

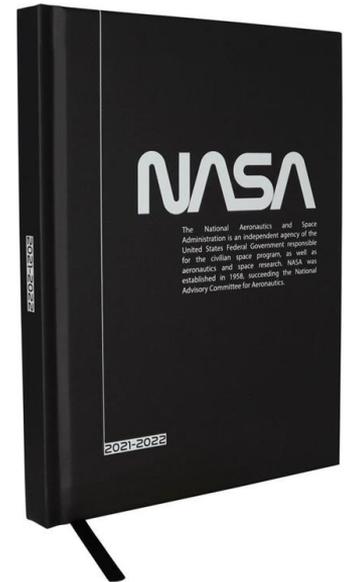


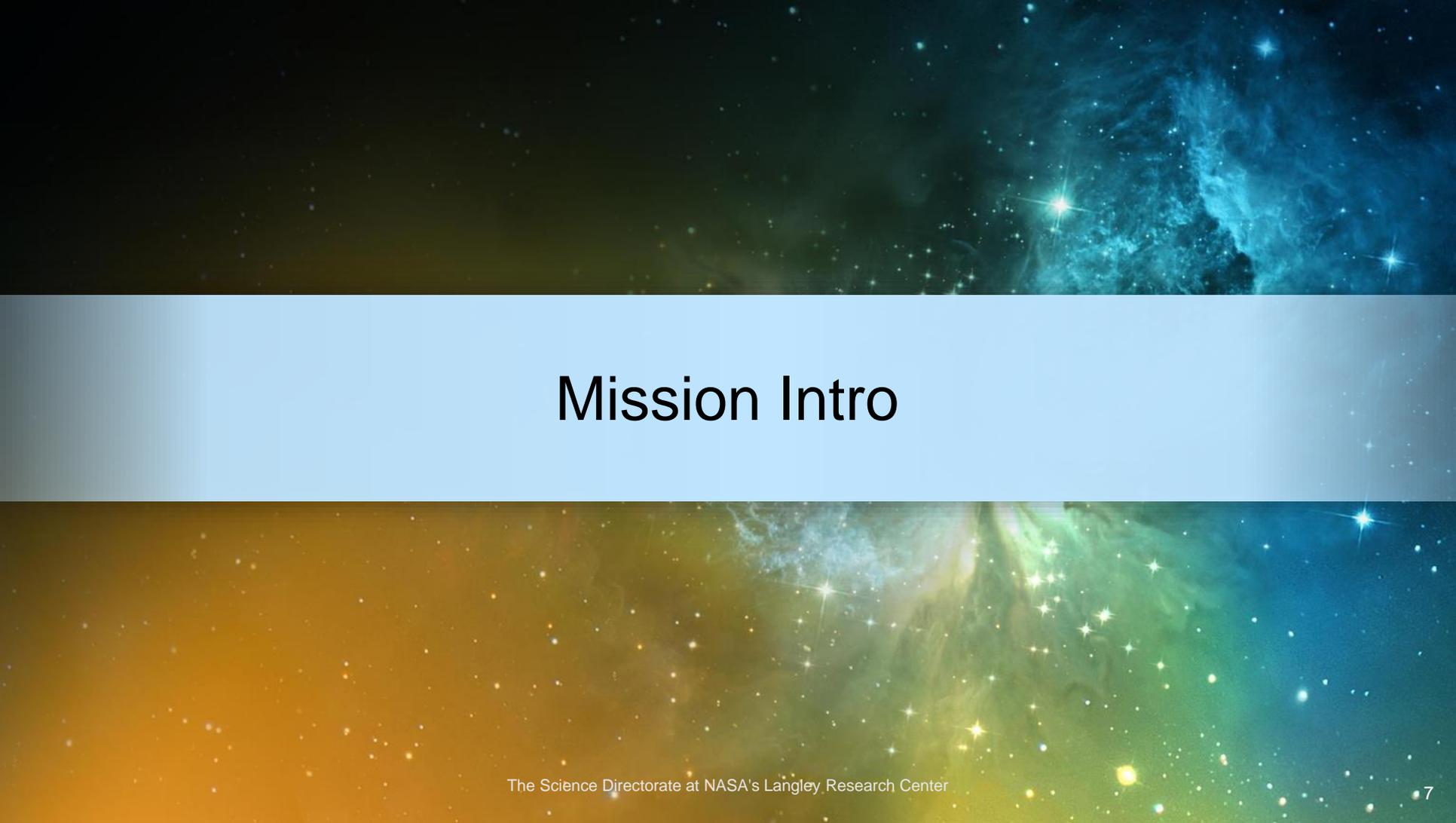
Finding your TEMPO: An introduction to the mission, products, and data services for air quality observations over N. America

Caroline Nowlan, Center for Astrophysics
Gonzalo González Abad, Center for Astrophysics
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, glowing blue nebula on the right side. The bottom half shows a similar starry field but with a warm, golden-yellow and greenish glow, suggesting a different spectral filter or a different region of space. The text 'Mission Intro' is centered in a white, sans-serif font across the middle of the slide.

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



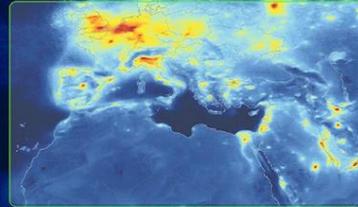
Credit: NASA's Scientific Visualization Studio

Atmospheric Composition Geostationary Constellation

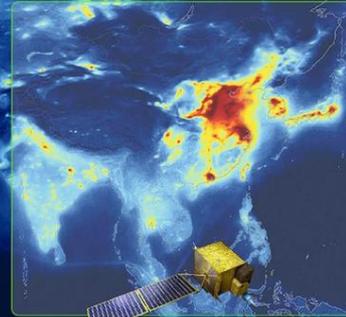
TEMPO (hourly)
Tropospheric Emissions:
Monitoring of Pollution



Sentinel-4 (hourly)



GEMS (hourly)
Geostationary Environmental
Monitoring Spectrometer



Sentinel-5P (once per day)



GaoFen-5 (once per day)





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



Multiple partners, 600+ early adopters

MAXAR
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	Mid-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)

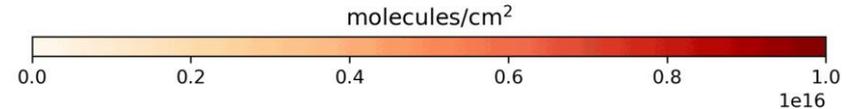
Twilight scans (city lights)

