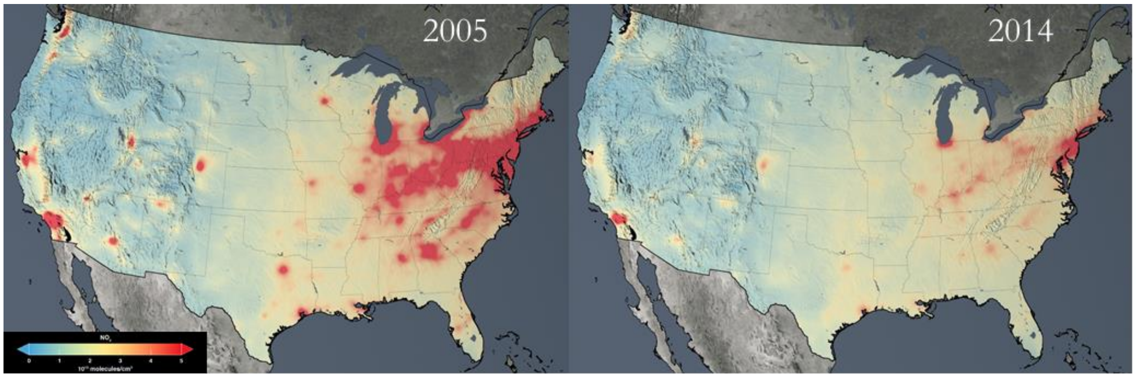
A Brief Tutorial on Using the Ozone Monitoring Instrument (OMI) Nitrogen Dioxide (NO_2) Data Product for SIPS Preparation



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VERSION 6-18

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VERSION 6-18

A Brief Tutorial on Using the Ozone Monitoring Instrument (OMI) Nitrogen Dioxide (NO_2) Data Product for SIPS Preparation

Please contact Bryan Duncan (Bryan.N.Duncan@nasa.gov) and Lok Lamsal (Lok.Lamsal@nasa.gov) with your questions.

Although State Implementation Plans (SIPs) typically rely on observations from ground-level monitoring networks and regulatory modeling, satellite data is increasingly available to state agencies. Below is an example of how one state agency used satellite data to supplement a state implementation plan to improve air quality. An advantage of satellite data is that it provides information for a broader area than sampled by ground-based networks. This document provides examples and guidance for using satellite products of nitrogen dioxide (NO_2), a precursor to ground-level ozone and nitrate aerosol, in state implementation plans. It also provides some guidance on using SO_2, a precursor to sulfate aerosol

1. SIP Case Study: Texas Commission on Environmental Quality (TCEQ)

Stakeholder Mark Estes (TCEQ) used OMI NO_2 data in 2016 Houston-Galveston-Brazoria attainment demonstration SIP revision for the 2008 eight-hour ozone standard. The data are used as part of the weight-of-evidence information in Chapter 5, specifically Section 5.2.2:

https://www.tceq.texas.gov/assets/public/implementation/air/sip/hgb/HGB_2016_AD_RFP/AD_Adoption/16016SIP_HGB08AD_ado.pdf.

Here are a few other (non-SIP) examples of how inferred trends in OMI NO_2 and SO_2 have been used by stakeholders:

a. See Section 3.3 (Page 57) of the TCEQ *Science Synthesis Report: Atmospheric Impacts of Oil and Gas Development in Texas*.

b. See the OMI NO_2 animation in the EPA report, *Our Nation's Air*. Here is a similar animation for SO_2.

c. Recently, former President Obama created a video using OMI NO_2 data to show that air quality is improving and to indicate that the Clean Air Act is working. The work presented was the subject of NASA press releases in June 2014 and December 2015.

2. Publicly-Available Images of Trends in NO_2 and SO_2 Obtained from NASA Satellite Data

In the example above, TCEQ simply presented images and graphics that were made by NASA and are publicly available via the NASA Air Quality website: https://airquality.gsfc.nasa.gov. (As a word of caution, the website will likely be restructured within the next year, so the following links may not work in the future. Please visit https://airquality.gsfc.nasa.gov to look for the images and data discussed below.) Here are a few of these images and graphics.

Animations of Annual Maps (2005-2016) over the U.S.:

- OMI NO_2: https://airquality.gsfc.nasa.gov/video/changes-nitrogen-dioxide-usa-2005-2014
- OMI SO_2 Trends: https://airquality.gsfc.nasa.gov/video/sulfur-dioxide-usa

Slider Maps of OMI NO_2 (2005-2011*):

- https://airquality.gsfc.nasa.gov/slider/ohio-valley
- https://airquality.gsfc.nasa.gov/slider/east-coast

*While the sliders are for 2005 and 2011, there have not been large decreases in NO_2 since 2011 as indicated by the satellite data as well as AQS data.

Images of OMI SO_2 over power plants (2005-7 vs. 2008-2010):

- https://www.nasa.gov/topics/earth/features/coal-pollution.html

Images of OMI NO_2 trends (see next two figures) over 20 large U.S. cities (2005-2016):

