

Credit: TROPOMI, ESA, Copernicus, KNMI

# Introducing TROPOMI - High Resolution NO<sub>2</sub> Observations from Space

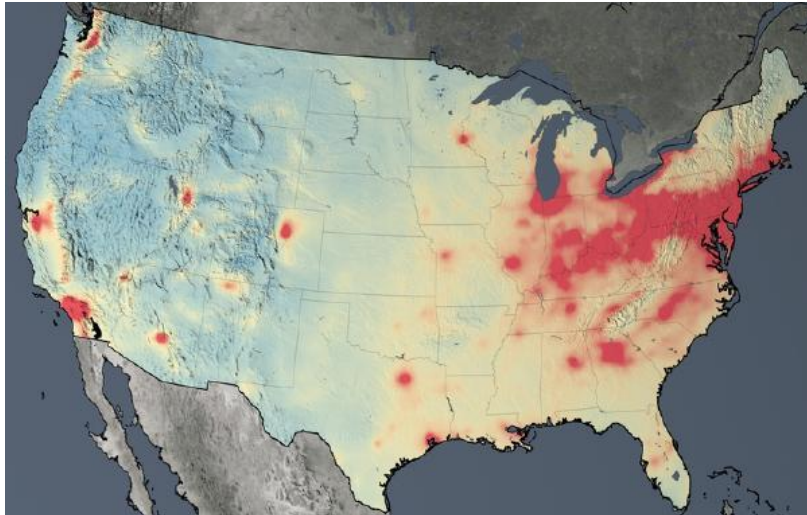
Pawan Gupta and Melanie Follette-Cook

Advanced Webinar: High Resolution NO<sub>2</sub> Monitoring From Space with TROPOMI, May 2019



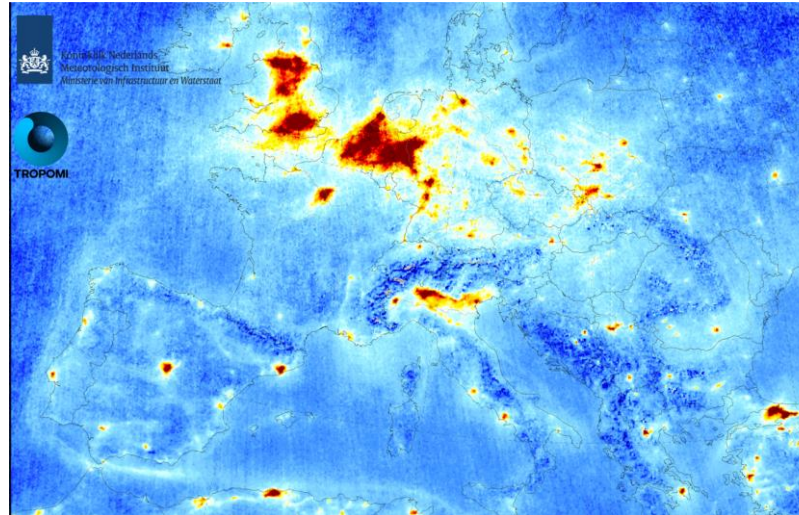
# Webinar Agenda

## Session 1



Remote sensing of NO<sub>2</sub>, OMI Data Products, and Tools

## Session 2



Introducing TROPOMI - High Resolution NO<sub>2</sub> Observations from Space

## Session 3

A screenshot of a Python IDE (Spyder) showing code for reading and processing TROPOMI data. The code includes imports for h5py, numpy, and Basemap, and uses h5py to read data from an HDF4 file. The code also uses Basemap to create a map of the data. The console output shows the execution of the code and the resulting map.

```
1 #!/usr/bin/python
2
3 # Module: read_and_map_omi_data.py
4
5 Disclaimer: The code is for demonstration purposes only, users are responsible to check for accuracy.
6 Author: Justin Roberts-Pierel, 2015
7 Organization: NASA ARES
8 Purpose: To extract AOD data from a MODIS HDF4 file (or series of files) and create a map of it.
9
10 See the README associated with this module for more information.
11
12
13
14
15 Import necessary modules
16 from pyproj import Proj
17 import numpy as np
18 from mpl_toolkits.basemap import Basemap, cm
19 import matplotlib.pyplot as plt
20 import sys
21 import time
22 import calendar
23
24
25 FILE_NAME = 'MY08_L1_A2017049_2105_000_2017250160035.hdf'
26
27 hdf = h5py.File(FILE_NAME)
28 lat = hdf['lat']
29 lon = hdf['lon']
30 lat_min = hdf.select('Latitude').min()
31 lat_max = hdf.select('Latitude').max()
32 lon_min = hdf.select('Longitude').min()
33 lon_max = hdf.select('Longitude').max()
34
35 # Create a map of the data
36 m = Basemap(projection='cyl', llcrnrlat=lat_min, llcrnrlon=lon_min, urcrnrlat=lat_max, urcrnrlon=lon_max,
37             resolution='l', area_thresh=10000)
38
39 # Read the AOD data
40 aod = hdf['aod']
41
42 # Scale the AOD data
43 aod_scaled = aod * 1000000000.0
44
45 # Create a map of the AOD data
46 fig = plt.figure()
47 m.imshow(aod_scaled, cmap=cm.magma)
48
49 # Save the map
50 plt.savefig('aod_map.png')
51
52 # Close the map
53 plt.close()
54
55 # Print the map
56 print('Map of AOD data saved to aod_map.png')
57
58 # End of script
```

Python Tools - TROPOMI

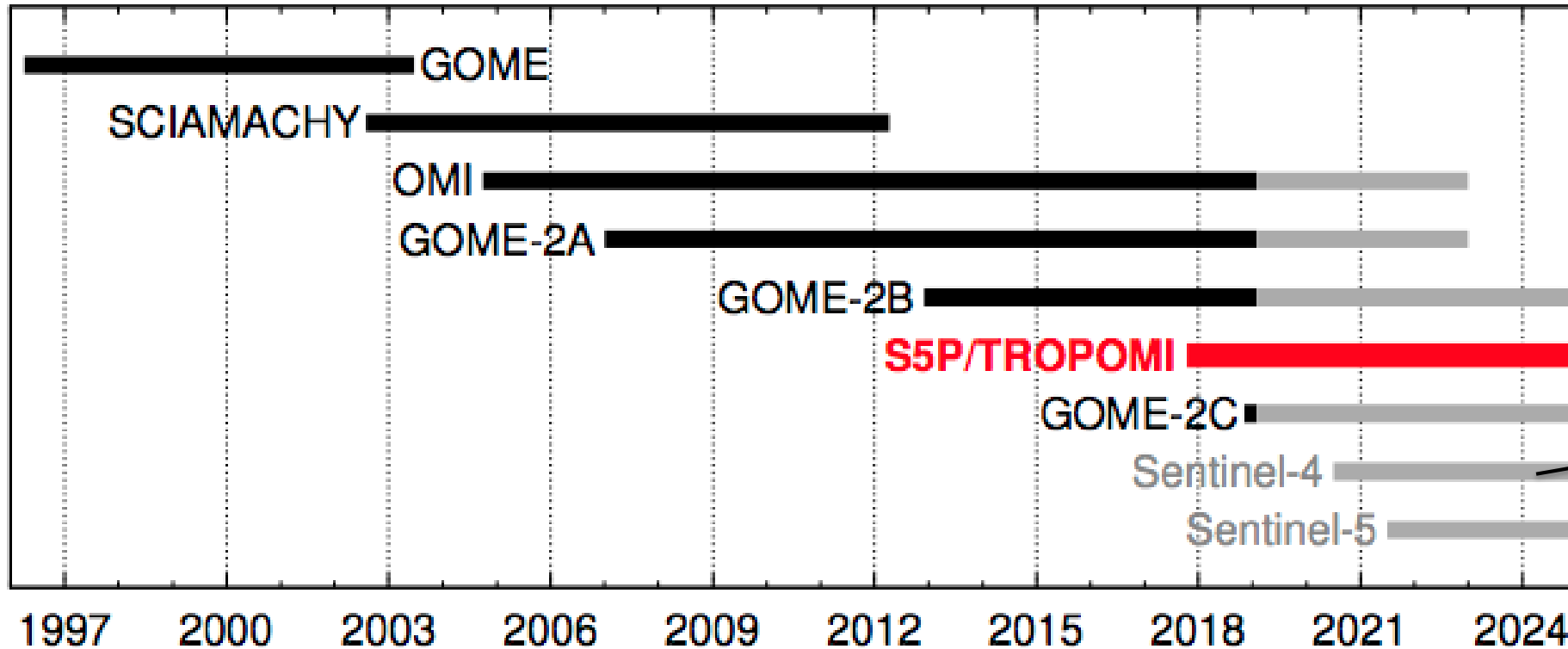
# Session 2

- Introduction to Tropospheric Monitoring Instrument (TROPOMI)
  - TROPOMI Data Products
  - TROPOMI Data Access
  - Tools to display TROPOMI data

# Learning Objectives

- By the end of this presentation, you will be able to:
- Describe TROPOMI satellite capabilities for global air quality monitoring
- download TROPOMI data
- Display and map TROPOMI data

# Past & Future (ESA view)



GEMS  
TEMPO

Image Credit: [TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products](#)

# TROPOMI – Tropospheric Monitoring Instrument

- Sentinel-5 Precursor
- Low Earth Orbit Atmospheric Chemistry Mission
- Launched – 13 October 2017 by ESA
- The TROPOMI instrument is a UV-VIS-NIR-SWIR push-broom grating spectrometer.
- The typical pixel size (near nadir) will be 7x3.5 km<sup>2</sup> for all spectral bands, with the exception of the UV1 band (7x28 km<sup>2</sup>) and SWIR bands (7x7 km<sup>2</sup>).



Image Credit/Copyright: [ESA/ATG medialab](#)

# TROPOMI – Tropospheric Monitoring Instrument

- Swath: 2600 km
- Repeat Cycle: 16 days
- LST: 13:30 at Ascending Node
- Designed Lifetime: 7 Years
- S-5P makes measurements within 5-minutes of NASA Suomi-NPP
- Synergy of TROPOMI and VIIRS/OMPS will provide additional information on aerosols, clouds and help produce better trace gas products.

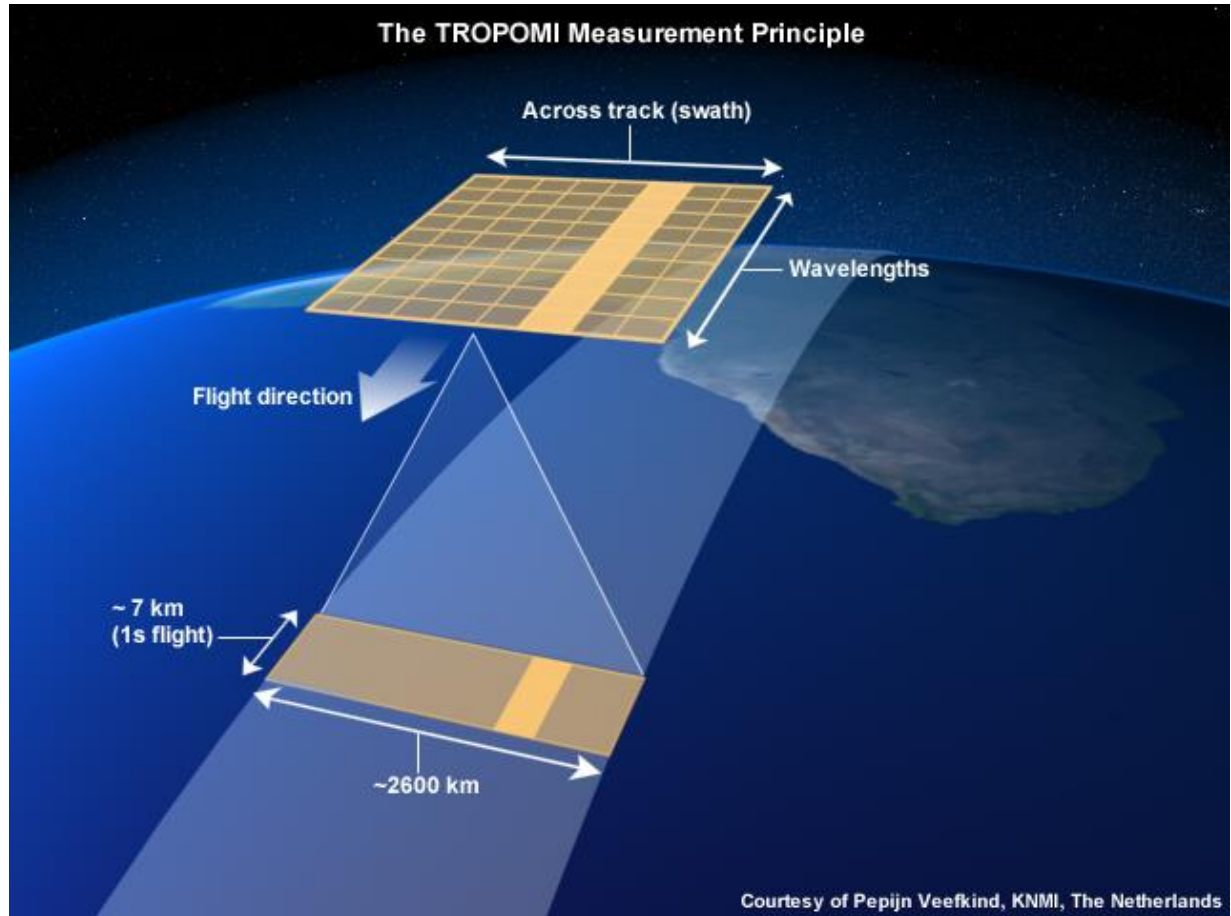


Image Credit/Copyright: [ESA/ATG medialab](https://www.esa.int/ATG/medialab)