- 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

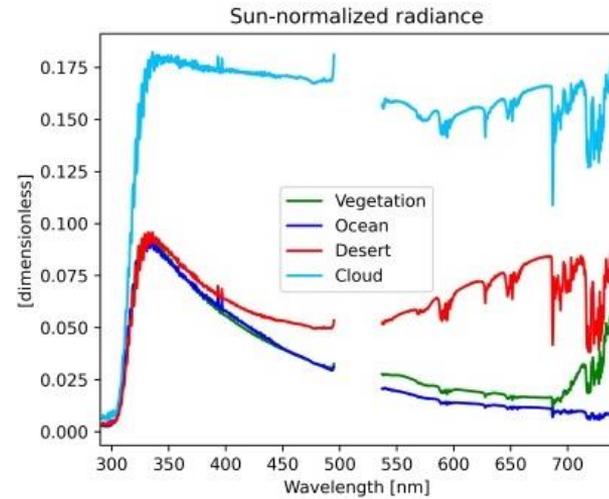
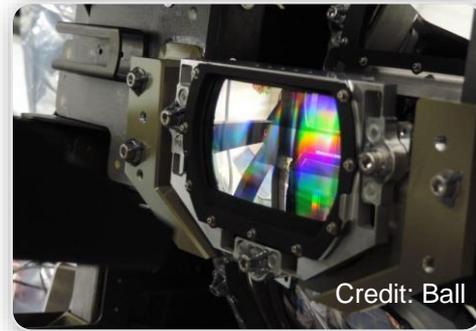
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2023 TerraMetrics

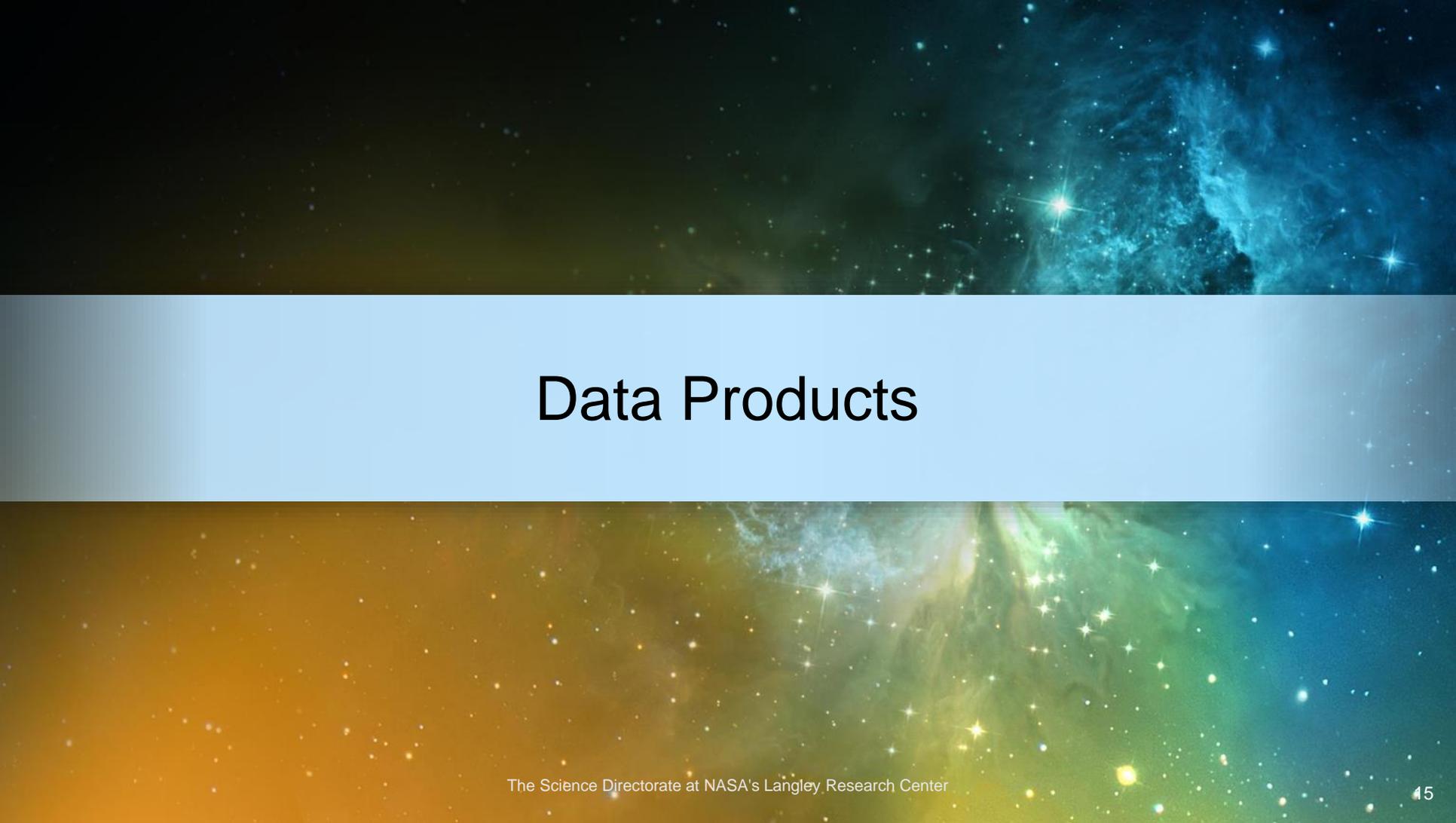
20 km



13

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.