- https://airquality.gsfc.nasa.gov/cities
-

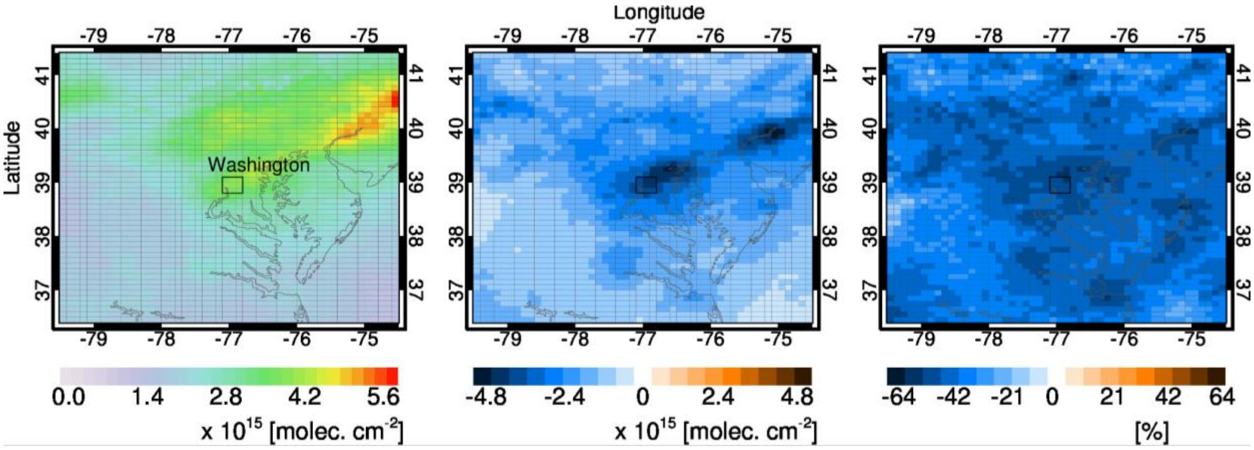


Figure Caption: (left) Annual average OMI NO_2 column (x10^{15} molecules/cm^2) over the Mid-Atlantic region for 2016. (middle) The absolute change in OMI NO_2 column (x10^{15} molecules/cm^2) from 2005 to 2016. (right) Same as middle, but for percent change (%).

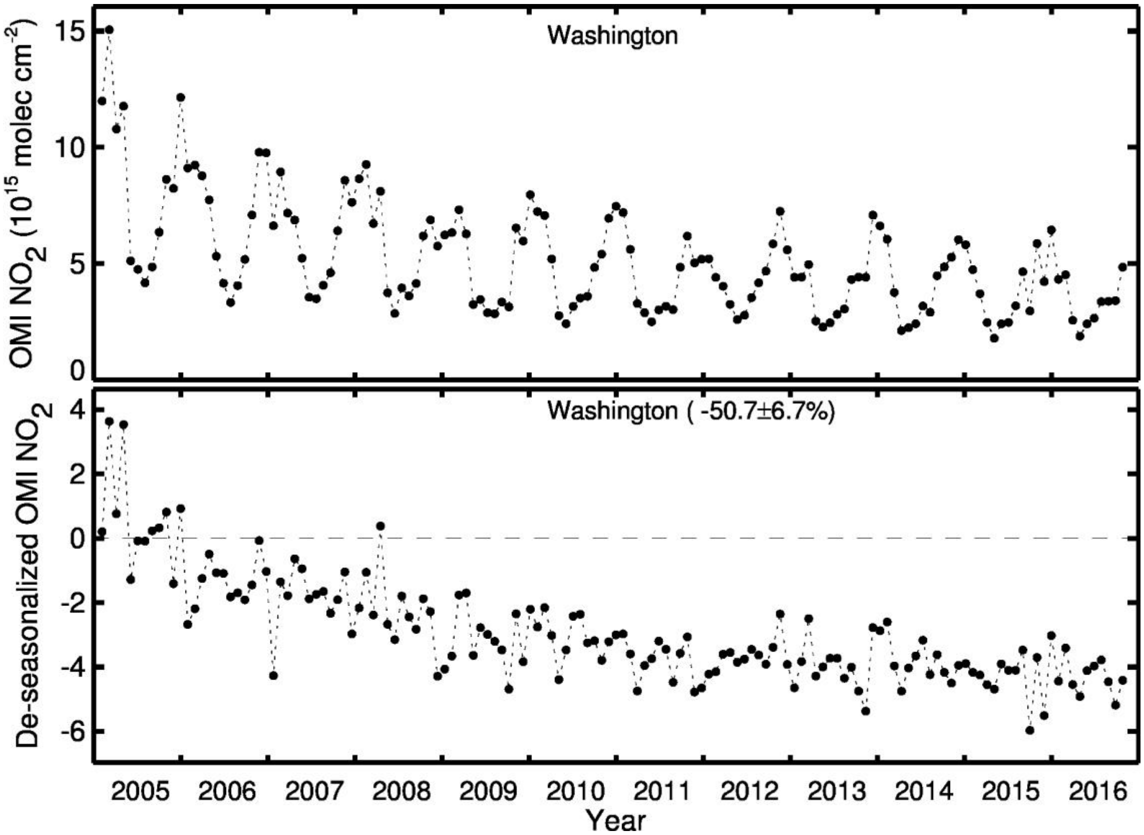


Figure Caption: (top) Monthly average OMI NO_2 column ($x10^{15}$ molecules/cm^2) over Washington, DC. (bottom) Deseasonalized OMI NO_2 column ($x10^{15}$ molecules/cm^2). The percent trend from 2005 to 2016 is shown in parenthesis next to the city name.

The data can be downloaded in ASCII and Excel files for each city.

OMI NO_2 trends (no images) for about 200 other U.S. cities (2005-2016):

- https://airquality.gsfc.nasa.gov/cities

Trends* (no images) of OMI NO_2 over U.S. power plants:

- https://airquality.gsfc.nasa.gov/power-plants

*Note that the trends over a give power plant may reflect a trend in emissions from the facility but there is likely a portion of the trend associated with regional background changes.

Ozone Sensitivity to Precursor Emissions:

- https://www.nasa.gov/feature/goddard/2017/nasa-satellite-tracks-ozone-pollution-by-monitoring-its-key-ingredients

3. Do Your Own Analyses of Changes in NO_2 or SO_2

If you are looking for more than the ready-made images presented in the previous section, please read on. Currently, there are numerous data websites and webtools available to the end-user. The problem is simply that there are too many and the options are difficult to navigate, particularly for the uninitiated. Fortunately, there are a number of NASA resources (e.g., webtools, tutorials, trainings) available for the beginner to the advance data end-users.