# TROPOMI Spectral Coverage

Spectral ranges	Number of channels	Spectral resolution
270-495 nm	1200	0.55 nm
710-775 nm	600	0.55 nm
2305-2385 nm	800	0.25 nm

For comparison:  
MODIS has 36 spectral bands

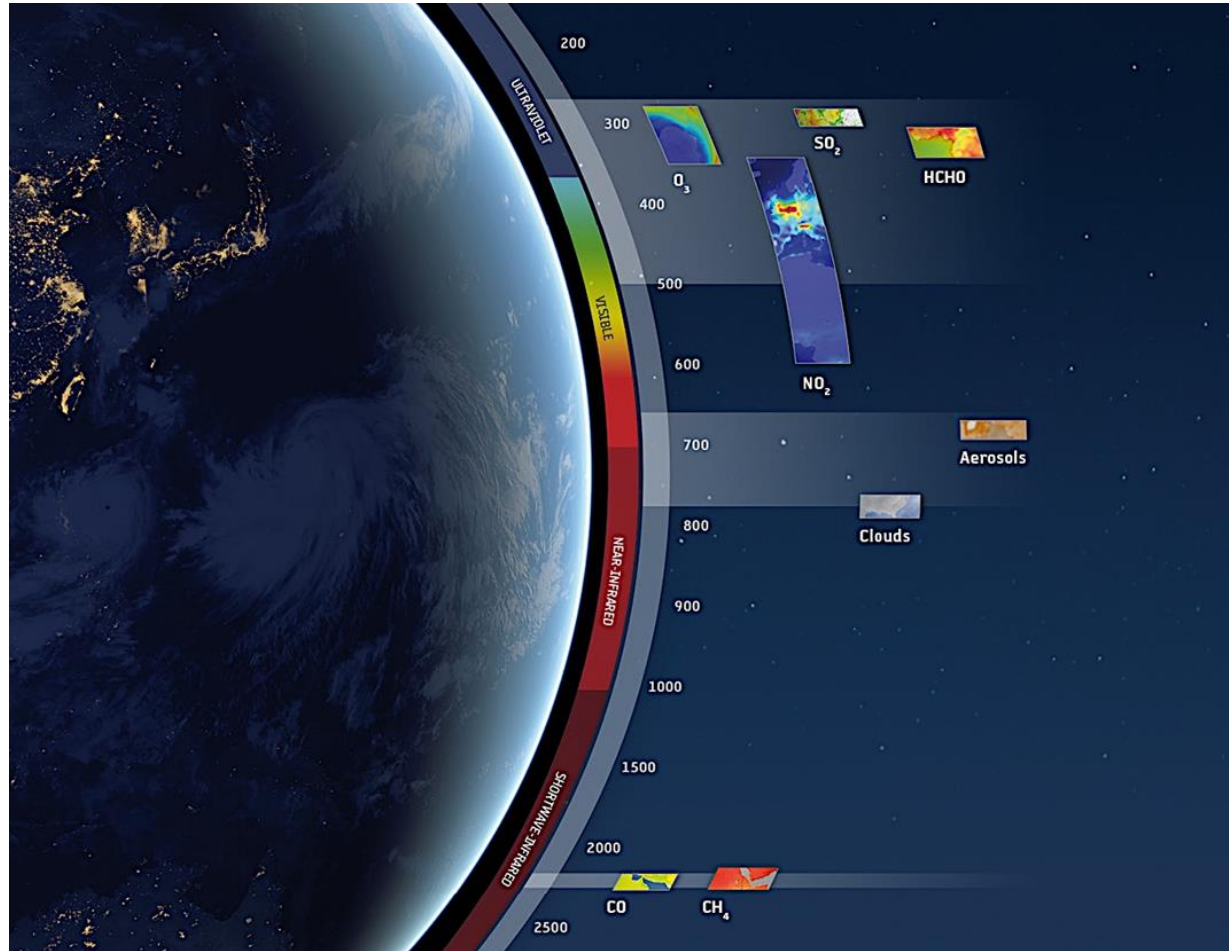


Image Credits (left to right): [WMO Oscar](#); Copyright [ESA](#)



# TROPOMI Advancements

- Better spatial resolution – 6+ times higher than OMI (7x7 vs 13x24 km<sup>2</sup>)
- 1-5 times higher signal to noise ratios
- Better cloud information from Oxygen A & B bands and synergy with VIIRS
- CO and CH<sub>4</sub> measurements using SWIR channels
- Data rate ~20 times of that OMI



# TROPOMI Resources

<http://www.tropomi.eu/>

**TROPOMI**  
TROPOspheric Monitoring Instrument

**OBSERVING  
OUR FUTURE**

- Ozone
- Ozone profile
- Nitrogen dioxide
- Sulfur dioxide
- Formaldehyde
- Surface UV-B
- Aerosols
- Carbon Monoxide
- Methane
- Clouds

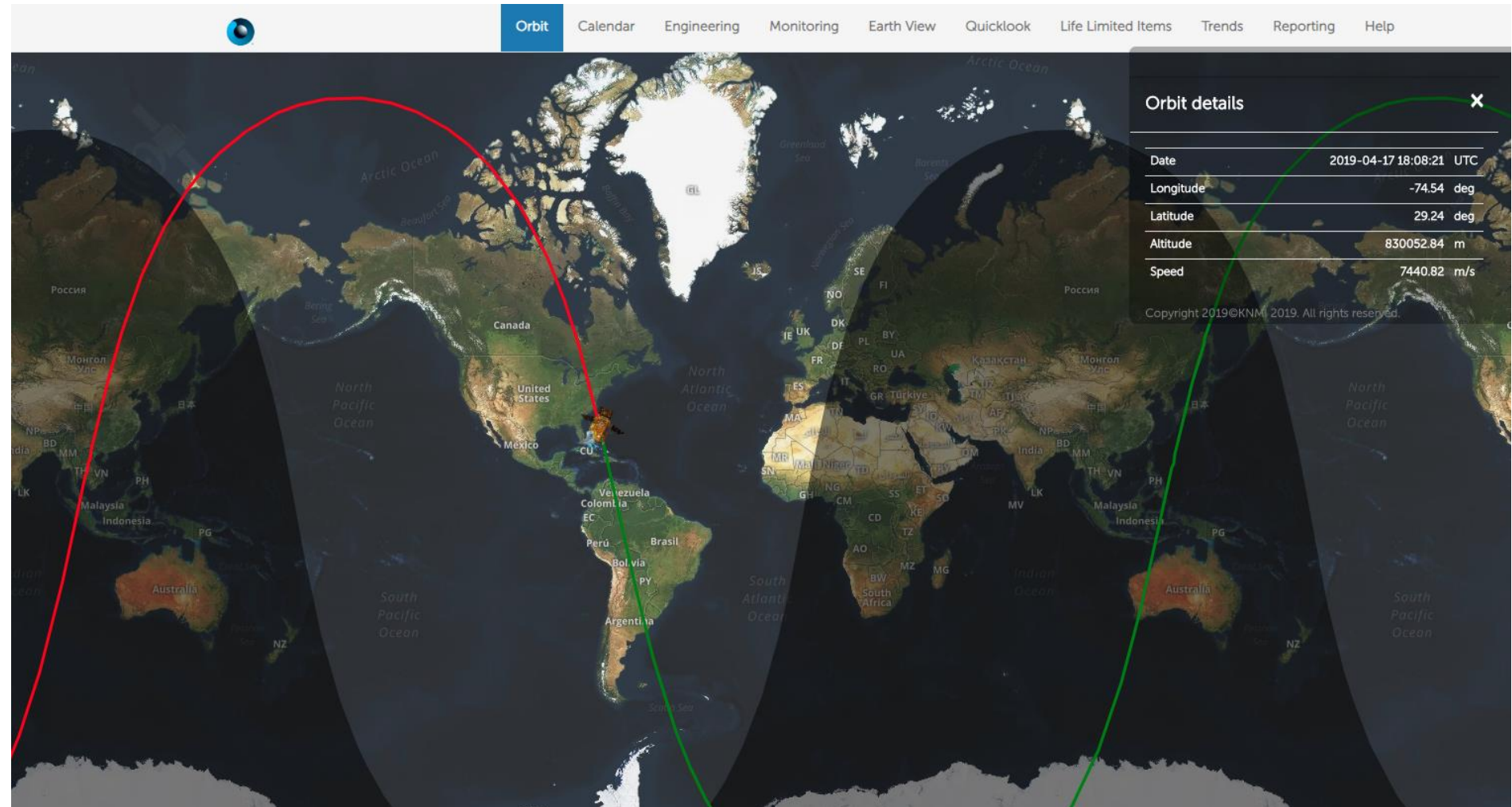
**SCIENCE WEBSITE**  
VISIT PUBLIC TROPOMI WEBSITE



# Current Position of TROPOMI

<http://mps.tropomi.eu/orbit>

S5P and S-NPP  
make  
measurements  
3 to 5 minutes  
apart



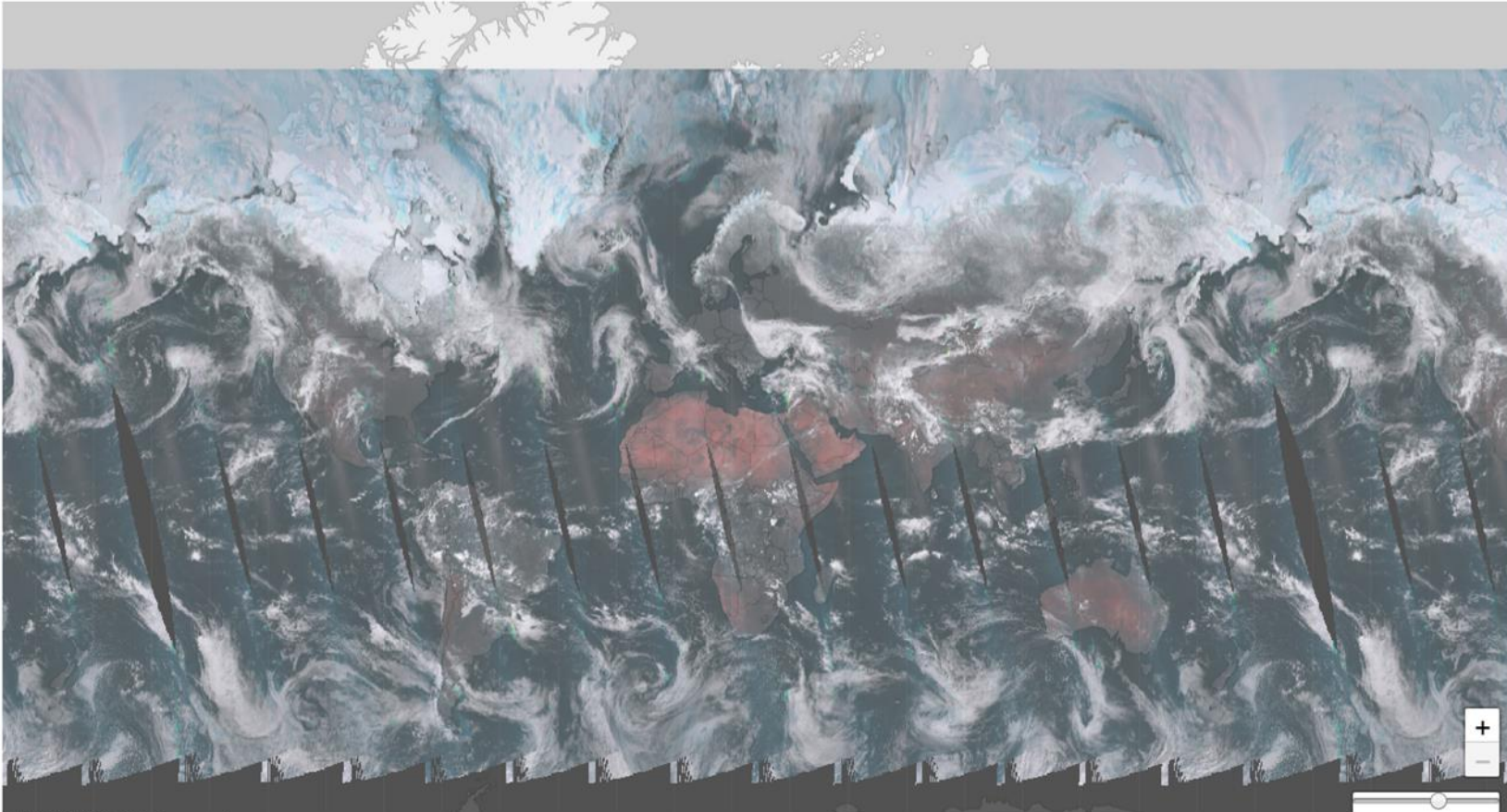
# Current Earthview

<http://mps.tropomi.eu/orbit>

← Previous day    Next day →

Date: 2019-04-16    Submit

- Daily RGB: True colour
- Daily RGB: False colour
- Heatmap image for UV detector
- Heatmap image for UVIS detector
- Heatmap image for NIR detector
- Heatmap image for SWIR detector
- Running minimum reflectance