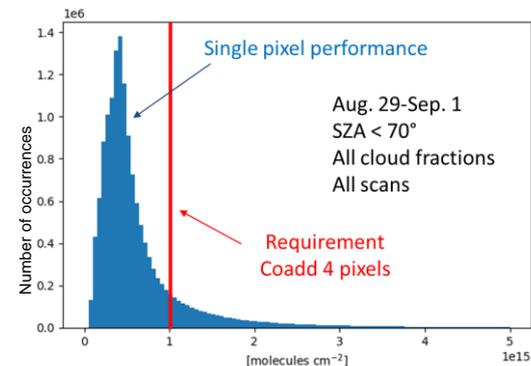
Level 3: All level 2 data from a TEMPO East-West scan on a regular grid (0.02° x 0.02°)

Level 2 product requirements

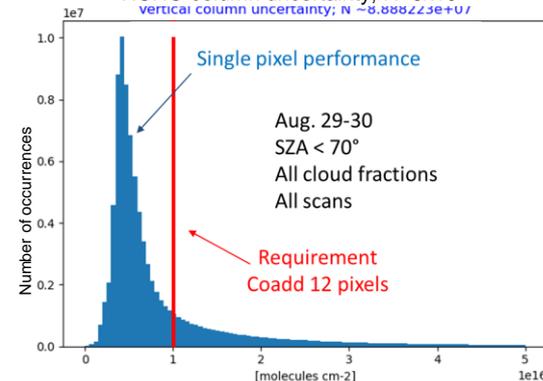
Product	Required precision	Temporal revisit*
0-2 km O ₃ (selected scenes)	10 ppbv	2 hour
Tropospheric O ₃	10 ppbv	1 hour
Total O ₃	3%	1 hour
Tropospheric NO ₂	1 x 10 ¹⁵ molecules cm ⁻²	1 hour
Tropospheric HCHO	1 x 10 ¹⁶ molecules cm ⁻²	3 hour

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

NO₂ tropospheric column uncertainty; N~2x10⁷



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



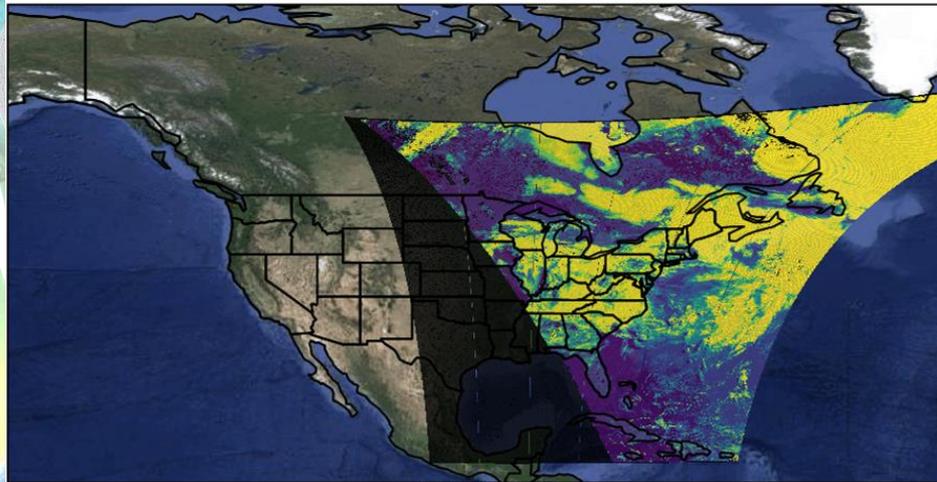
There are ongoing efforts to expand the suite of TEMPO operational products with aerosol information (AOD, layer height, UVAI) and traces gases (SO₂, CHOCHO, BrO, H₂O and HONO) in the near future.

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.

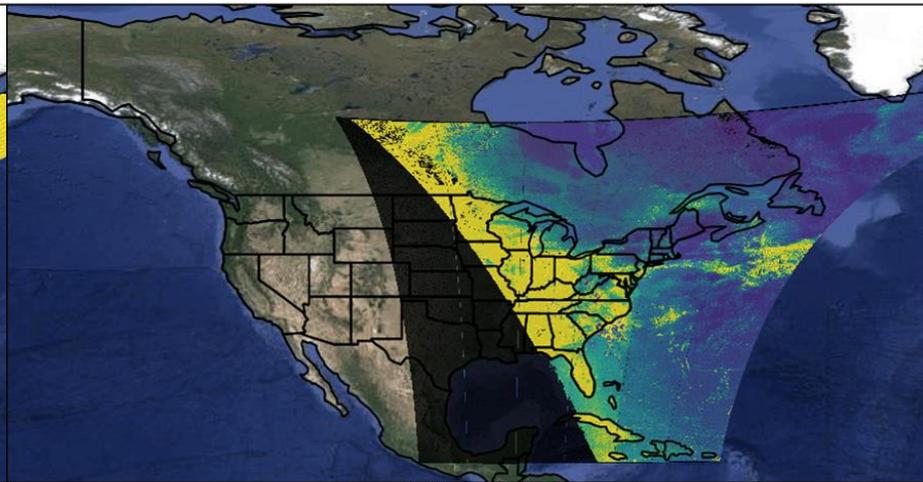
2024-05-09 10:41:07 to 2024-05-09 11:14:16; SCAN S001

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



Basemap Google (c)

Cloud fraction

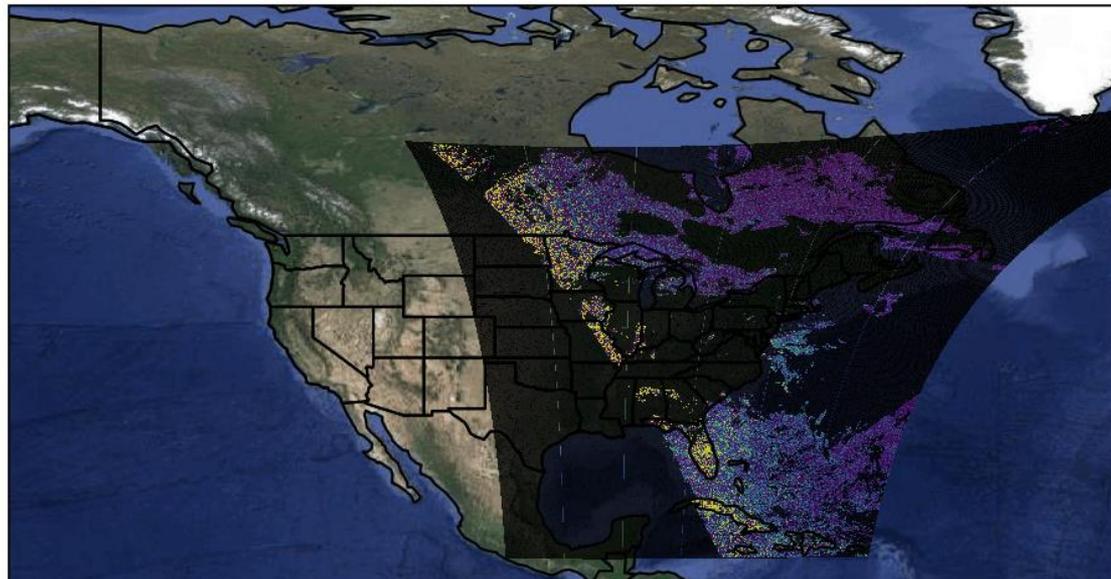


Basemap Google (c)

