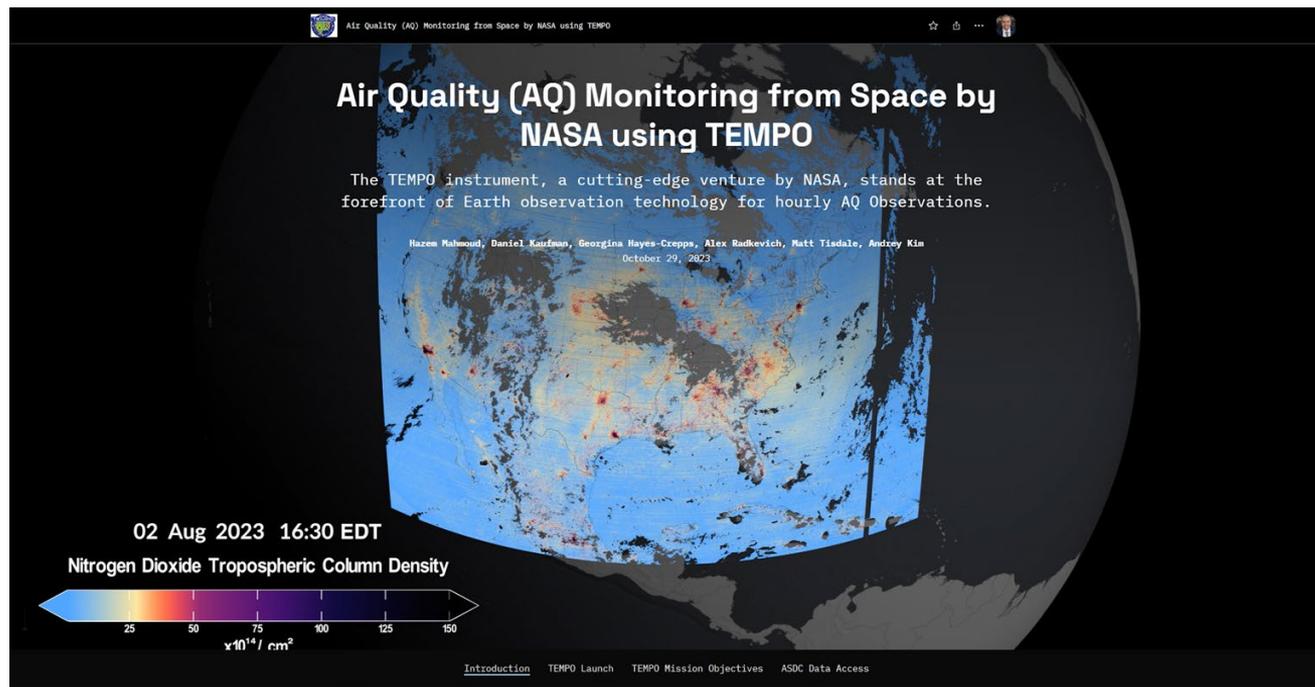
The primary mission objectives of TEMPO involve understanding the dynamics of air quality, pollution sources, and their impact on climate change. By providing near real-time data and comprehensive atmospheric composition measurements, TEMPO will assist scientists in studying pollution patterns, evaluating the efficacy of environmental policies, and predicting future trends in air quality.

TEMPO was launched on a SpaceX Falcon 9 rocket from Florida's Cape Canaveral Space Force Station on the commercial Maxar Technologies manufactured communications satellite Intelsat 40e on April 7, 2023. The instrument beamed back its first images on August 2nd, 2023. The TEMPO mission is a collaboration between the Smithsonian Astrophysical Observatory and NASA, supported by the NASA Science Mission Directorate.

The TEMPO Science Team released a limited set of unvalidated TEMPO data products on February 5, 2024. The primary purpose of this release is for users to become familiar with the file format and

<https://asdc.larc.nasa.gov/project/TEMPO>

TEMPO Storymap





Atmospheric Science Data Center
NASA Langley Research Center
Hampton, Virginia (USA)
<https://asdc.larc.nasa.gov/>
support-asdc@earthdata.nasa.gov