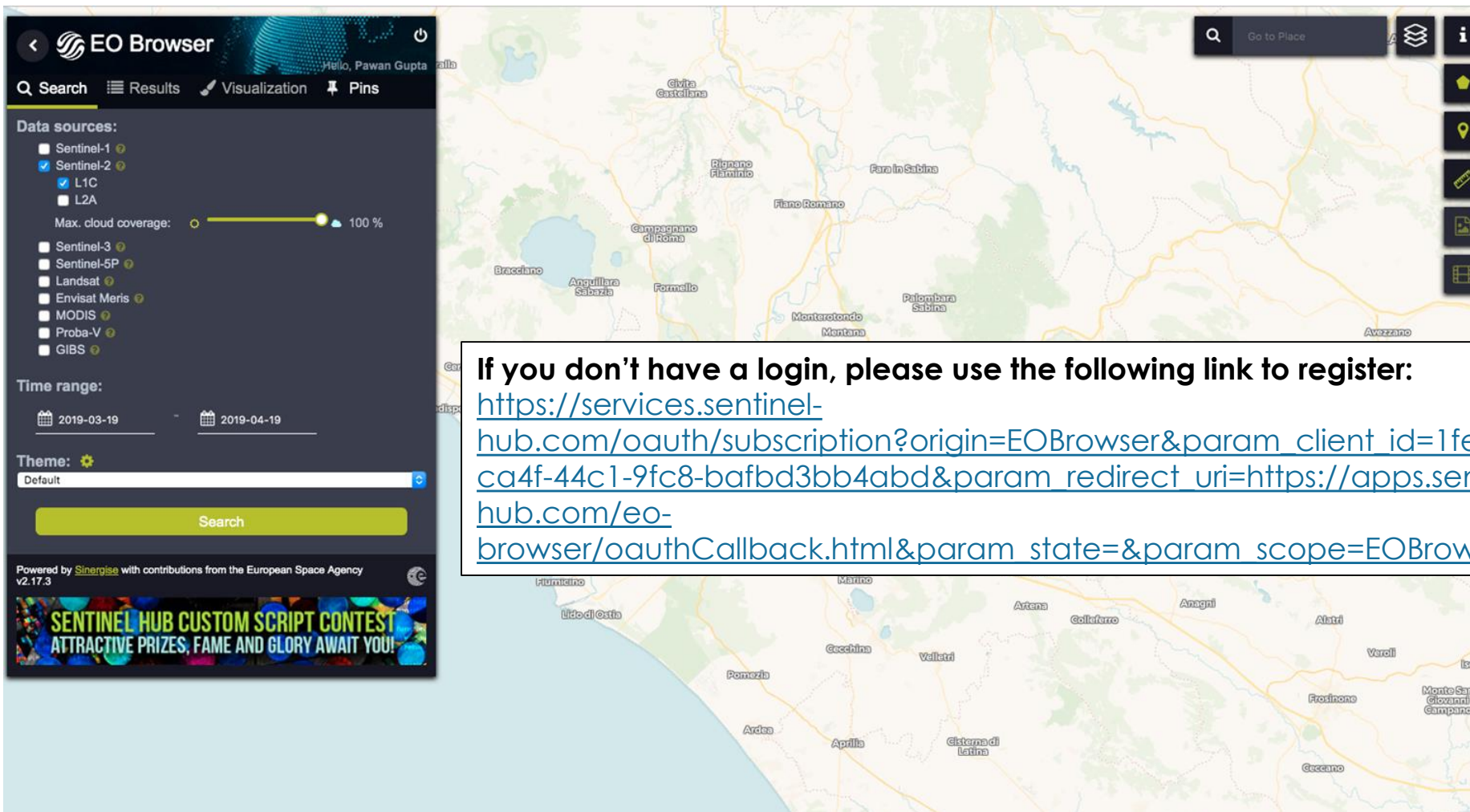


The image displays a satellite view of Earth from the Tropomi satellite. The view is centered on the Atlantic Ocean, showing the Americas on the left and Europe and Africa on the right. The image is a composite of multiple scans, indicated by the vertical black lines at the bottom. The clouds are shown in white and grey, with some darker areas indicating higher cloud cover. The landmasses are shown in shades of brown and green. The image is presented in a true color format. There are navigation controls at the top and bottom of the image, including a date selector and a submit button.

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# EO Browser

<https://apps.sentinel-hub.com/eo-browser/?lat=41.9000&lng=12.5000&zoom=10>



The screenshot displays the EO Browser interface. On the left, a sidebar contains the following elements:

- EO Browser** header with a user greeting: "Hello, Pawan Gupta".
- Navigation tabs: Search, Results, Visualization, Pins.
- Data sources:**
  - Sentinel-1 (unchecked)
  - Sentinel-2 (checked) with sub-options L1C (checked) and L2A (unchecked).
  - Max. cloud coverage: A slider set to 100%.
  - Sentinel-3 (unchecked)
  - Sentinel-5P (unchecked)
  - Landsat (unchecked)
  - Envisat Meris (unchecked)
  - MODIS (unchecked)
  - Proba-V (unchecked)
  - GIBS (unchecked)
- Time range:** A date range from 2019-03-19 to 2019-04-19.
- Theme:** A dropdown menu set to "Default".
- A prominent green **Search** button.
- Footer text: "Powered by Sinergise with contributions from the European Space Agency v2.17.3".
- A promotional banner for the "SENTINEL HUB CUSTOM SCRIPT CONTEST" with the text "ATTRACTIVE PRIZES, FAME AND GLORY AWAIT YOU!".

The main map area shows a satellite view of a region in Italy, with labels for various towns and geographical features. A search bar at the top right of the map area contains the text "Go to Place". A vertical toolbar on the right side of the map includes icons for search, layers, information, home, location, and other map controls.

If you don't have a login, please use the following link to register:  
[https://services.sentinel-hub.com/oauth/subscription?origin=EOBrowser&param\\_client\\_id=1febe974-ca4f-44c1-9fc8-bafbd3bb4abd&param\\_redirect\\_uri=https://apps.sentinel-hub.com/eo-browser/oauthCallback.html&param\\_state=&param\\_scope=EOBrowser](https://services.sentinel-hub.com/oauth/subscription?origin=EOBrowser&param_client_id=1febe974-ca4f-44c1-9fc8-bafbd3bb4abd&param_redirect_uri=https://apps.sentinel-hub.com/eo-browser/oauthCallback.html&param_state=&param_scope=EOBrowser)

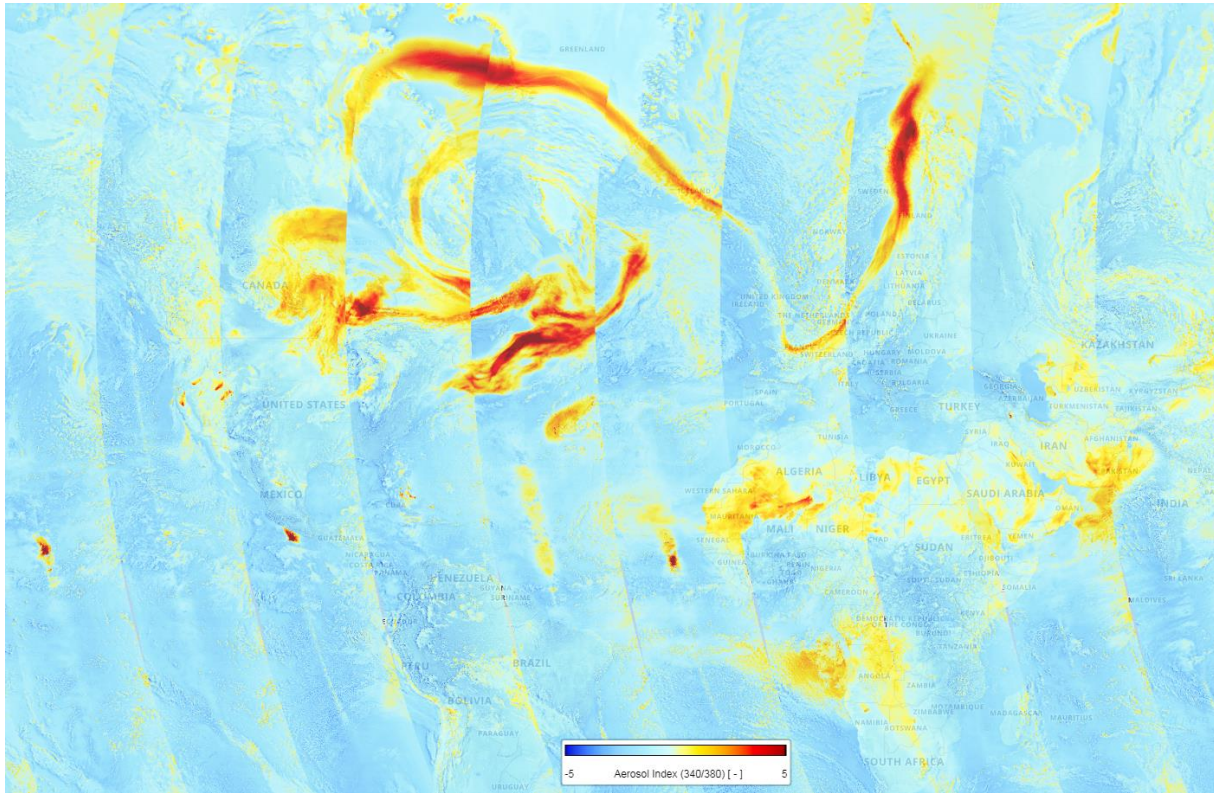
# Level 2 Data Product

<http://www.tropomi.eu/data-products/level-2-products>

Product	Main Parameter	Data file descriptor	Developers	(Planned) Release
<u>UV Aerosol Index</u>	aerosol index	AER_AI	KNMI	Released
<u>Aerosol Layer Height</u>	mid-level pressure	AER_LH	KNMI	Mid-2019
<u>Carbon monoxide (CO)</u>	total column	CO_____	SRON	Released
<u>Cloud</u>	fraction, albedo, top pressure	CLOUD_	DLR	Released
<u>Formaldehyde (HCHO)</u>	total column	HCHO__	BIRA-IASB	Released
<u>Methane (CH4)</u>	total column	CH4_____	SRON	Released
<u>Nitrogen oxide (NO2)</u>	total column	NO2_____	KNMI	Released
<u>Ozone profiles</u>	total and tropospheric profiles	O3_PR_ O3_TPR	KNMI	Late-2019
<u>Sulphur dioxide (SO2)</u>	total column	SO2_____	BIRA-IASB	Released
<u>Ozone (O3)</u>	total column	O3_____	DLR	Released
<u>Tropospheric Ozone (O3)</u>	tropospheric column	O3_TCL	DLR	Released
<u>UV<sup>1</sup></u>	surface irradiance erythemal dose	-----	FMI	-----