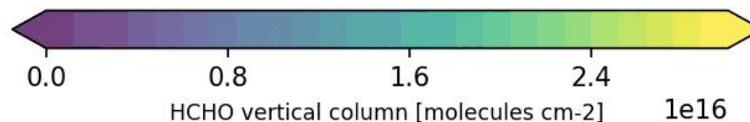
Vertical column uncertainty

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



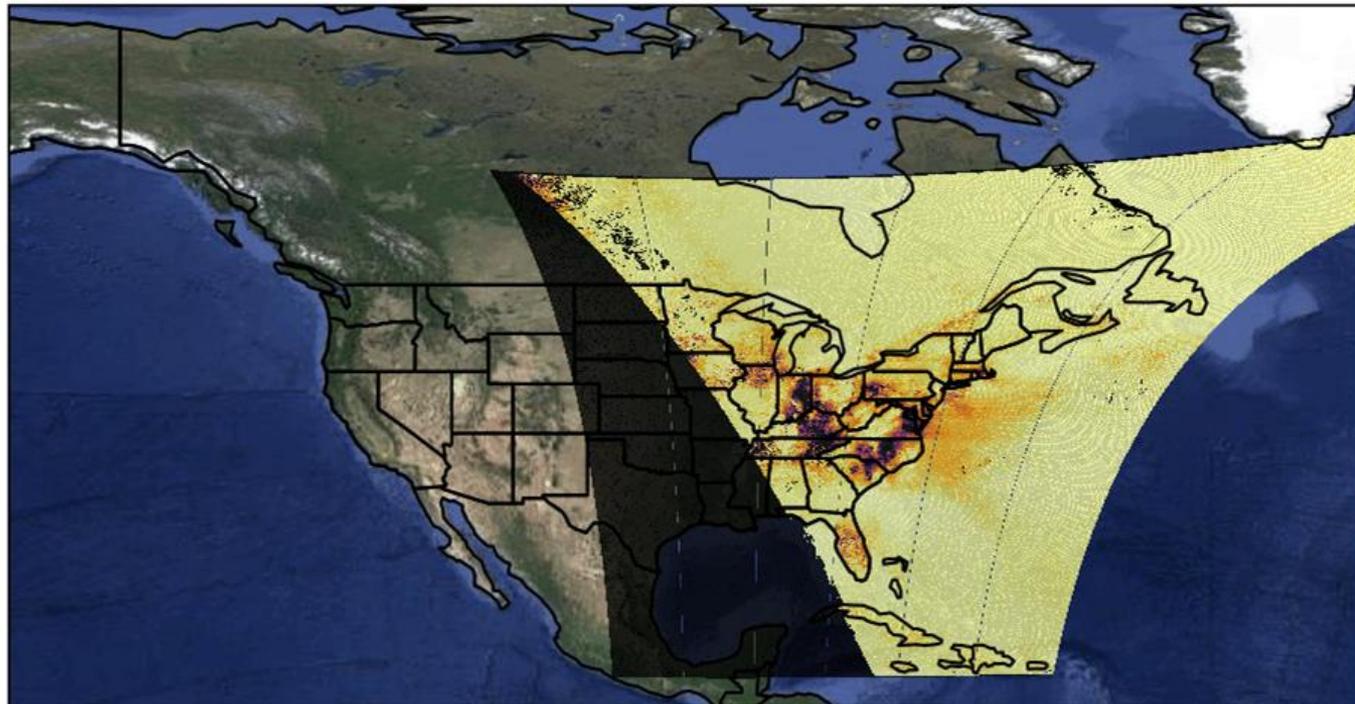
Basemap Google (c)



The Science Directorate at NASA's Langley Research Center

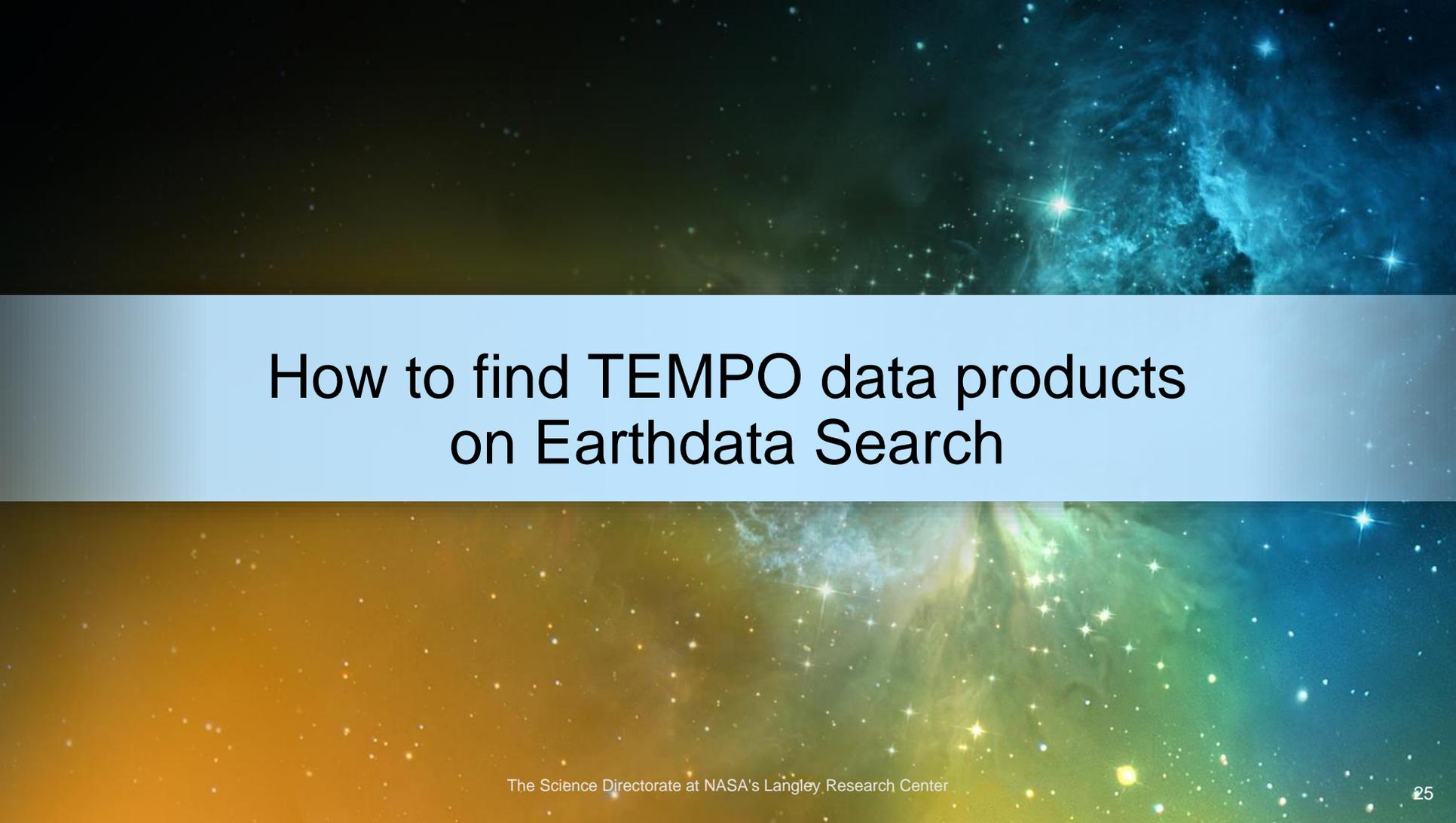
One day of NO₂ retrievals (unfiltered)