- *General Overview:* For general questions on the use of satellite data in air quality, please refer to the review to the following overview paper: Duncan, B., et al., *Satellite Data of Atmospheric Pollution for U.S. Air Quality Applications: Examples of Applications, Summary of Data End-User Resources, Answers to FAQs, and Common Mistakes to Avoid*, Atmos. Environ., doi:10.1016/j.atmosenv.2014.05.061, 2014. If you don't have time to read the article, you can read an abbreviated version in Section 4.
- *Webtools:* There are numerous webtools that may be used for subsetting, downloading and plotting NASA air quality data. Some of these webtools are listed at https://airquality.gsfc.nasa.gov/resources and https://arset.gsfc.nasa.gov/about/models-tools. For instance, one popular webtool is Giovanni – see the following link for introductory materials on using Giovanni for air quality applications: https://arset.gsfc.nasa.gov/about/models-tools#giovanni.
- *Tutorials & In-Person Trainings:* If after looking at the webtools and you are feeling overwhelmed, you may want to turn to the NASA Applied Remote Sensing Training (ARSET) program (https://arset.gsfc.nasa.gov/), which has many resources, such as the latest on inferring surface $PM_{2.5}$ from AOD data. For instance, the Giovanni weblink above is on the ARSET website. Check out their webinar page, which lists their free archived and upcoming live webinars on how to use satellite data for health and air quality applications.
- *Speak with a Scientist:* The NASA Health and Air Quality Applied Sciences Team (HAQAST; https://haqast.org) may be able to help you. HAQAST's goal is to facilitate the use of satellite data by health and air quality managers.
- *Get it from the Horse's Mouth:* Ultimately, the best resources for accurately using satellite data for specific applications are the people who develop the retrievals themselves. As a word of caution, the developers are not funded to provide specific analysis or tailored plots for the end-user. Nevertheless, they are the people who know the strengths and limitations of the data for specific applications and are often willing to provide new and improved datasets that aren't currently publicly available. Their advice will be invaluable. Since there are so many datasets and retrieval algorithm developers, it is best to do a little search via the web for contact information of the appropriate people.

In the next section, we present two examples of the steps that an air quality manager used to download and plot OMI NO_2 data.

4. General background on the use of satellite data for health and air quality applications

If you don't have time to read Duncan et al. (2014), here is a brief summary.

Satellite instruments are perched high above the Earth's surface, affording a "God's Eye" view of the planet's air pollution. This spatial coverage has opened new areas of investigation by the air quality community, such as for inferring surface pollutant levels, emissions, and trends, and the health effects of specific pollutants (e.g., Streets et al. 2013; Duncan et al. 2014). Instruments measuring ultraviolet (UV)/visible wavelengths of light allow the detection of NO_2, SO_2, and small organic molecules, like formaldehyde and glyoxal, and instruments measuring infrared (IR) wavelengths of light detect CO, methane, and ammonia. Particulate matter (PM) may be inferred via aerosol optical depth (AOD) using IR/visible wavelengths, but a direct relationship with PM emissions is still elusive (e.g., Duncan et al. 2014, and references therein). Satellite data of pollutants have proven valuable for health and air quality applications, despite some challenges that must be overcome (Martin 2008; Streets et al. 2013; Duncan et al. 2014; and references therein).

A retrieval algorithm is the method used to convert electromagnetic radiation observed by the satellite instrument to an atmospheric quantity, such as a column density. For example, the NASA Aura Ozone Monitoring Instrument (OMI) data are given in the sum of all molecules from the instrument to the Earth's surface and typically reported in units of molecules/cm^2. The overall uncertainty associated with data products is a combination of uncertainties associated with the instrument and those introduced in the retrieval algorithm, which is a multi-step and sometimes imperfect process (e.g., Duncan et al., 2014).

A fundamental challenge of using these data is the proper "translation" of the observed quantities to more useful quantities, such as emissions and surface concentrations. From a column density, one may infer a surface concentration (e.g., at "nose-level") or emission flux if the chemical species at the surface is not greatly perturbed by physical transport or chemical conversion; then to first order it can be presumed that it is closely related to the direct emissions from sources within the observed surface grid. Generally, this is the case for NO_2, SO_2 and formaldehyde as their chemical lifetimes are relatively short and their primary sources are located near the Earth's surface. These assumptions work best for isolated point sources. Otherwise, the use of a chemical transport model may be necessary to allow for transport into and out of any grid and for chemical conversion processes.

Emissions: Streets et al. (2013) reviewed the current capability to estimate emissions from space, and in this paragraph we highlight studies of emissions using NASA Aura data that have been published subsequently. NO_x emission sources continue to be the primary focus because of the strength of the OMI signal and therefore its potential to detect low-intensity sources. Applications have included ship emissions (Vinken et al. 2014a), Canadian oil sands (McLinden et al. 2012, 2014), soil emissions (Vinken et al. 2014b), biomass burning (Castellanos et al. 2014), and urban areas (Vienneau et al. 2013; Lamsal et al., 2015). Another recent development has been the application of OMI NO_x data to studies of nitrogen deposition flux (Nowlan et al. 2014). Though the SO_2 signal from OMI is two to three orders of magnitude weaker than the NO_x signal, statistical data enhancement techniques have enabled valuable new studies of SO_2 emissions from Canadian oil sands (McLinden et al., 2014); and Fioletov et al. (2013) reviewed the ability of OMI to detect large SO_2 sources worldwide, including power plants, oil fields, metal smelters, and volcanoes. Recent retrieval improvements and new statistical techniques have allowed for the detection of even smaller SO_2 sources (McLinden et al., 2016).

Power Plant Emissions: Work continues on the challenge of developing reliable quantitative relationships between observations and source emissions for large isolated power plants. Previous work had only moderate success in correlating observations with emissions (Kim et al. 2009; Russell et al. 2012; Duncan et al. 2013; Lu et al., 2012). Based on earlier work by Martin et al. (2003) and Beirle et al. (2004), new techniques have now been developed to enhance the predictive power of the single-source relationship by taking into account such factors as chemical lifetime and dispersion lifetime within the framework of high-resolution data statistical techniques. Such techniques to account for these complex factors have been explored by Beirle et al. (2011), Fioletov et al. (2011), Lamsal et al. (2011), Valin et al. (2013), and de Foy et al. (2014). The greater the sophistication of the technique, the more it relies on additional weather data (wind speed and direction) or model calculations to simulate the surface column density. Undoubtedly, the availability of hourly observations at higher resolution from a new geostationary satellite would greatly enhance the capability.