# Aerosol Product

UV Aerosol Index – 8/24/2018



Aerosol Layer Height – 12/12/2017

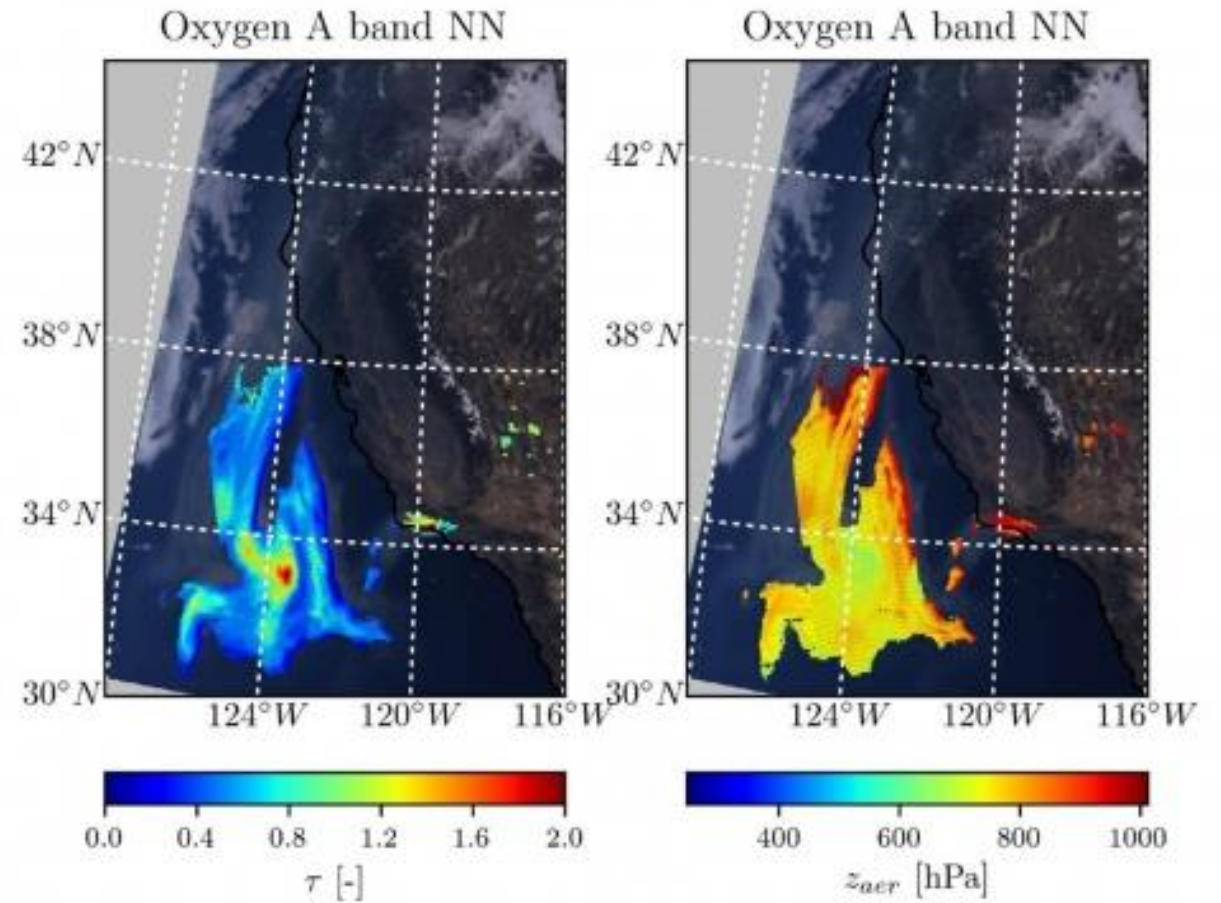
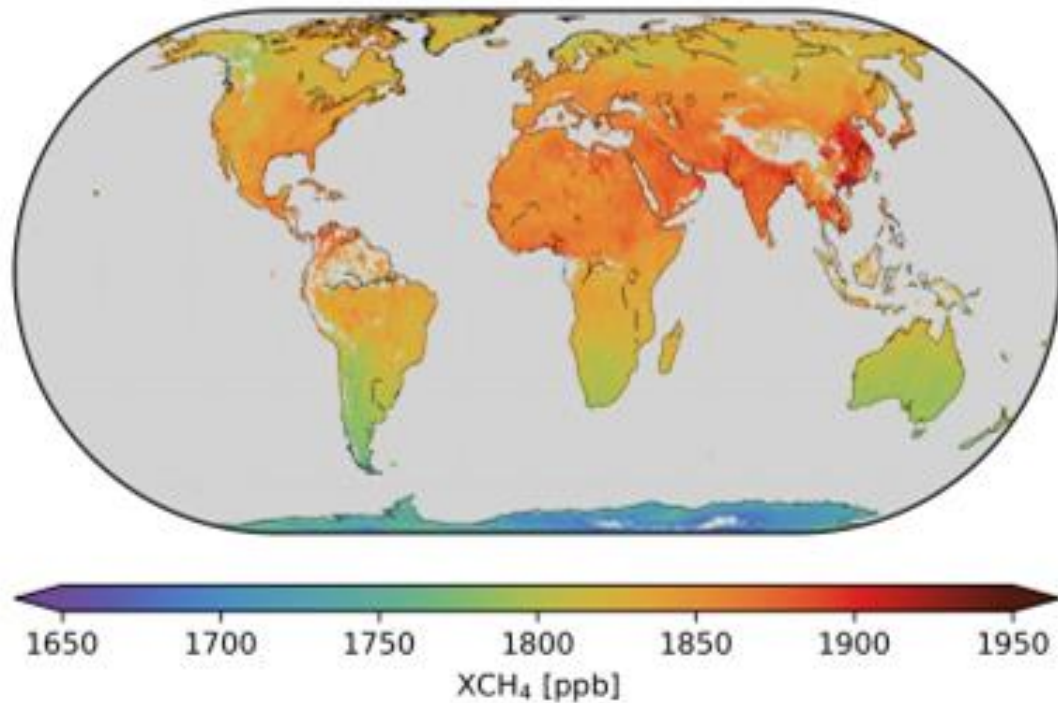


Image Credits (left to right): [TROPOMI](#); [TROPOMI](#)

# Methane (CH<sub>4</sub>) & Sulphur Dioxide (SO<sub>2</sub>)

May 2018 to Jan 2019



SO<sub>2</sub> - Nov 2017 to Jul 2018

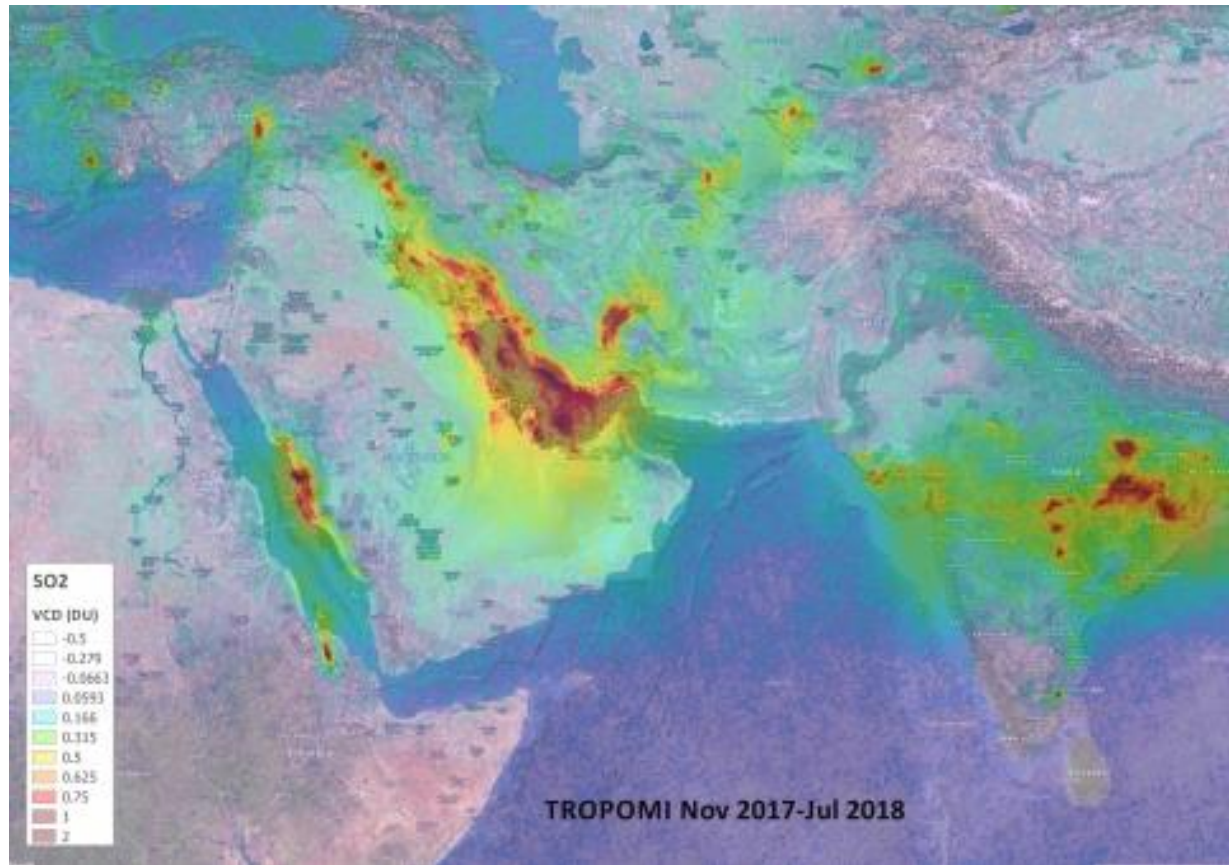


Image Credits (left to right): [TROPOMI](#); [TROPOMI](#)



# NO<sub>2</sub> Data Product

Version number	Version Effective Date	Summary of Changes
<u>1.03.00</u>	NRTI: 2019-03-27 (orbit 07519 to present) OFFL: 2018-03-20 (orbit 07425 to present)	Current version
1.02.02	NRTI: 2018-12-05 (orbit 05932 to 07518) OFFL: 2018-11-28 (orbit 05833 to 07424)	
1.02.00	NRTI: 2018-10-24 (orbit 05336 to 05929) OFFL: 2018-10-17 (orbit 05236 to 05832)	

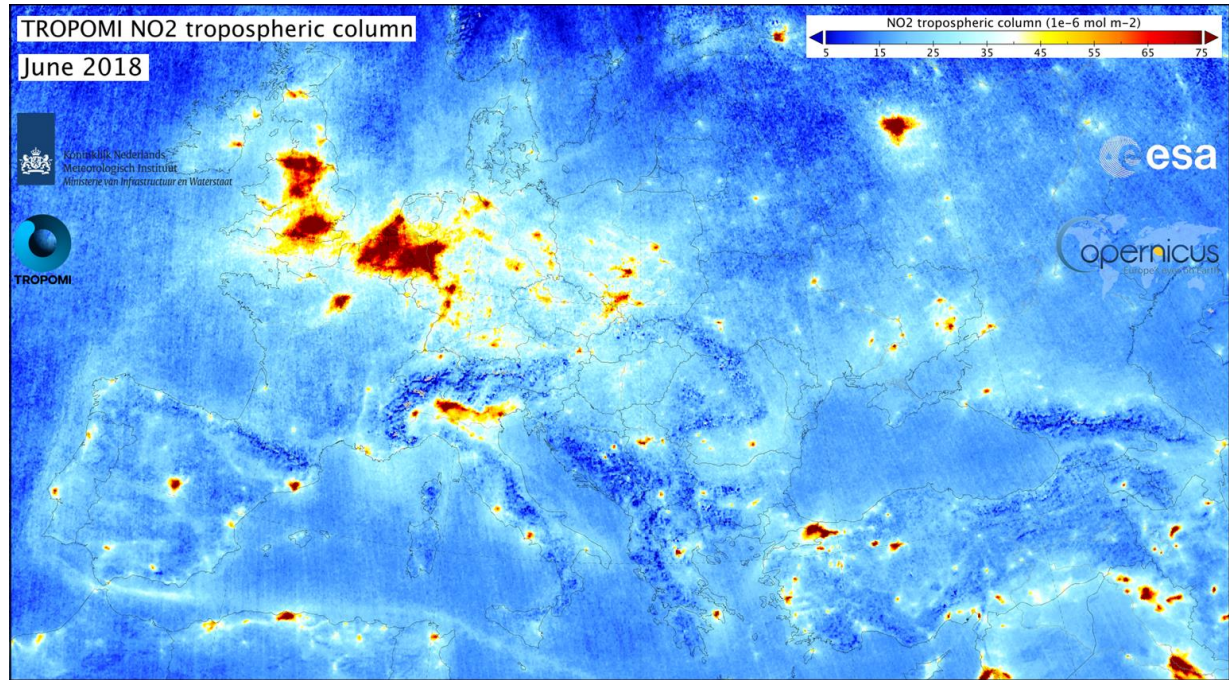
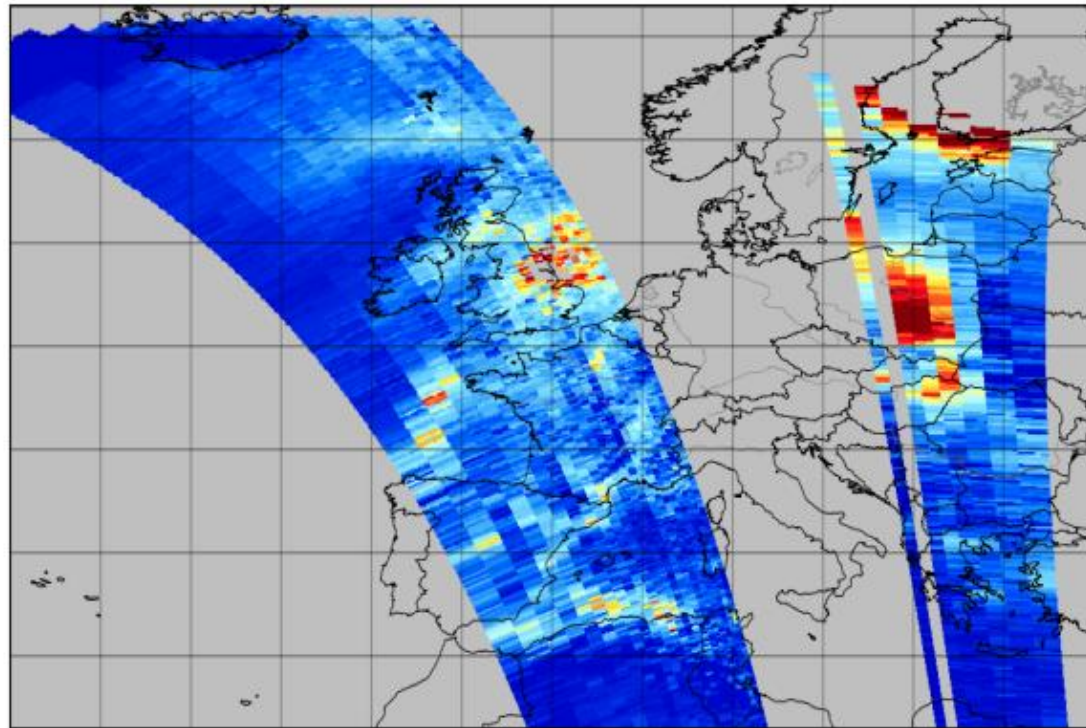