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



Basemap Google (c)

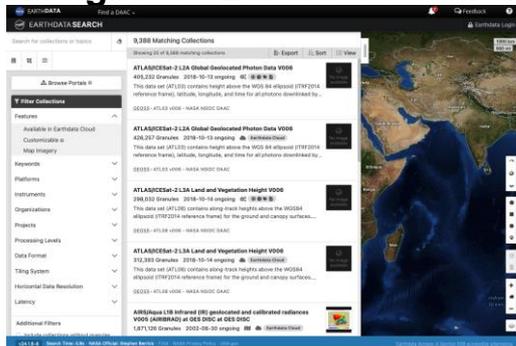
As mentioned previously it is important to filter data using the criteria described in the user guides



How to find TEMPO data products on Earthdata Search

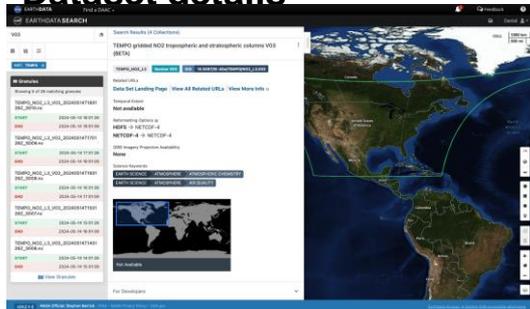
Summary

Navigate to Earthdata Search

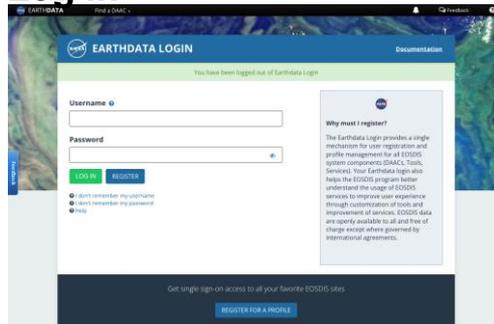


search.earthdata.nasa.gov/

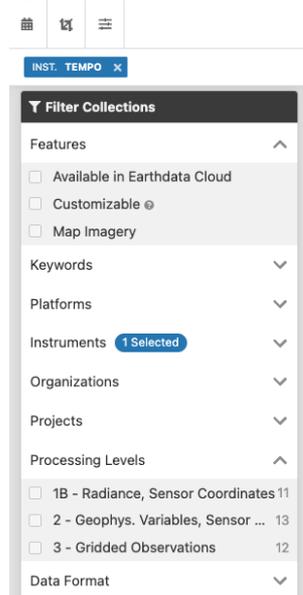
Dataset details



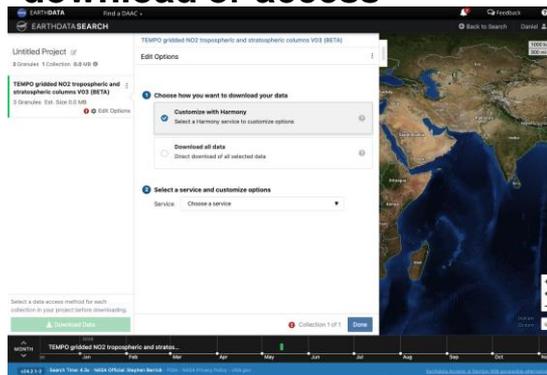
Log in



Search and filter



Customizing the download or access





Demonstration

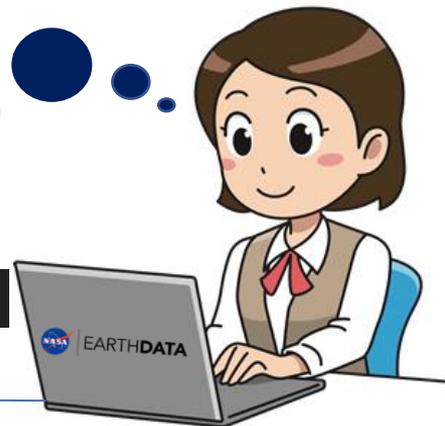
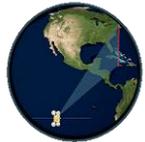


Demonstration Links - for reference

- **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



```
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100
```



> 100 Gbps

EARTHDATA
CLOUD



+/- 30 Mbps



-SAMBAA
-HOSS



Amazon S3

OPeNDAP



Database



CUMULUS
EOSDS

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.