Surface Concentrations: There has been considerable effort over the last decade to improve techniques to infer surface concentrations from satellite data, particularly for NO_2 (e.g., Lamsal et al., 2008) and $PM_{2.5}$ (e.g., van Donkelaar et al., 2015, 2016). There are issues with inferring surface concentrations and making apple-to-apple comparisons between the satellite data and surface observations. For instance, estimating surface $PM_{2.5}$ from satellite AOD data is complicated as it requires knowledge of various factors that influence AOD, such as relative humidity, aerosol composition, and the altitude of the aerosol layer (e.g., Hoff and Christopher, 2009; Duncan et al., 2014, and references therein). As another example, the spatial footprint of the satellite data is often large (e.g., 10x10 km^2), so that a surface observation may not accurately represent the larger area. This is particularly true for short-lived pollutants, such as NO_2. Nevertheless, the inferred surface concentrations largely agree well with surface observations (e.g., Figure below; Duncan et al., 2013, Lamsal et al., 2015). The agreement often improves with temporal averaging as random errors cancel. Consequently, the comparison of monthly, seasonal, and annual means is often favorable, so that satellite data may be used to estimate trends in surface concentrations. A few satellite datasets are useful for inferring surface trends directly from trends in a column density if most of the pollutant is found near the surface. This is the case for two common air pollutants, NO_2 and SO_2.

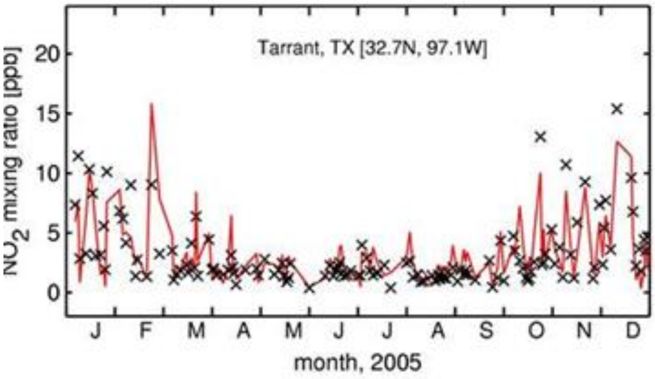


Figure Caption: Daily OMI-derived surface NO_2 data (red line) versus in situ observations (crosses). OMI data are not available for every day due to clouds at satellite overpass.

Looking Forward: Our ability to infer surface concentrations and emissions is expected to continue to improve.

- First, new and improved instruments (e.g., ESA TROPOMI, NOAA GOES-R ABI) have recently been launched, which have substantially better temporal and spatial resolutions, among other improvements. Upcoming (2-5 years) instruments will fly in geostationary orbits, allowing hourly data to be collected over any given location over the Earth's surface, thus providing high quality data at unprecedented spatial and temporal resolutions. (A geostationary satellite's orbital period matches the Earth's rotational period, so the satellite appears to be motionless to an observer on the Earth's surface. Most current instruments are on polar-orbiting satellites, which overpasses any given location on the Earth's surface approximately once per day during daylight hours.) With current polar-orbiting satellites, clouds often interfere with data collection so that daily data are often not possible; there will be more opportunities to observe cloud-free scenes throughout the day with upcoming geostationary satellites. The geostationary NASA TEMPO, Korean GEMS, and ESA Sentinel-4 instruments are planned to launch within the next five years and will provide data over North America, East Asia and Europe/North Africa, respectively.

- Second, techniques to infer surface concentrations from quantities observed by satellite instruments are always evolving (e.g., van Donkelaar et al., 2015) as mentioned above.
- Third, continuing refinements to the satellite retrieval algorithms have resulted in column density data products that are now of sufficient maturity for some species (e.g., NO_2) to allow reliable and quantitative estimation of concentrations, trends, and fluxes of some surface pollutants. This is an achievement given that the OMI team, for instance, was initially uncertain as to whether it was practical to credibly derive these quantities with the early versions of the retrieval algorithms.

If you would like more information on $PM_{2.5}$ or OMI data in general, please take a look at these articles:

Overview paper on AOD and $PM_{2.5}$: Hoff, R., and S. Christopher, Remote sensing of particulate pollution from space: have we reached the promised land?, J. Air Waste Manag. Assoc., 59, 6, 645-675.

Science of OMI overview paper: Levelt, P., et al.: The Ozone Monitoring Instrument: Overview of twelve years in space, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2017-487 , in review, 2017.

5. NO_2 column data

Here are a few places to look for information on OMI NO_2 trends in the U.S. and around the world:

- *NO_2 trends:* US and worldwide trends in NO_2 pollution over the last decade: https://airquality.gsfc.nasa.gov/
- Duncan, B.N., L.N. Lamsal, A.M. Thompson, Y. Yoshida, Z. Lu, D.G. Streets, M.M. Hurwitz, and K.E. Pickering, A space-based, high-resolution view of notable changes in urban NO_x pollution around the world (2005-2014), J. Geophys. Res., doi:10.1002/2015JD024121, 2016. http://onlinelibrary.wiley.com/doi/10.1002/2015JD024121/abstract
- Krotkov, N. A., et al.: Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015, Atmos. Chem. Phys., 16, 4605-4629, https://doi.org/10.5194/acp-16-4605-2016, 2016.

In addition to OMI, there are several NO_2 column data products from other instruments (Table 1). These include GOME (Global Ozone Monitoring Experiment), OMI, GOME-2 and SCIAMACHY (Envisat SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY). The ESA Tropospheric Ozone Monitoring Instrument (TROPOMI), which is a follow-on instrument to OMI but with finer horizontal resolution (next two figures below), launched in October 2017 on the polar-orbiting Sentinel-5 Precursor satellite and is targeting a

7x7 km^2 pixel size. TROPOMI also measures CO, CH_4, SO_2, and other gases that will be useful for AQ studies. The NASA TEMPO instrument is planned to launch in the next few years. TEMPO will be in geostationary orbit over North America, which will collect hourly data throughout the day at high spatial resolution (pixel size of 2.1x4.7 km^2) (figurebelow).