Image Credit: [TROPOMI](#)

# Spatial Resolution

tropospheric column of NO<sub>2</sub>, QA4ECV OMI, 22 Nov 2017

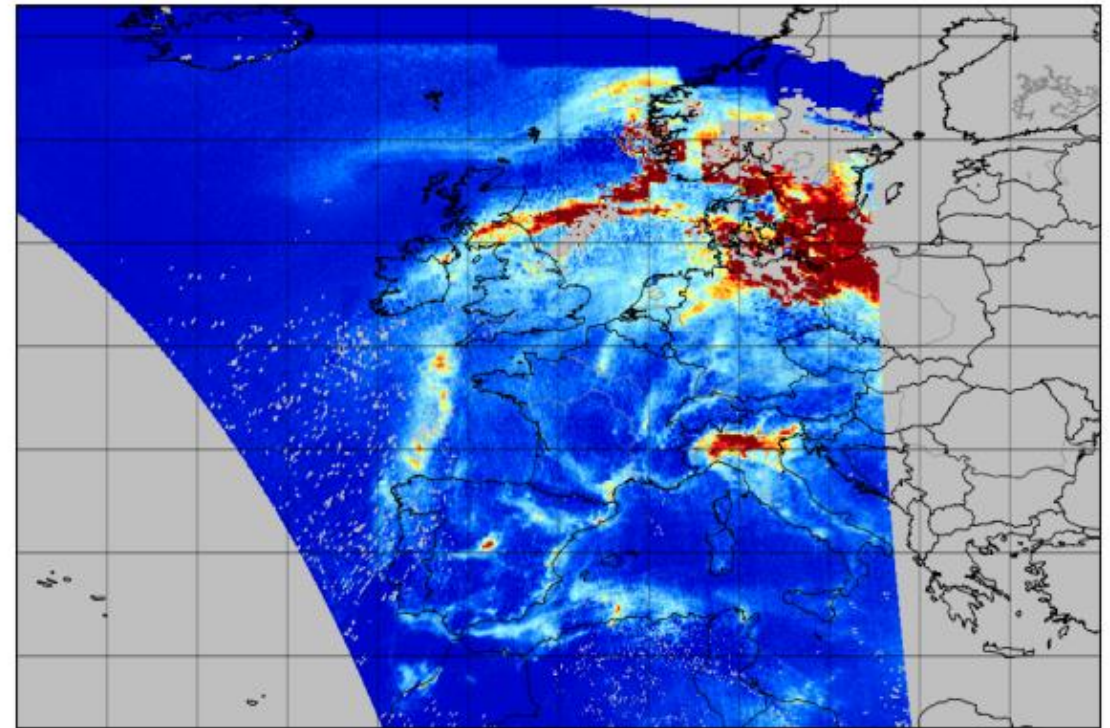


tropospheric vertical column of nitrogen dioxide ( $10^{15}$  molecules  $\text{cm}^{-2}$ )



Data Min = -8, Max = 39

tropospheric column of NO<sub>2</sub>, S5P, 22 Nov 2017



tropospheric vertical column of nitrogen dioxide ( $10^{-6}$  mol  $\text{m}^{-2}$ )



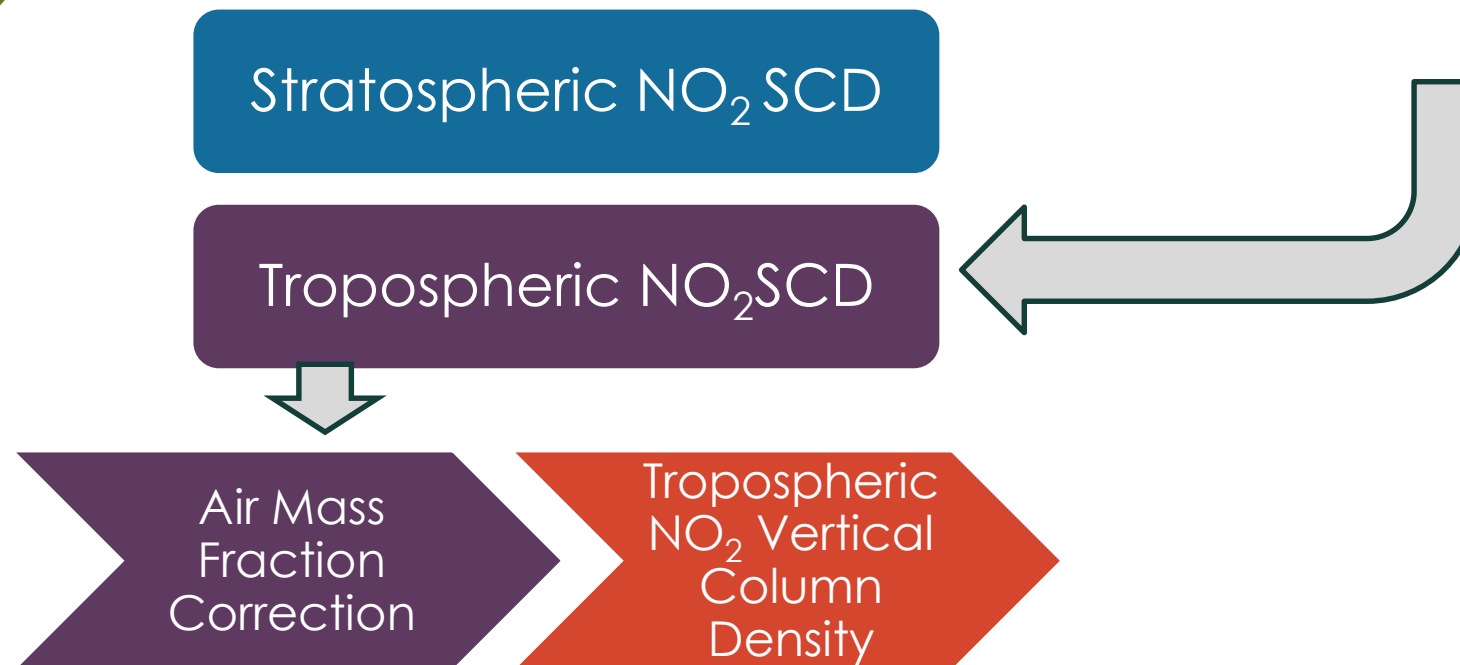
Data Min = -15403, Max = 1582

*Sentinel-5 Precursor and the upcoming Sentinels for monitoring atmospheric Composition.* (2018, October). Presented at the CAMS 3rd General Assembly, Lisbon, Portugal. Retrieved from [https://atmosphere.copernicus.eu/sites/default/files/2018-11/2\\_Zehner\\_S5p\\_CAMS\\_18.pdf](https://atmosphere.copernicus.eu/sites/default/files/2018-11/2_Zehner_S5p_CAMS_18.pdf)

# NO<sub>2</sub> Retrieval



- DOAS (see Platt [1994], Platt and Stutz [2008])
- 405 to 465 nm wavelengths



Content Source: [TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products](#)

# NO<sub>2</sub> - Filename

S5P\_NRTI\_L2\_NO2\_20140101T000000\_20140102T000000\_00099\_01\_000200\_20141010T173511.nc

Start	End	Length	Meaning
0	3	3	Mission name, always "S5P"
4	8	4	Processing stream, one of "NRTI" (near real-time), "OFFL" (offline) or "RPRO" (reprocessing)
9	19	10	Product identifier, as listed in table 1
20	35	15	Start of granule in UTC as "YYYYMMDDTHHMMSS". The "T" is a fixed character.
36	51	15	End of the granule in UTC as "YYYYMMDDTHHMMSS". The "T" is a fixed character.
52	57	5	Orbit number
58	60	2	Collection number
61	67	6	Processor version number as "MMmmpp", with "MM" the major version number, "mm" the minor version number, and "pp" the patch level.
68	83	15	The time of processing for this granule in UTC as "YYYYMMDDTHHMMSS". The "T" is a fixed character.
84	86	2	The file name extension. All Sentinel 5 precursor files are netCDF-4 files and use the extension ".nc"

Image Credit: [Sentinel-5 precursor/TROPOMI Level 2 Product User Manual NPP Cloud](#)

# QA Filtering

- `qa_value > 0.75`.  
For most users this is the recommended pixel filter. This removes cloud-covered scenes (cloud radiance fraction  $> 0.5$ ), part of the scenes covered by snow/ice, errors and problematic retrievals.
- `qa_value > 0.50`.  
This adds the good quality retrievals over clouds and over scenes covered by snow/ice. Errors and problematic retrievals are still filtered out. In particular this choice is useful for assimilation and model comparison studies where the averaging kernels are used.

The `qa_value` indicates whether the footprint is cloud covered or not, and whether there is snow or ice on the surface. It is set to 0 if anywhere in the processing an error occurred, as indicated by the `processing_quality_flags`. Warnings related to the South Atlantic Anomaly, sun glint, or missing non-critical input

Image Credit: [Sentinel-5 precursor/TROPOMI Level 2 Product User Manual Nitrogendioxide](#)

# NO<sub>2</sub> Algorithm Theoretical Basis Document (ATBD) & Product User Manual



**TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products**



**Sentinel-5 precursor/TROPOMI Level 2 Product User Manual Nitrogen dioxide**



Source: [TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products](#)

[Sentinel-5 precursor/TROPOMI Level2 Product User Manual Nitrogen dioxide](#)



# NO<sub>2</sub> Product Bias

- Validation – PANDORA & MAX-DOAS

**Table 1:** NO<sub>2</sub> data product requirements for the TROPOMI NO<sub>2</sub> data products, where accuracies are split in the systematic and random components. The numbers are taken from [RD11] (see also [RD12]).

NO <sub>2</sub> data product	Vertical resolution	Bias	Random
Stratospheric NO <sub>2</sub>	Stratospheric column	< 10%	$0.5 \times 10^{15}$ molec/cm <sup>2</sup>
Tropospheric NO <sub>2</sub>	Tropospheric column	25 – 50%	$0.7 \times 10^{15}$ molec/cm <sup>2</sup>

Content Source: [TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products](#)

# TROPOMI Validation

<http://mpc-vdaf.tropomi.eu/>

## VALIDATION FACILITY

SENTINEL 5P MISSION PERFORMANCE CENTER

Ozone, O3 profile, Nitrogen dioxide, Sulfur Dioxide, Formaldehyde, Surface UV-B, Aerosols, Carbon Monoxide, Methane, Cloud