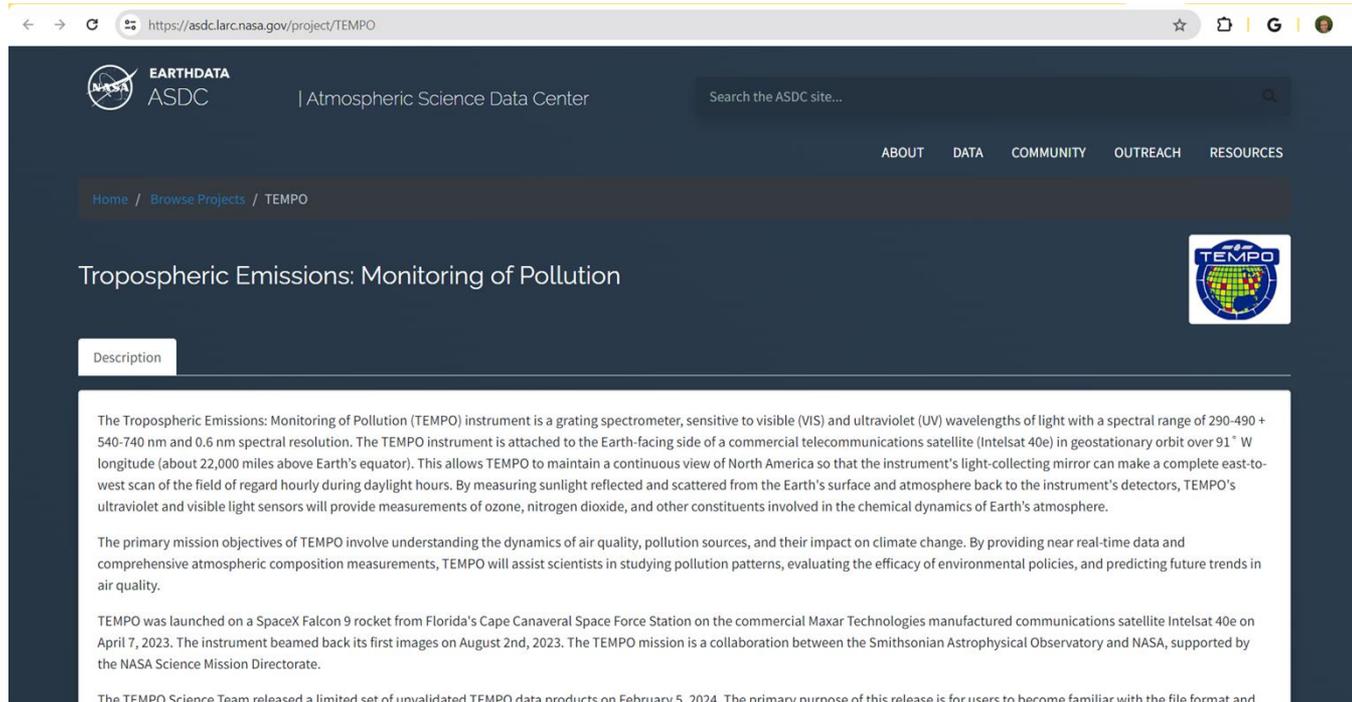
DAAC User Services can swiftly provide inquirers with an authoritative source related to DAAC data products & services.

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 the header is a blue 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 this is a search section with a search bar and an "Advanced Search" link. An "OR" separator is followed by a "SEARCH BY TAGS" section with four dropdown menus for "Discipline", "DAAC", "Major Projects", and "Services/Usage", each with a "Select" option. A "Submit" button is below the dropdowns, and a link "What do these tags mean?" is at the bottom right. Another "OR" separator is followed by a "FORUM" section with a table of forum posts.

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



← → ↻ <https://asdc.larc.nasa.gov/project/TEMPO> ☆ 🏠 G 🌐 ⋮

 | Atmospheric Science Data Center

ABOUT DATA COMMUNITY OUTREACH RESOURCES

[Home](#) / [Browse Projects](#) / TEMPO

Tropospheric Emissions: Monitoring of Pollution

Description

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.

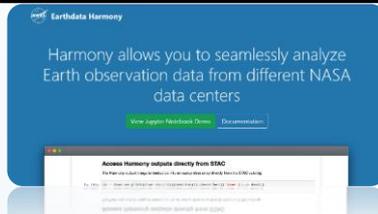
The TEMPO Science Team released a limited set of unvalidated TEMPO data products on February 5, 2024. The primary purpose of this release is for users to become familiar with the file format and