*Table **1** Information on the satellite instruments that measure tropospheric NO_2 column density.*

Instrument	**Platform**	**Time Period**	**Nadir Resolution (km^2)**	**Overpass time (Local Time)**	**Global coverage (days)**
GOME	ERS-2	1995–2003	320 × 40	10:30 AM	3
SCIAMACHY	ENVISAT	2002–2012	60 × 30	10:00 AM	6
OMI	Aura	2004–	24 × 13	1:45 PM	2
GOME-2	MetOp	2006–	80 × 40	9:30 AM	1
TROPOMI	Sentinel-5 Precursor	2017-	7x7	1:30 PM	1
TEMPO	?	Anticipated launch in early 2020s	2.1x4.7	daylight hours	1 (for North America)

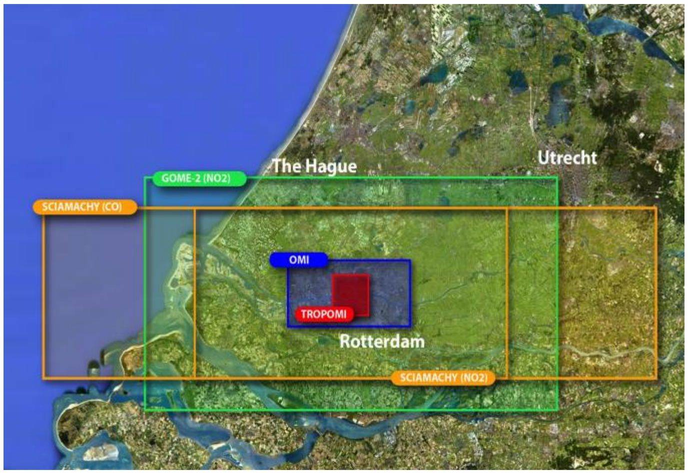


Figure Caption: Comparison of horizontal resolutions (at nadir) of several instruments that observe NO_2.

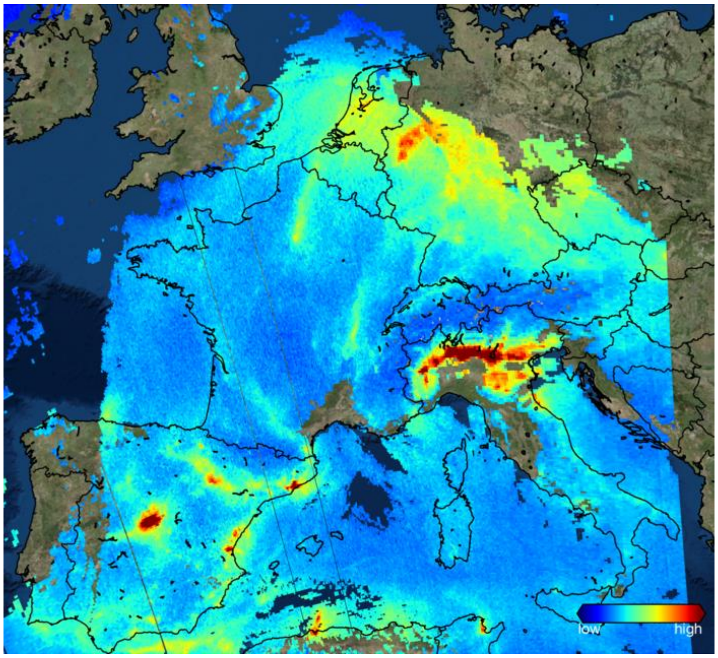


Figure Caption: "First look" TROPOMI NO_2 data for one overpass on November 22, 2017 illustrates the superior horizontal resolution of this latest instrument. The TROPOMI data are expected to be publicly released in spring 2018.

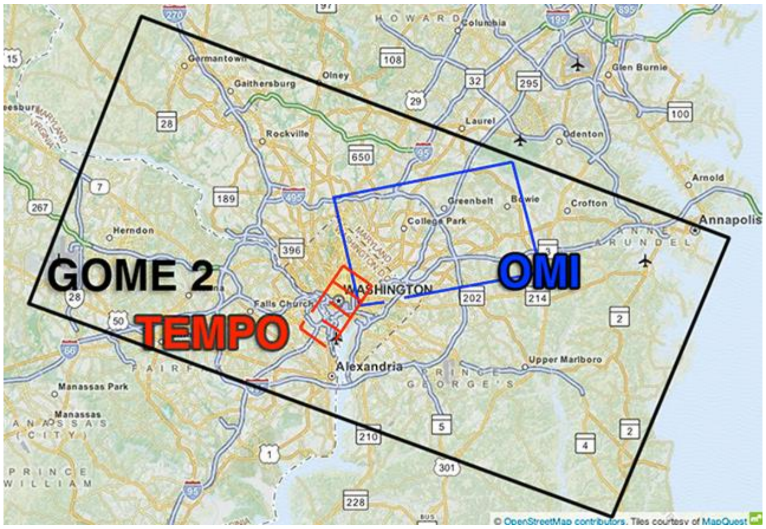


Figure Caption: Comparison of the horizontal resolutions (at nadir) of several instruments that currently (or will) observe NO_2 over the Washington, DC metro area.

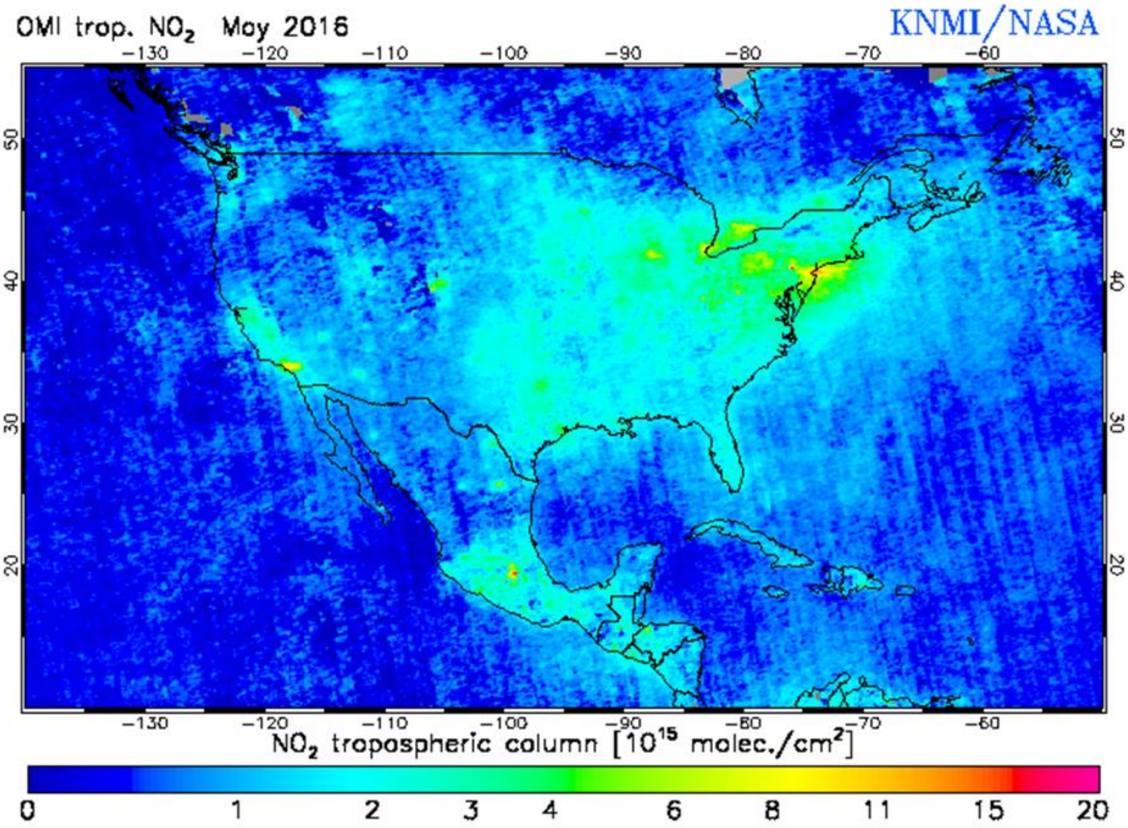
2a. Accessing GOME, SCIAMACHY, OMI, GOME-2 NO_2 Data