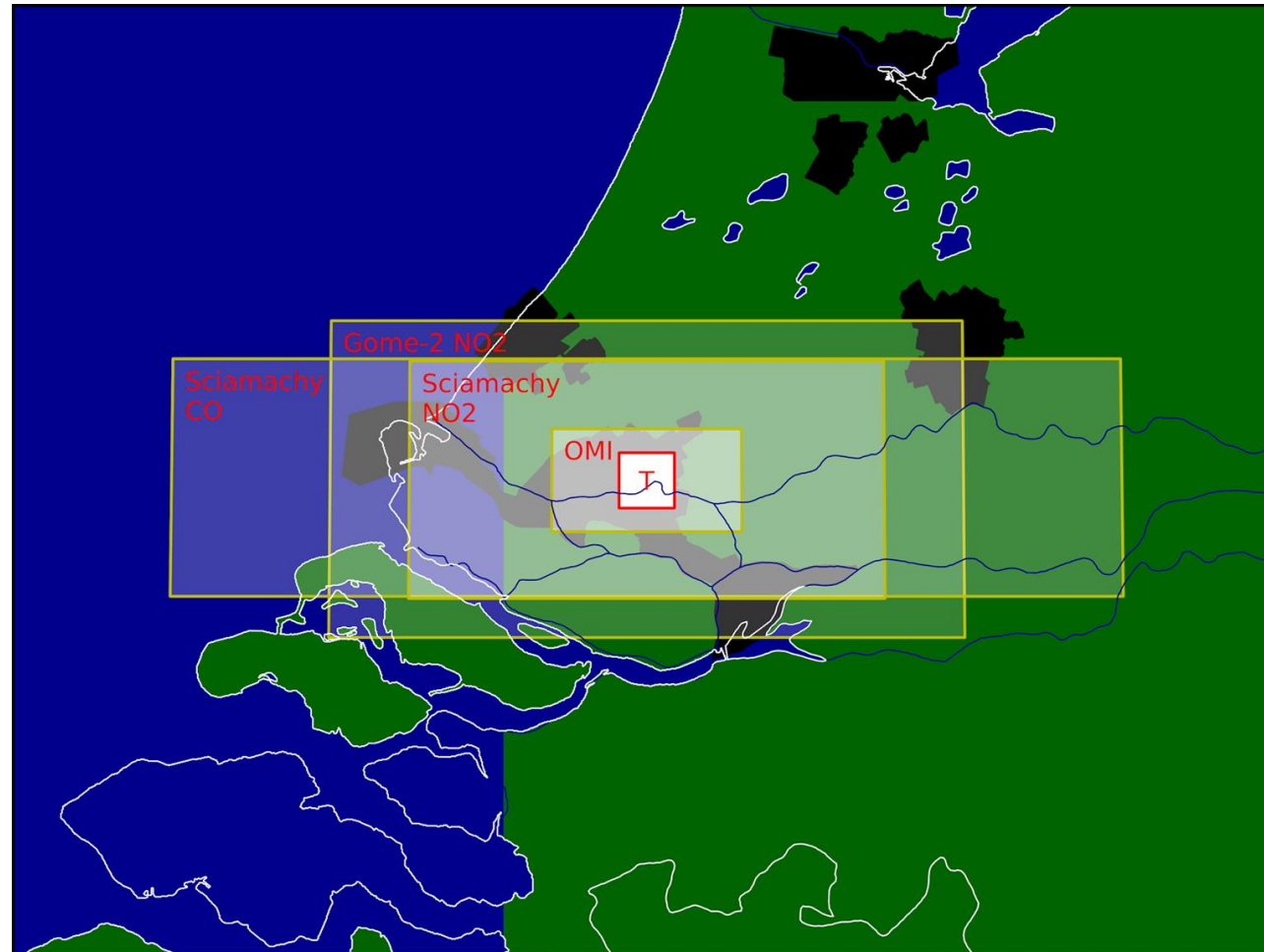
### Most recent contributions

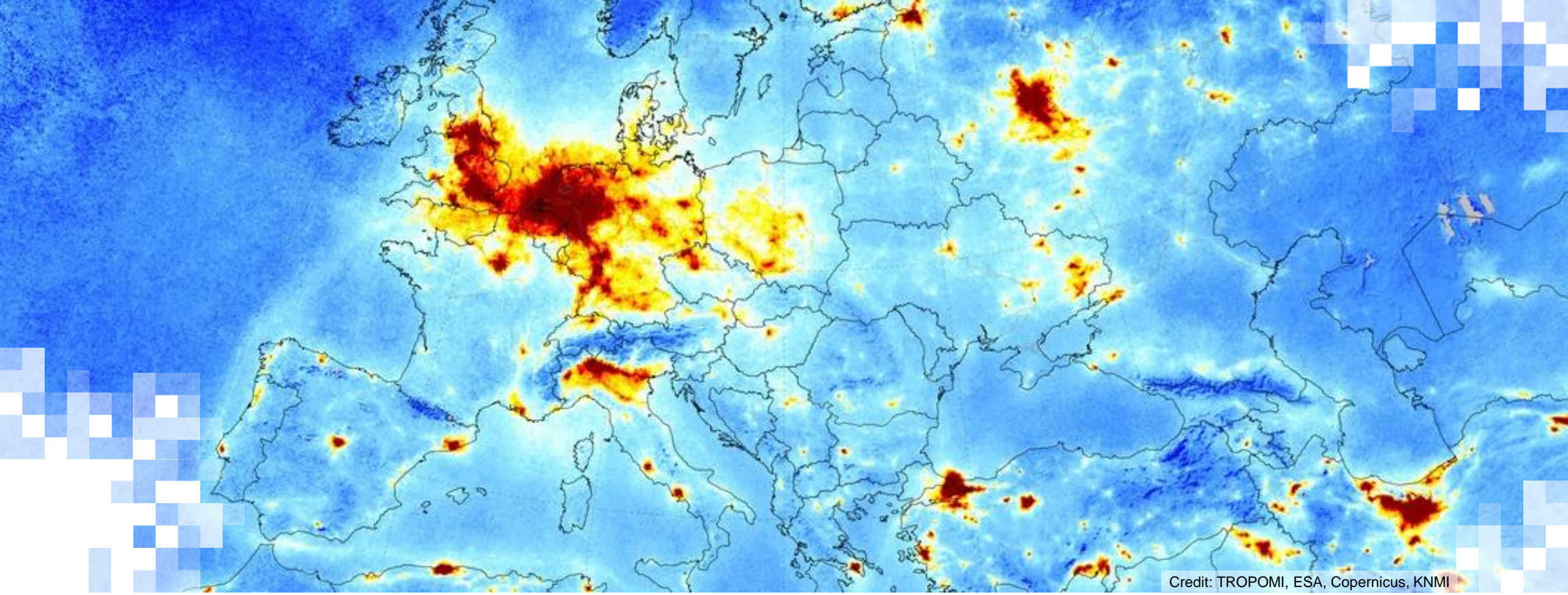
- First comparison results for the S5P CH4 product based on correlative reference measurements acquired by FTIR instruments contributing to NDACC and TCCON networks. This VDAF web article gives further details on the first comparison results presented in the CH4 product readme file for the methane data product release (see <http://www.tropomi.eu/data-products/methane>). The main conclusion is that the product quality of this initial L2 CH4 dataset complies with the S5P mission requirements.
- Quarterly Validation Report of the Sentinel-5 Precursor Operational Data Products #01: July – October 2018. This document reports consolidated results of the routine operations validation service for the Sentinel-5 Precursor Tropospheric Monitoring.
- First validation results for Sentinel-5p NO2 column data. This report describes initial validation results for Sentinel-5p TROPOMI L2\_NO2 tropospheric column, stratospheric column.
- A first validation against NDACC and WUOUC ground-based data confirms that the TROPOMI/S5p NRT1 total O3 (L2\_O3) product meets mission requirements. Initial Sentinel-5p TROPOMI L2\_O3 O3 column data retrieved with the PDGS.
- Preliminary comparison of TROPOMI/S5p RPRO CLOUD CAL cloud top height and CRB cloud height against ground-based.
- First comparison results for the S5P CO product based on correlative reference measurements acquired by FTIR instruments contributing to



# Data User Guide

<https://sentinel.esa.int/documents/247904/2474726/Sentinel-5P-Level-2-Product-User-Manual-Nitrogen-Dioxide>

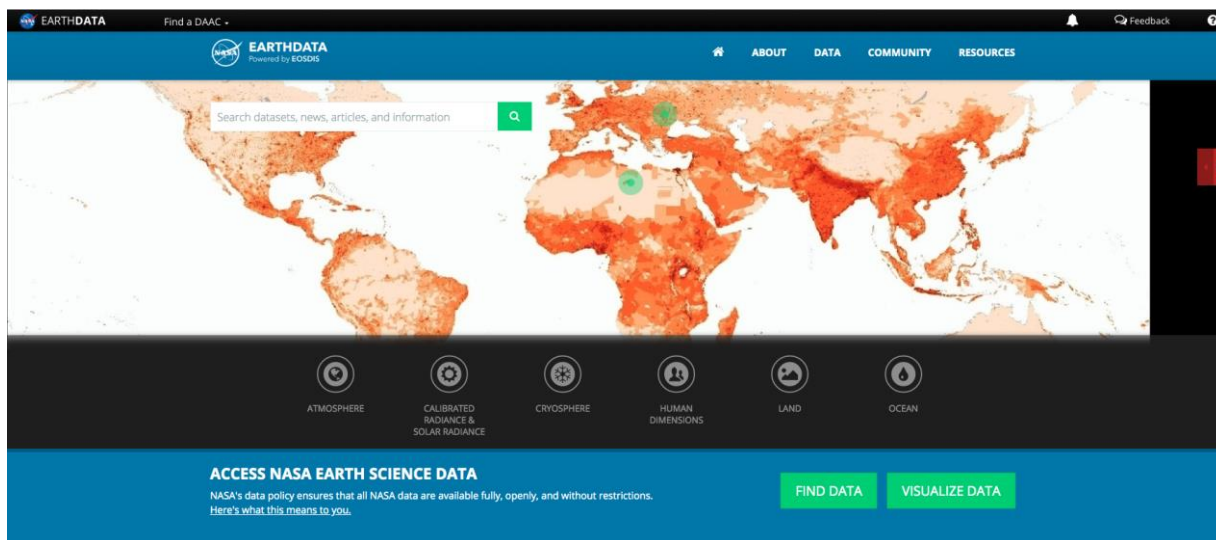




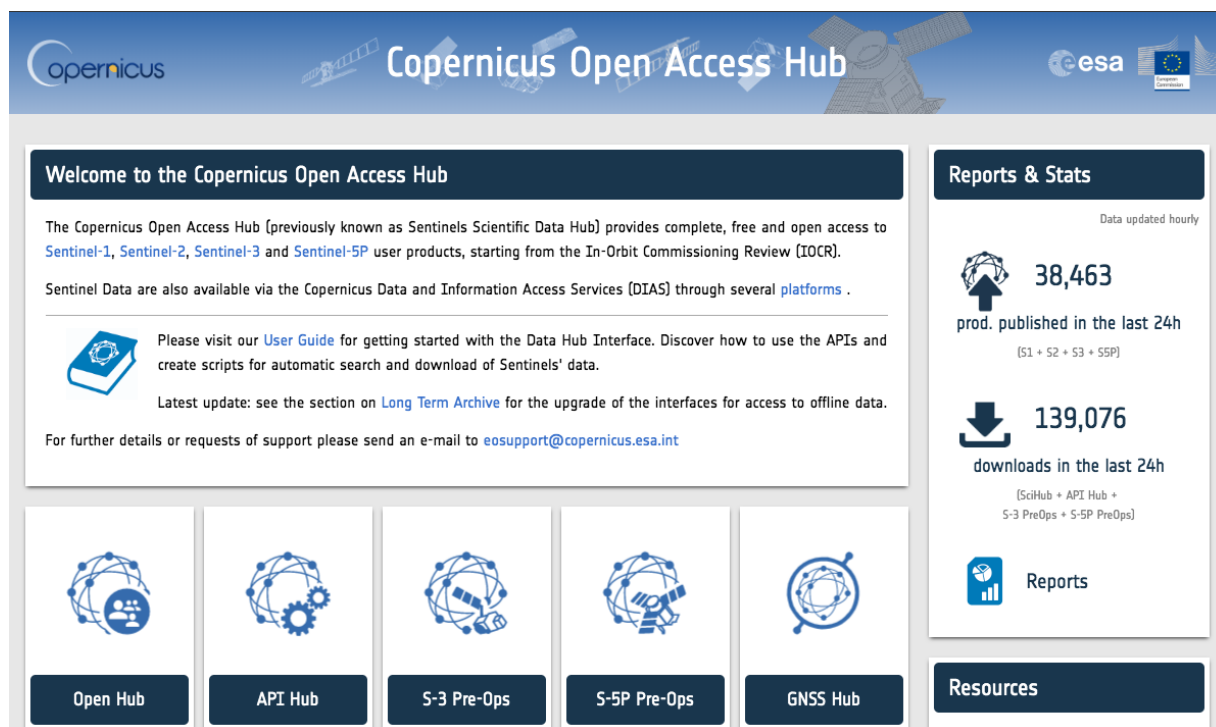
# Panoply Exercise

# Data Access

NASA – Earthdata  
<https://earthdata.nasa.gov/>



ESA – Copernicus Open Access Hub  
<https://scihub.copernicus.eu/>



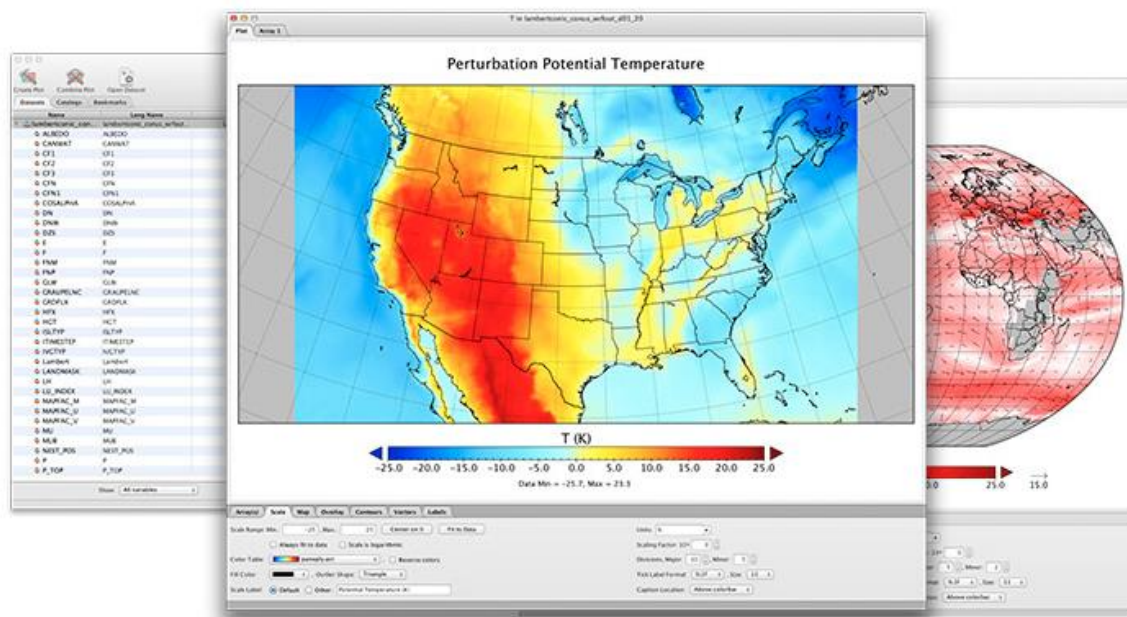


# Panoply

<https://www.giss.nasa.gov/tools/panoply/>

## Panoply netCDF, HDF and GRIB Data Viewer

*panoply* \PAN-uh-plee\, noun: 1. A splendid or impressive array. ...