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

Additional Resources

Harmony Services

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



Worldview

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



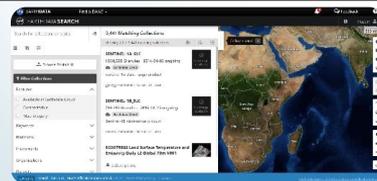
Earthdata GIS EGIS

<https://gis.earthdata.nasa.gov/portal/>



Earthdata Search

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



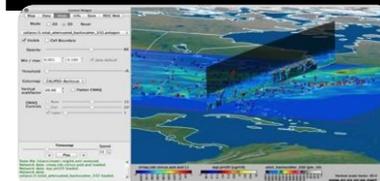
OPeNDAP

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

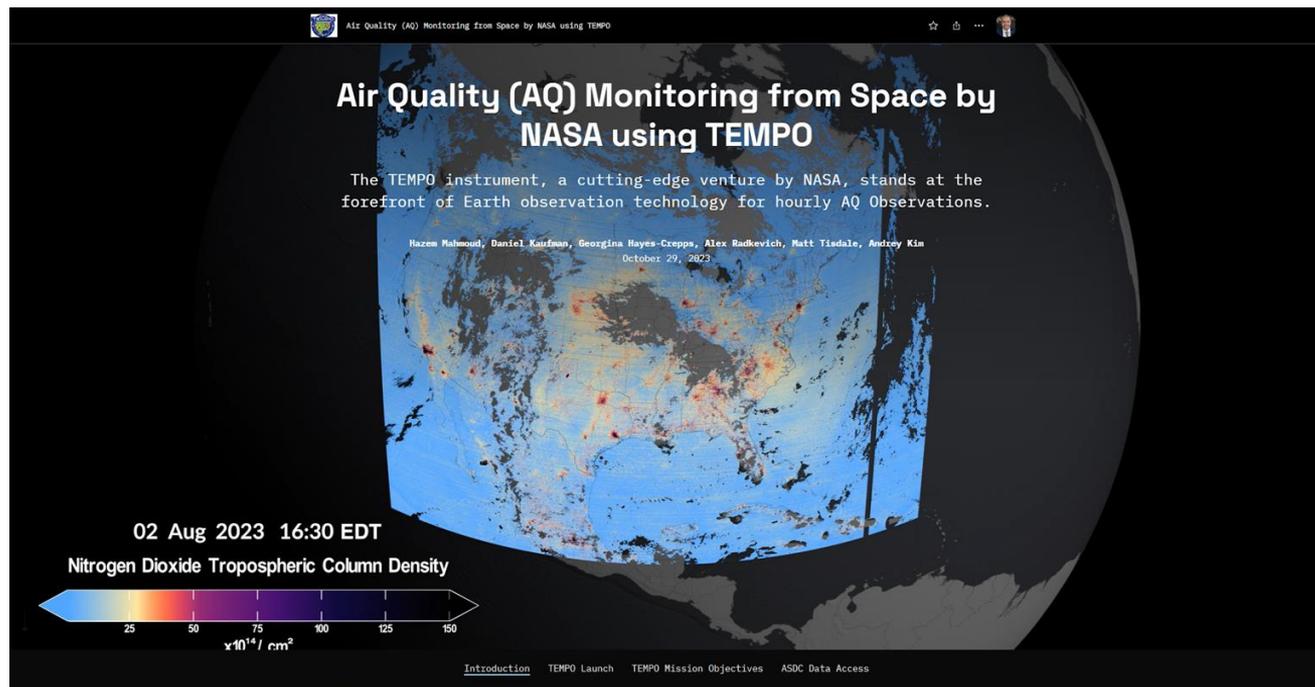


Remote Sensing Information Gateway

<https://www.epa.gov/hesc/rsig3d-data-inventory>



TEMPO Storymap





Atmospheric Science Data Center

NASA Langley Research Center
Hampton, Virginia (USA)

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

support-asdc@earthdata.nasa.gov

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 stars and a prominent, glowing blue nebula on the right side. The bottom half shows a similar starry field but with a vibrant green and yellow nebula on the right, transitioning into a golden-brown glow on the left. The text "Extra Slides Follow" is centered in a white, sans-serif font across the middle of the slide.

Extra Slides Follow

Daily Log

[TEMPO nominal-operation data-products daily log - Google Docs](#)

•(<http://github.com/JeanFitzmaurice/TEMPO-Observation-Log>)

TEMPO Daily Log during Nominal Operation (10/17/2023-present)

Jean Fitzmaurice, John Houck, Xiong Liu

Last updated on 3/21/2024

Date	Log
10/17/2023	SDPC v4.1 operational processing started (9 hrs)
10/18/2023	Frequent data dropouts (missing data), INR might fail and no subsequent data products
10/19/2023	Solar cal Working Diffuser (WD) Frequent data dropouts (missing data), INR might fail and no subsequent data products
10/20/2023	Frequent data dropouts (missing data), INR might fail and no subsequent data products
10/21/2023	Frequent data dropouts (missing data), INR might fail and no subsequent data products
10/23/2023	Some data dropout
10/26/2023	Solar cal WD
10/29/2023	Bad INR almost all day (no L2 data products) (R2.3.8 restart issue), will be reprocessed later with SDPC v4.2.



Additional Resources

- Point to programmatic access tools (ASDC GitHub, earthaccess, Harmony-py)
- Opendap access
- Worldview GIBS
- Imagery in AGOL
- Training, tutorials, storymap, rsig to share



Questions?

A large graphic on the left side of the slide depicts a space scene. It features a bright sun in the lower left, a blue and white Earth in the bottom foreground, and several other celestial bodies including a ringed planet (Saturn), a reddish planet (Mars), and a grey planet (Moon) in the background. A vibrant blue and green nebula is visible in the upper right. A white curved line separates the graphic from the text area.

deadlines

Webinar Date: 05/29/24 2pm EDT

Presenter Training: April 29 through May 3, 2024

First Dry Run- Week of May 13-17,2024

Second Dry Run- Week of May 20-24,2024

05/02/24:

- Agenda,
- Webinar banner imagery,
- Title and Talk Abstract,
- Name, professional title, bio, and photo(s) of the speaker(s)

05/09/24: List of invitees

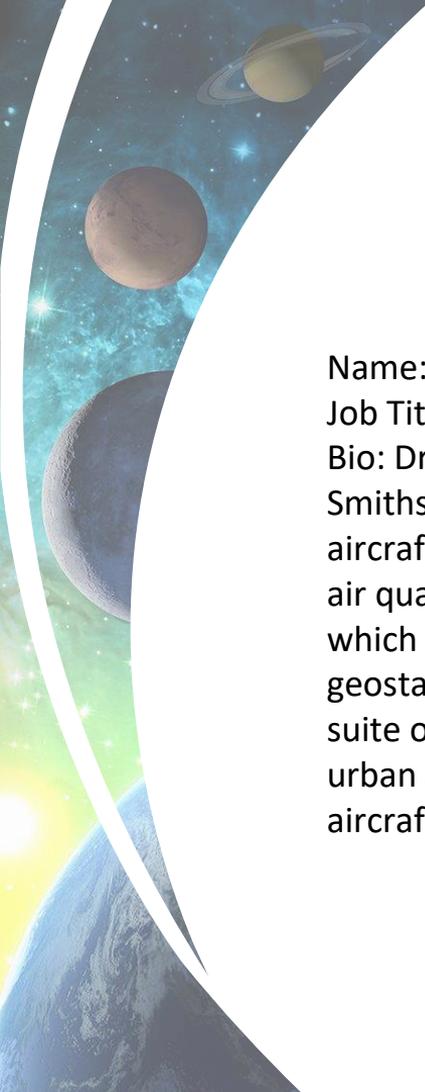
05/24/24: Polling questions (short answer, multiple choice, multiple answer)