GOME, SCIAMACHY, OMI and GOME-2 NO_2 data may be obtained from the TEMIS website and OMI data from the NASA website. A step by step set of instructions (contributed by Michael Geigert, CT DEEP, with additions from Bryan Duncan and Lok Lamsal) is given here for downloading the data.

TEMIS (Dutch website)

NO_2 products and documentation from the European TEMIS project (KNMI, Netherlands) can be found at http://www.temis.nl/airpollution/no2.html. TEMIS is a web-based service used to browse and download atmospheric satellite data products. These tropospheric NO_2 columns are derived from satellite observations based on slant column NO_2 retrievals with the DOAS technique, and the KNMI combined modelling/retrieval/assimilation approach. The slant columns from GOME, SCIAMACHY and GOME-2 observations are derived by BIRA-IASB, the slant columns from OMI by KNMI/NASA. The KNMI OMI NO_2 product is often referred to as the “DOMINO Product”.

On the TEMIS products web page, there is a link for monthly regional NO_2 products: http://www.temis.nl/airpollution/no2col/no2regioomimonth_v2.php. Since ozone sensitivity analysis uses NO_2 monthly means, it is useful to get an image of the data that is being analyzed. A sample image from the OMI link for NO_2 in May 2016 looks like this:



During May 2016, much of the upper Midwest and Northeast States were being affected by the smoke plume from the Fort McMurray, Alberta wildfires, and this image of elevated NO_2 over those areas may be indicative of that.

2b. Accessing the OMI Data from the NASA Website

The NASA website is another repository for OMI NO_2 satellite data. OMI NO_2 data products are archived and distributed from the Goddard Earth Sciences Data and Information Services center (GES-DISC). OMI products are written in HDF-EOS5 format. GES-DISC also provides a list of tools that read HDF-EOS5 data files. Table 2 shows the data that are available for Levels 2, 2g and 3. There are a number of “derivative” products of this OMI NO_2 product as illustrated in Figure 5.

As with all remote sensing data sets, there are subtleties in the OMNO2 data that are due to geophysics, instrumental measurements, and the retrieval algorithm. Users of the data are encouraged to communicate directly with members of the respective algorithm team. Users of these products are recommended to read their product related publications and README documents.

For advanced uses, Level-2 products are recommended. When using Level-2 products, it is recommended to seek guidance from the developers to ensure appropriate screening and quality control measures are applied. Particular attention should be paid to the various data quality flags. For most users, the Summary Quality Flag (e.g., vcdQualityFlags for NO_2) should suffice. In row-anomaly-affected field-of-views (FOVs), the column amount fields have been either incorrect values or set to their respective fill values, so XTrackQualityFlags need to be explicitly checked. In certain periods of time, using these flags will result in up to 50% field-of-view rejection rate.

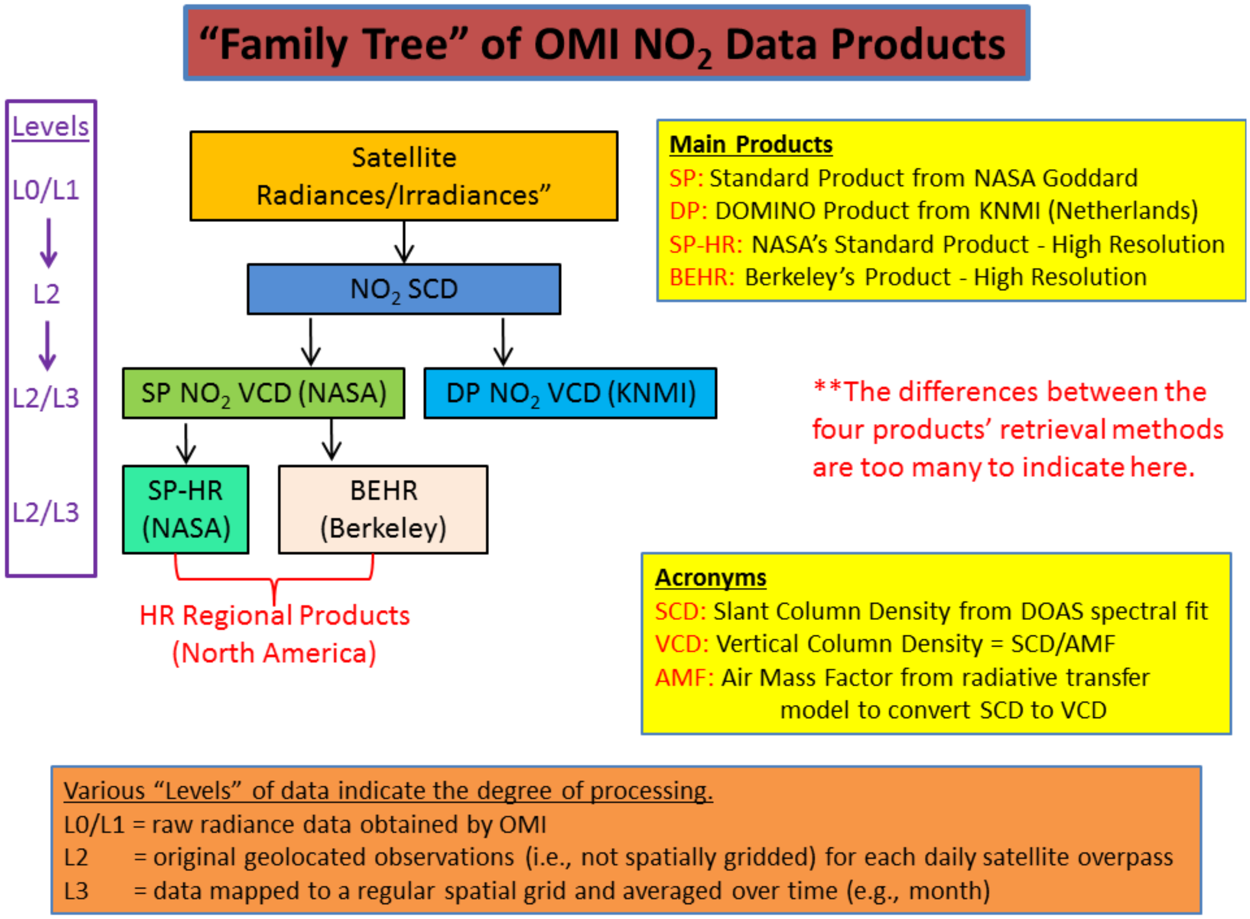
Since the L2 data are copied directly into the L2G data product, the general quality of the data is the same. For some purposes, in some geographical regions (e.g., in polar regions), more than 15 L2 FOVs may have their centers land in a particular cell, and some L2 data, whose optical path lengths are longer than the others, may be excluded. This should happen rarely, but may lead to slight shifts in statistical measures.