Panoply plots geo-referenced and other arrays from netCDF, HDF, GRIB, and other datasets.

Panoply is a cross-platform application that runs on Macintosh, Windows, Linux and other desktop computers.

With Panoply 4 you can:

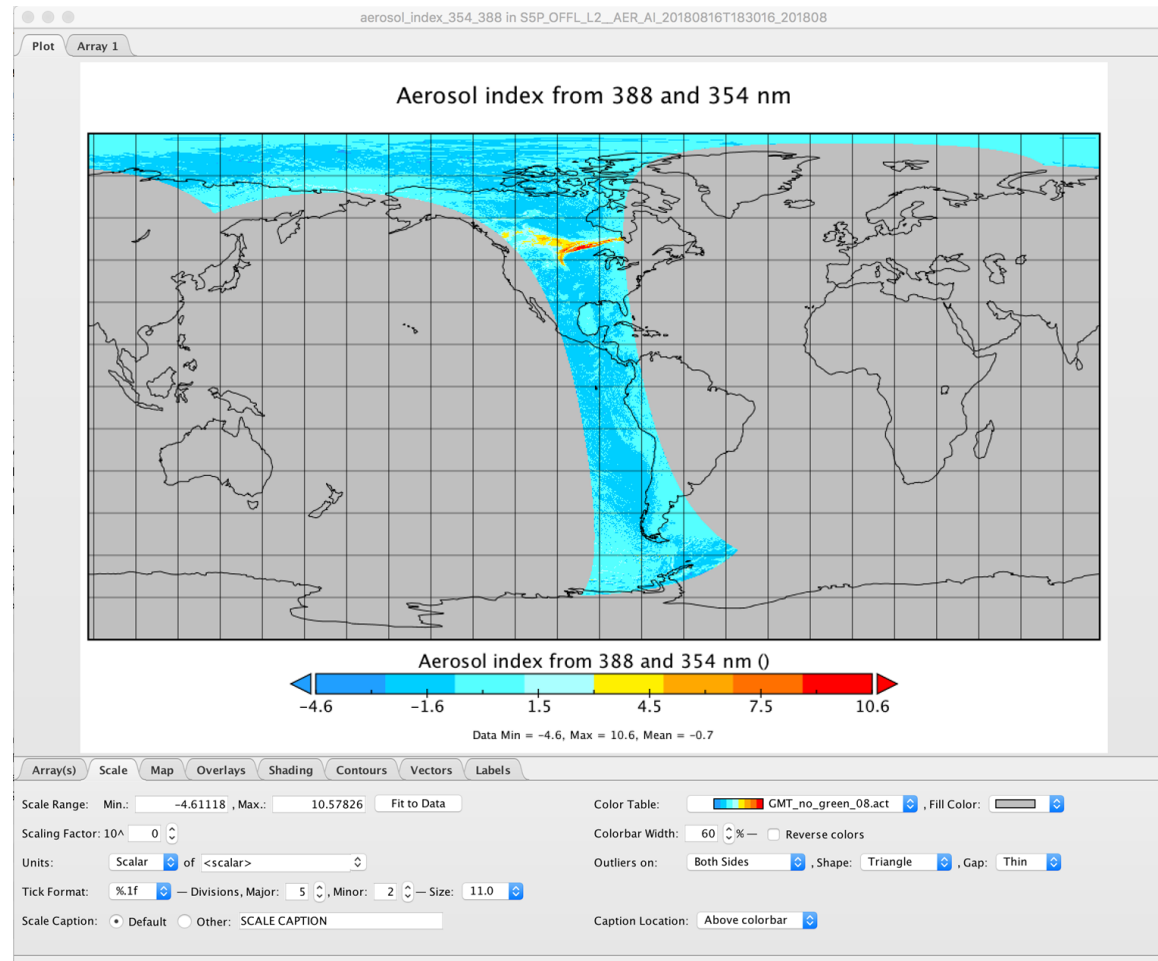
- Slice and plot geo-referenced latitude-longitude, latitude-vertical, longitude-vertical, time-latitude or time-vertical arrays from larger multidimensional variables.
- Slice and plot "generic" 2D arrays from larger multidimensional variables.
- Slice 1D arrays from larger multidimensional variables and create line plots.
- Combine two geo-referenced arrays in one plot by differencing, summing or averaging.
- Plot lon-lat data on a global or regional map using any of over 100 map projections or make a zonal average line plot.
- Overlay continent outlines or masks on lon-lat map plots.
- Use any of numerous color tables for the scale colorbar, or apply your own custom ACT, CPT, or RGB color table.
- Save plots to disk GIF, JPEG, PNG or TIFF bitmap images or as PDF or PostScript graphics files.
- Export lon-lat map plots in KMZ format.
- Export animations as MP4 video or as a collection of individual frame images.
- Explore remote THREDDS and OpenDAP catalogs and open datasets served from them.

### Get Panoply

Panoply requires that your computer have a [Java SE 8 runtime environment](#) installed.

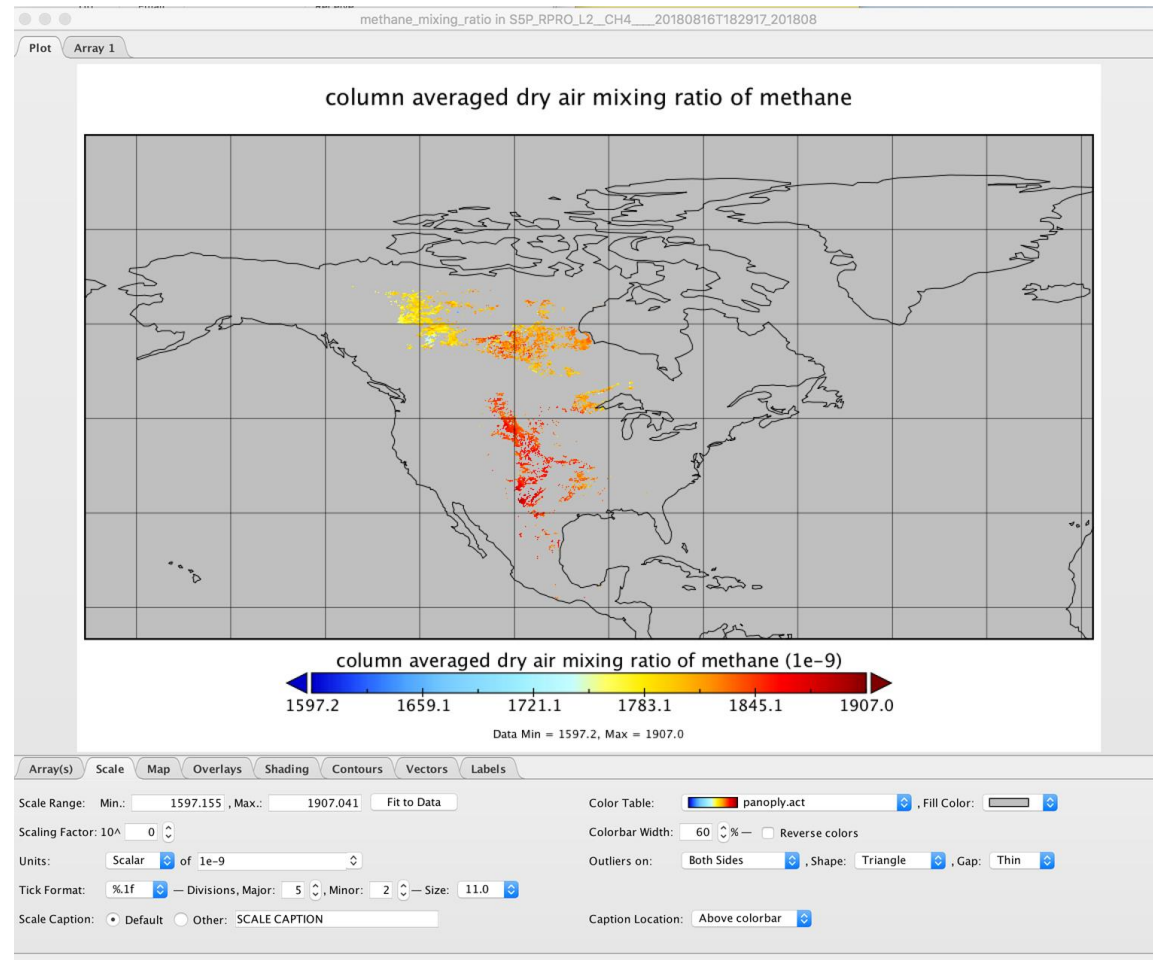
# Aerosol Index (AI)

[https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P\\_TROPOMI\\_Level2/S5P\\_L2\\_AER\\_AI.1/2018/228/S5P\\_OFFL\\_L2\\_AER\\_AI\\_20180816T183016\\_20180816T201146\\_04361\\_01\\_010100\\_20180822T174822.nc](https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P_TROPOMI_Level2/S5P_L2_AER_AI.1/2018/228/S5P_OFFL_L2_AER_AI_20180816T183016_20180816T201146_04361_01_010100_20180822T174822.nc)



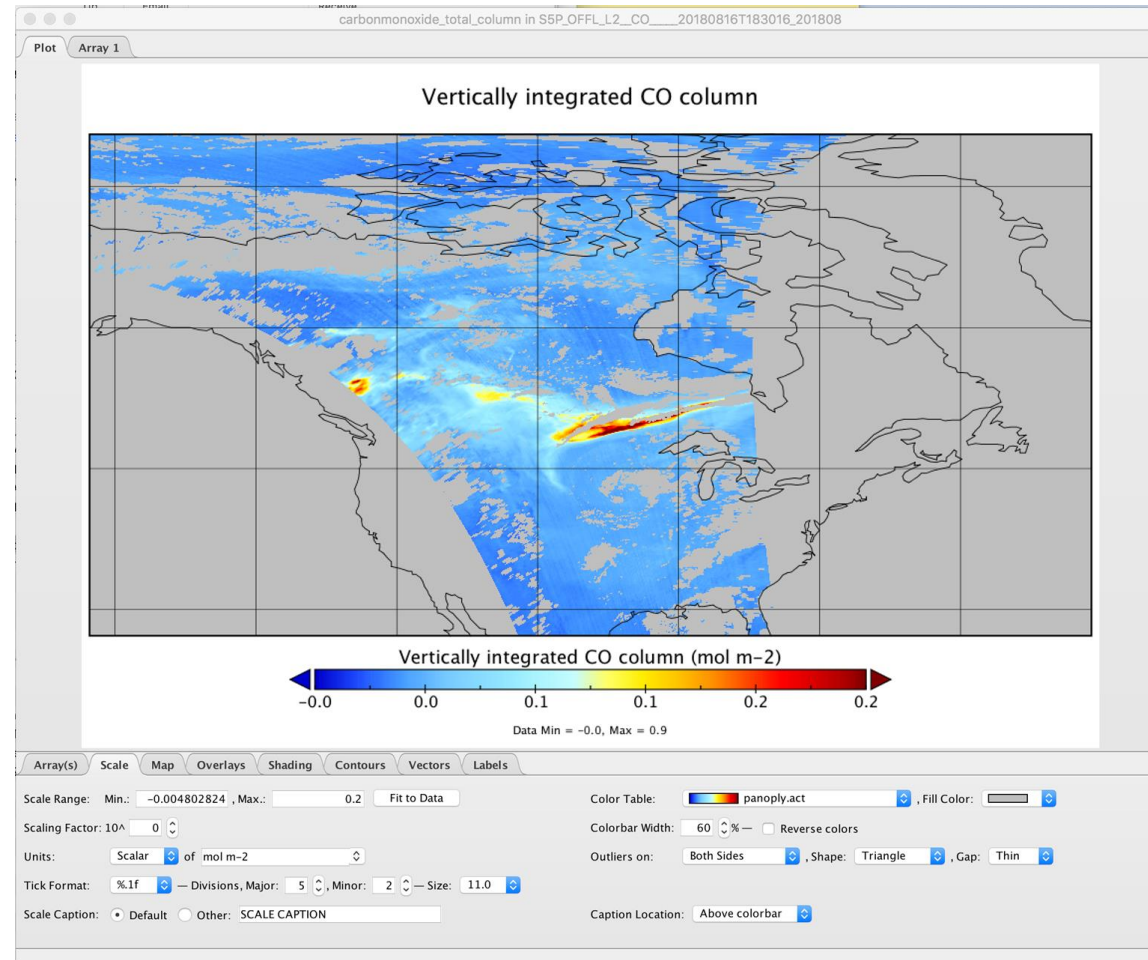
# Methane

[https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P\\_TROPOMI\\_Level2/S5P\\_L2\\_CH4\\_.1/2018/228/S5P\\_RPRO\\_L2\\_CH4\\_20180816T182917\\_20180816T201245\\_04361\\_01\\_010202\\_20190101T194705.nc](https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P_TROPOMI_Level2/S5P_L2_CH4_.1/2018/228/S5P_RPRO_L2_CH4_20180816T182917_20180816T201245_04361_01_010202_20190101T194705.nc)