Hazem Mahmoud

Science Lead at NASA LaRC ASDC ADNET



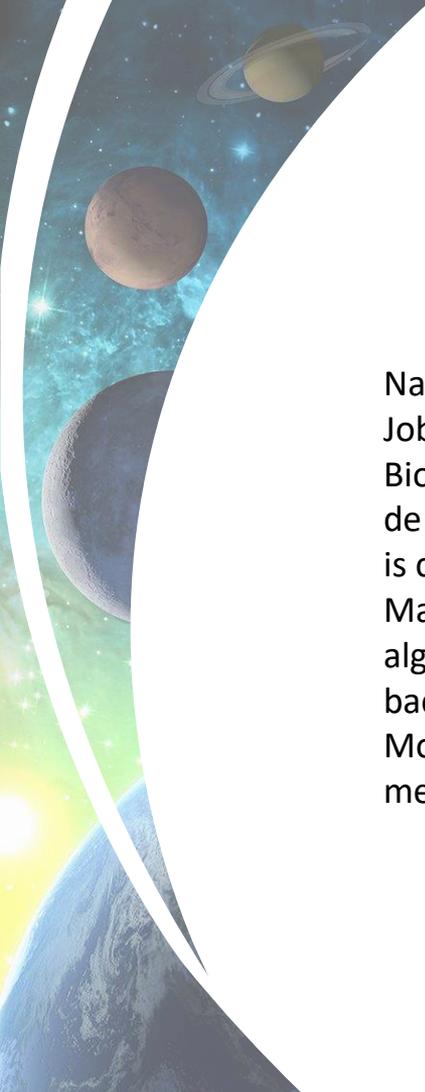
Bio: Dr. Hazem Mahmoud, the DAAC Scientist at the Atmospheric Science Data Center, brings a wealth of expertise in geophysics and environmental engineering to his role. His primary focus lies in utilizing both orbital and suborbital instruments for remote sensing of the Earth's atmosphere. Dr. Hazem specializes in analyzing radiation budget, cloud formations, aerosol distribution, and tropospheric composition. His ultimate goal is to achieve near real-time air quality monitoring from space and study the impact of the air we breathe on our health. His passion for this field ignited when he confronted the challenge of limited Earth data availability early in his career, compelling him to dedicate his research to remote sensing applications. He firmly advocates for the integration of remote sensing data into scientific endeavors, believing it to be a crucial step in advancing global research efforts.



Name: Caroline Nowlan

Job Title: Atmospheric Physicist / Center for Astrophysics | Harvard & Smithsonian

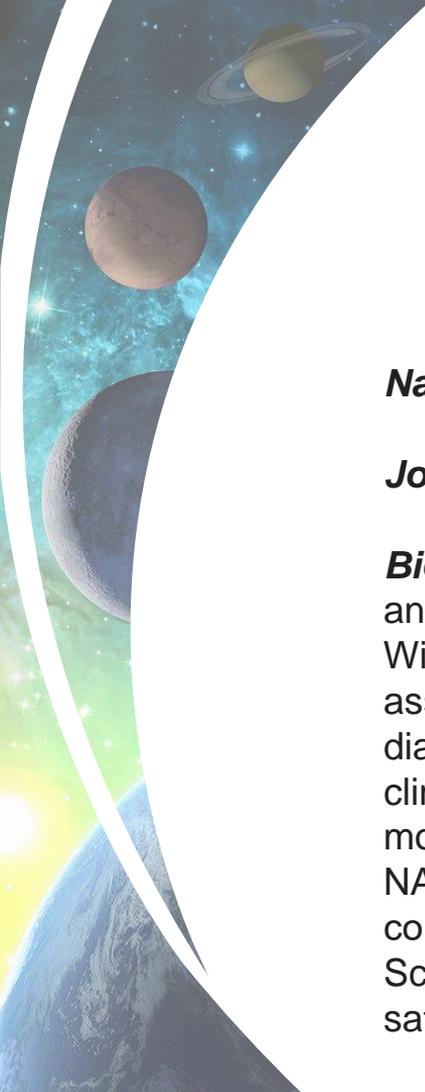
Bio: Dr. Caroline Nowlan is an atmospheric physicist at the Center for Astrophysics | Harvard & Smithsonian, where she works on remote sensing of the Earth's atmosphere using satellite and aircraft instruments. She is a member of the team leading the Smithsonian/NASA next-generation air quality monitoring instrument TEMPO (Tropospheric Emissions: Monitoring of Pollution), which recently began making measurements of air pollutants over North America from geostationary orbit. Dr. Nowlan is also responsible for global formaldehyde measurements from a suite of NASA/NOAA satellite instruments, and has been an investigator on projects examining urban air pollution in the U.S. and South Korea using remote sensing of the atmosphere from aircraft. She holds a Ph.D. in physics from the University of Toronto.



Name: Gonzalo Gonzalez Abad

Job Title: Atmospheric Physicist / Center for Astrophysics | Harvard & Smithsonian

Bio: Gonzalo Gonzalez Abad received his B. Sc. degree in physics in 2008 from the Universidad de Valencia, Spain and a Ph.D. in Chemistry from the University of York, York, UK in 2012. He is currently a physicist at the Center for Astrophysics | Harvard & Smithsonian, in Cambridge, Massachusetts, USA. His main research interest is the development of trace gas retrieval algorithms applicable to observations by space-borne ultraviolet and visible solar light backscattered spectrometers. He leads the development of Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument formaldehyde retrievals and is a member of the Atmospheric Composition Instrument (ACX) science team.



Name: Daniel Kaufman

Job Title / Affiliation: ASDC TEMPO Lead Data Scientist / Booz Allen Hamilton

Bio: Dr. Daniel Kaufman received his B.Sc. in physics from the University of Maryland and a Ph.D. in Marine Science at the Virginia Institute of Marine Science, College of William and Mary. Daniel's research and data science work has included analyses and assimilation of biogeophysical data from autonomous ocean gliders, formulating diagnostics of atmospheric carbon dioxide concentrations as simulated in global climate models, and the development of a large-scale mathematical optimization model and decision support tool for watershed pollution management. Daniel supports NASA's Atmospheric Science Data Center (ASDC) as one of the center points of contact for TEMPO, serves as a Center Champion for NASA's Transform to Open Science (TOPS) initiative, and co-develops tools that provide user-friendly access to satellite-based atmospheric science data.

TEMPO Resources at ASDC

- (~5 min)
 - Data pages
 - Data log
 - <https://asdc.larc.nasa.gov/project/TEMPO>
 - https://docs.google.com/document/d/1X06_F2FjVGgwad3Ya70_GSxbpausgak04_M8bUYkiO0/edit
 - <https://storymaps.arcgis.com/stories/01e82aefbc8b4d7a951fe089c818bc0c>