Level-3 satellite products are produced from Level-2 products by using best pixel data over each grid cell, so these products already incorporate the appropriate quality control measures. The product development team has chosen a cloud screening criterion of the effective cloud fraction (e.g. cloud fraction < 0.3 for NO_2), which reflects a compromise between data quality and quantity. While the L3 data product can be used to assess the daily NO_2 column densities, it is important to remember that the values in the grid cells are weighted averages of a number of OMI measurements, and the value in a cell may not correspond to any one actual measurement.

Table 2: OMI NO_2 data products from the NASA websites. These products are often referred to as the "Standard Product".

Image	**Dataset**	**Temporal Resolution**	**Spatial Resolution**	**Process Level**	**Begin Date**	**End Date**
OMNO2 sample image	OMI/Aura Nitrogen Dioxide (NO_2) Total and Tropospheric Column 1-orbit L2 Swath 13x24 km^2 V003 (OMNO2.003) - Atmospheric Chemistry Get Data/ Subset Data	1 hour	13 km x 24 km	2	2004-10-01	2017-11-01
OMNO2d sample image	OMI/Aura NO2 Cloud-Screened Total and Tropospheric Column L3 Global Gridded 0.25 degree x 0.25 degree V3 (OMNO2d.003) – Atmospheric Chemistry Get Data/ Subset Data	1 day	0.25° x 0.25°	3	2004-10-01	2017-11-01
OMNO2G sample image	OMI/Aura NO2 Total and Tropospheric Column Daily L2 Global Gridded 0.25 degree x 0.25 degree V3 (OMNO2G.003) – Atmospheric Chemistry Get Data /Subset Data	1 day	0.25° x 0.25°	2G	2004-10-01	2017-11-01
No images	OMI/Aura NO2 Cloud-Screened Tropospheric Column L3 Global Gridded 0.1 degree x 0.1 degree, https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L3/OMNO2D_HR/	1 day	0.1 x 0.1	3	2004-10-01	2017-11-01

**For a more detailed list of available OMI NO_2 data products, please visit this ARSET weblink: https://arset.gsfc.nasa.gov/airquality/applications/trace-gases/omi-no2-data-and-imagery



“Family Tree” of OMI NO_2 Data Products

Main Products
SP: Standard Product from NASA Goddard
DP: DOMINO Product from KNMI (Netherlands)
SP-HR: NASA’s Standard Product - High Resolution
BEHR: Berkeley’s Product - High Resolution

**The differences between the four products’ retrieval methods are too many to indicate here.

Acronyms
SCD: Slant Column Density from DOAS spectral fit
VCD: Vertical Column Density = SCD/AMF
AMF: Air Mass Factor from radiative transfer model to convert SCD to VCD