# Carbon Monoxide

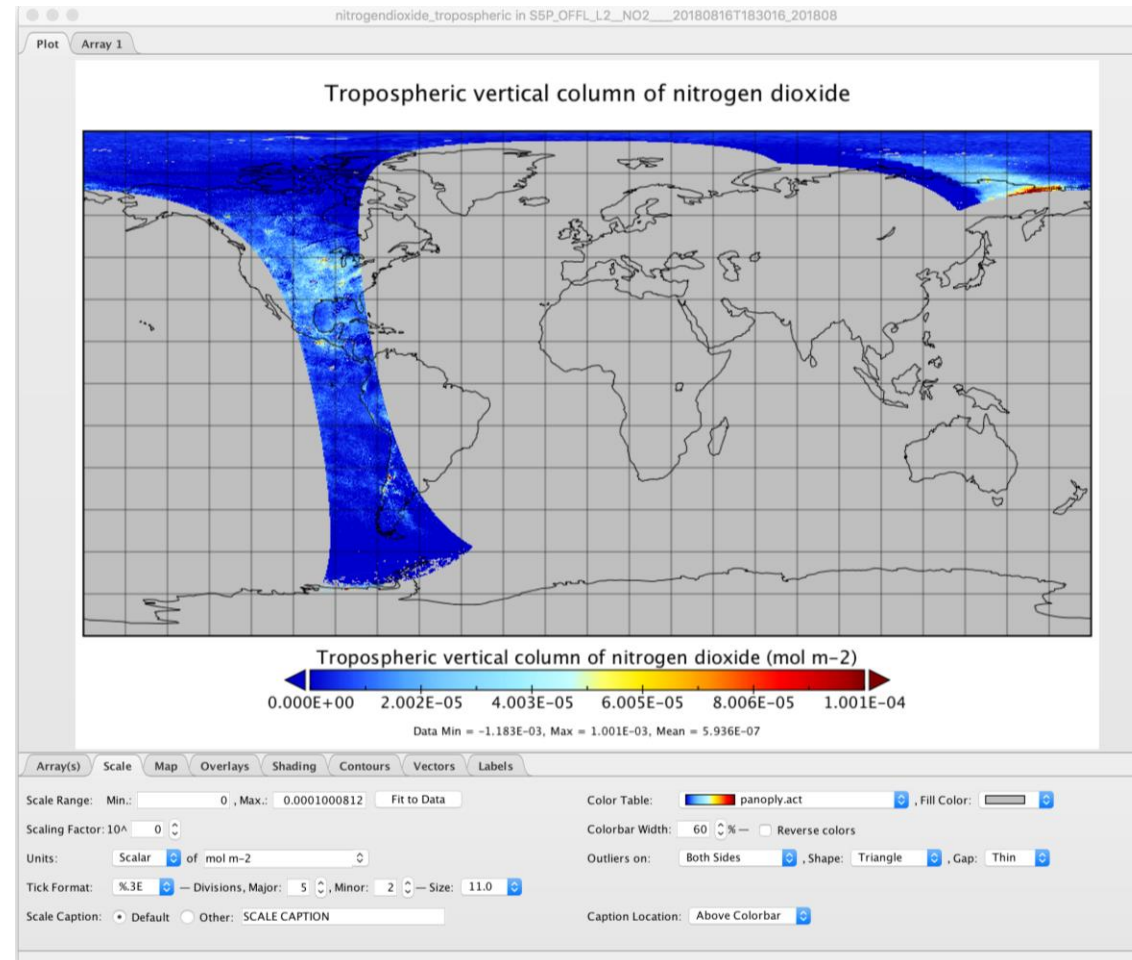
[https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P\\_TROPOMI\\_Level2/S5P\\_L2\\_CO\\_.1/2018/228/S5P\\_OFFL\\_L2\\_CO\\_20180816T183016\\_20180816T201146\\_04361\\_01\\_010100\\_20180822T174815.nc](https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P_TROPOMI_Level2/S5P_L2_CO_.1/2018/228/S5P_OFFL_L2_CO_20180816T183016_20180816T201146_04361_01_010100_20180822T174815.nc)



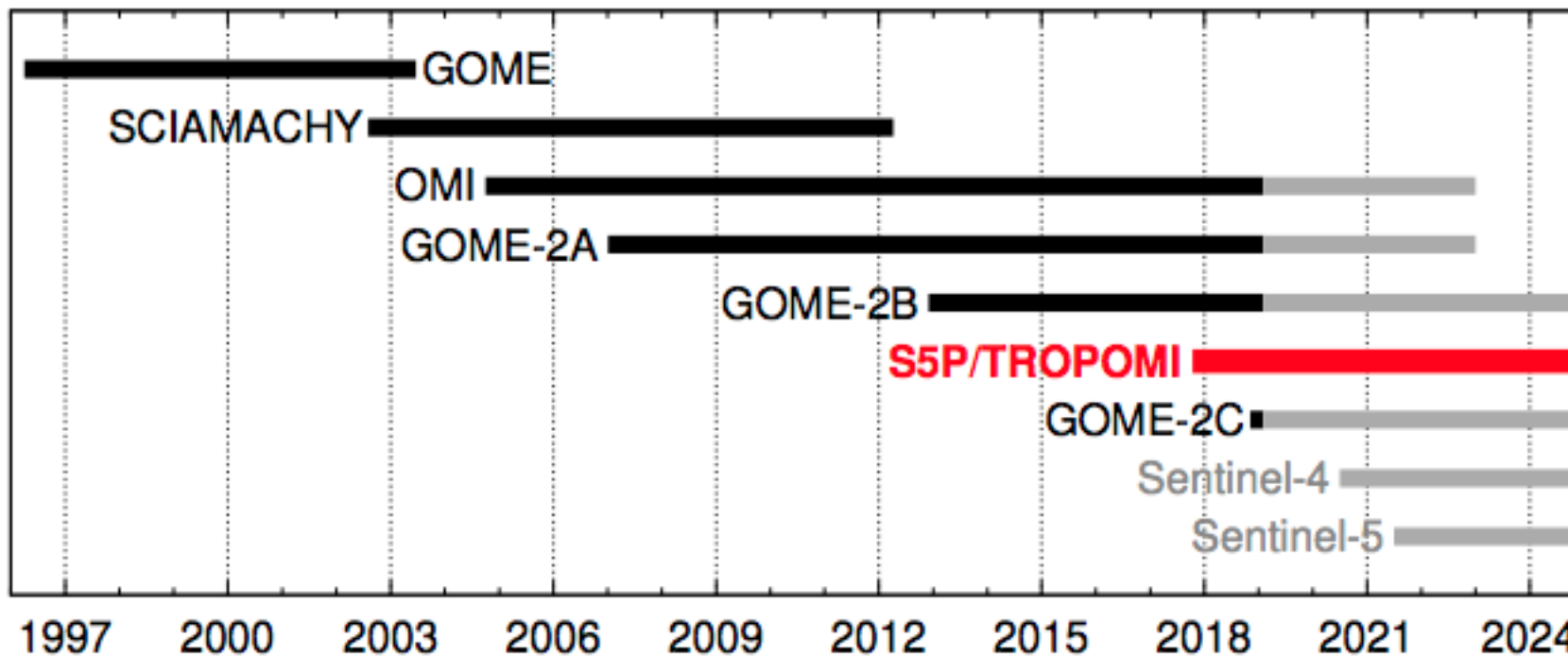


# Nitrogen Dioxide

[https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P\\_TROPOMI\\_Level2/S5P\\_L2\\_NO2\\_.1/2018/228/S5P\\_RPRO\\_L2\\_NO2\\_20180816T182917\\_20180816T201245\\_04361\\_01\\_010202\\_20190218T070149.nc](https://tropomi.gesdisc.eosdis.nasa.gov/data//S5P_TROPOMI_Level2/S5P_L2_NO2_.1/2018/228/S5P_RPRO_L2_NO2_20180816T182917_20180816T201245_04361_01_010202_20190218T070149.nc)



# Past & Future (ESA view)

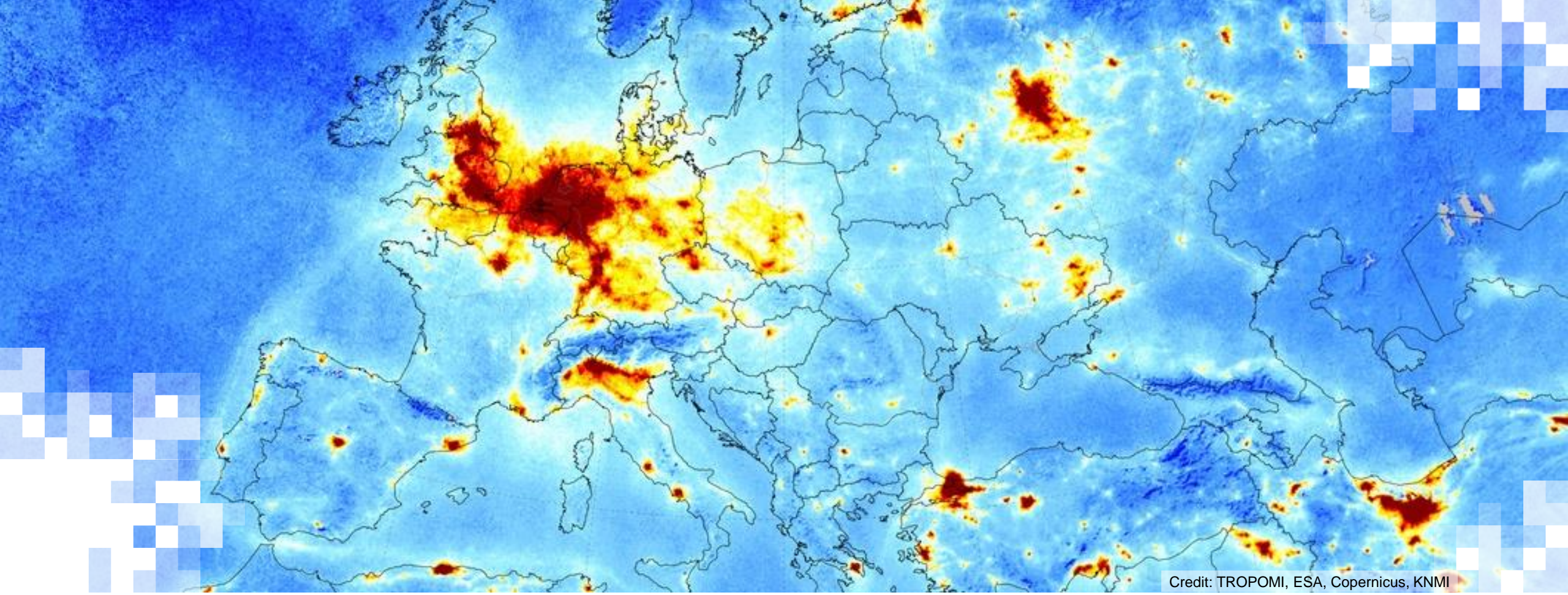


→ GEMS  
TEMPO

Image Credit: [TROPOMI ATBD of the total and tropospheric NO<sub>2</sub> data products](#)

# Preparing for Part 3 (session # 3)

- Python instruction
- Data download instruction



## Question & Answers