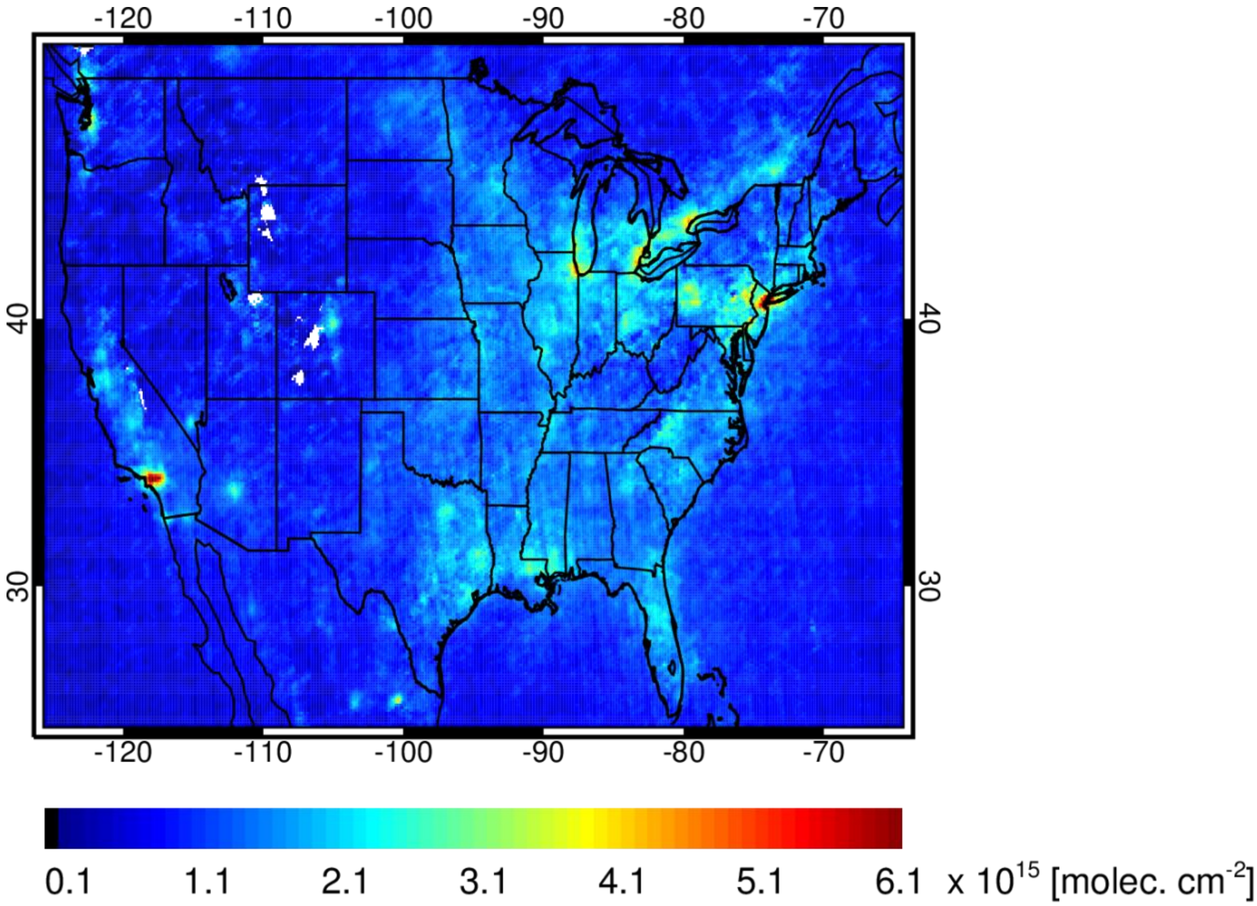
Various “Levels” of data indicate the degree of processing.
L0/L1 = raw radiance data obtained by OMI
L2 = original geolocated observations (i.e., not spatially gridded) for each daily satellite overpass
L3 = data mapped to a regular spatial grid and averaged over time (e.g., month)

Figure 1: Note to the User: There are quite a few derivatives of the NASA OMI NO_2 data product, which is sometimes referred to as the “Standard Product”. The “Family Tree” schematic illustrates these derivatives, but there are too many differences between the products to mention here. For the high-resolution products, the reader is referred to the NASA and BEHR websites.

2c. Data Uncertainties

Significant error sources in the retrieval of the tropospheric NO_2 column are associated with the slant column densities, the air mass factor, and with the separation of the stratosphere and troposphere. The uncertainty due to spectral fitting is 0.75×10^{15} molec cm^{-2} [Boersma et al., 2007] dominates the overall retrieval error over the oceans and remote areas. The uncertainty arising from the stratosphere-troposphere separation is 0.3×10^{15} molec cm^{-2} [Bucsela et al., 2013]. The air mass factor errors arise primarily from uncertainties in cloud parameters, surface reflectivity, profile shape, and aerosols [Martin et al., 2002; Boersma et al., 2011; Bucsela et al., 2013], and dominates over the continental source regions. The overall error in the OMI vertical column density for clear and polluted conditions is estimated to be 30%, but could be over 60% in the presence of clouds [Boersma et al., 2004].

Users could exclude cloudy observations using cloud radiance fractions exceeding 0.5-0.6. The stripes affecting the slant columns in the swath direction can add additional uncertainties. This effect is minimized in the NASA product by implementing correction for the stripes. The DOMINO product is not corrected for the stripes. For example, compare the image below with the one downloaded from the TEMIS website, which is shown above.



2d. Downloading the Data – An Example from Michael Geigert (CT DEEP)

To do a proper analysis, it is necessary to download the data files. Retrieving the actual NO_2 satellite data can be challenging if one is not familiar with the process. The TEMIS web site provides downloads for a KML file, and zip-ed ASCII data files in TOMS and ESRI grid formats. The NASA website provides downloads in the '.he5' format, which can be read by various tools.

2d1. Preliminary Steps

Here are some preliminary steps (for windows operating systems) to take before downloading the data that will facilitate the data analysis:

2d1a. Obtain a file 'unpacking' utility

Many of the data files are compressed in .tar format and will need something like this open source 'unpacking' utility from http://www.7-zip.org/ . You can use 7-Zip on any computer, including a computer in a commercial organization. You don't need to register or pay for 7-Zip.

After downloading and installing this application, you can use it to unpack any compressed file right from the Windows file manager.

2d1b. Understanding Satellite File Identifiers.

In order to download data, you may need to know the actual swath identifier that you are interested in. As described on the TEMIS web site, there are several satellites that provide NO_2 data, but only the OMI and GOME-2 have current data. The following is a description for the OMI data sets.

OMI is one of the instruments on the Aura satellite. Aura is part of the so called “A-train” series of satellites, which orbits with the MODIS AQUA satellite. This spacecraft orbits at 705 km above the Earth with a sixteen-day repeat cycle. In a single orbit, OMI measures approximately 1650 swaths from terminator to terminator. With an orbital period of 99 minutes, OMI views the entire sunlit portion of the Earth in 14–15 orbits. It has a 1:45 PM ±15 minute equator crossing time and typically, the orbit times for the daytime ascending North American orbits begin around 1700 UTC. OMI measures criteria pollutants such as O_3, NO_2, SO_2, and aerosols. The OMI NO_2 README file is available at: https://aura.gesdisc.eosdis.nasa.gov/data//Aura_OMI_Level2/OMNO2.003/doc/README.OMNO2.pdf.

There are generally 3 data levels that are available, with level 1 being the raw data and level 3 is the most quality assured data set. Level 2 is the most commonly available and below is an example of a downloaded level 2 NO_2 OMI file:

OMI-Aura_L2-OMNO2_2011m1010t2318-o38499_v003-2011m1011t154524.he5

where:

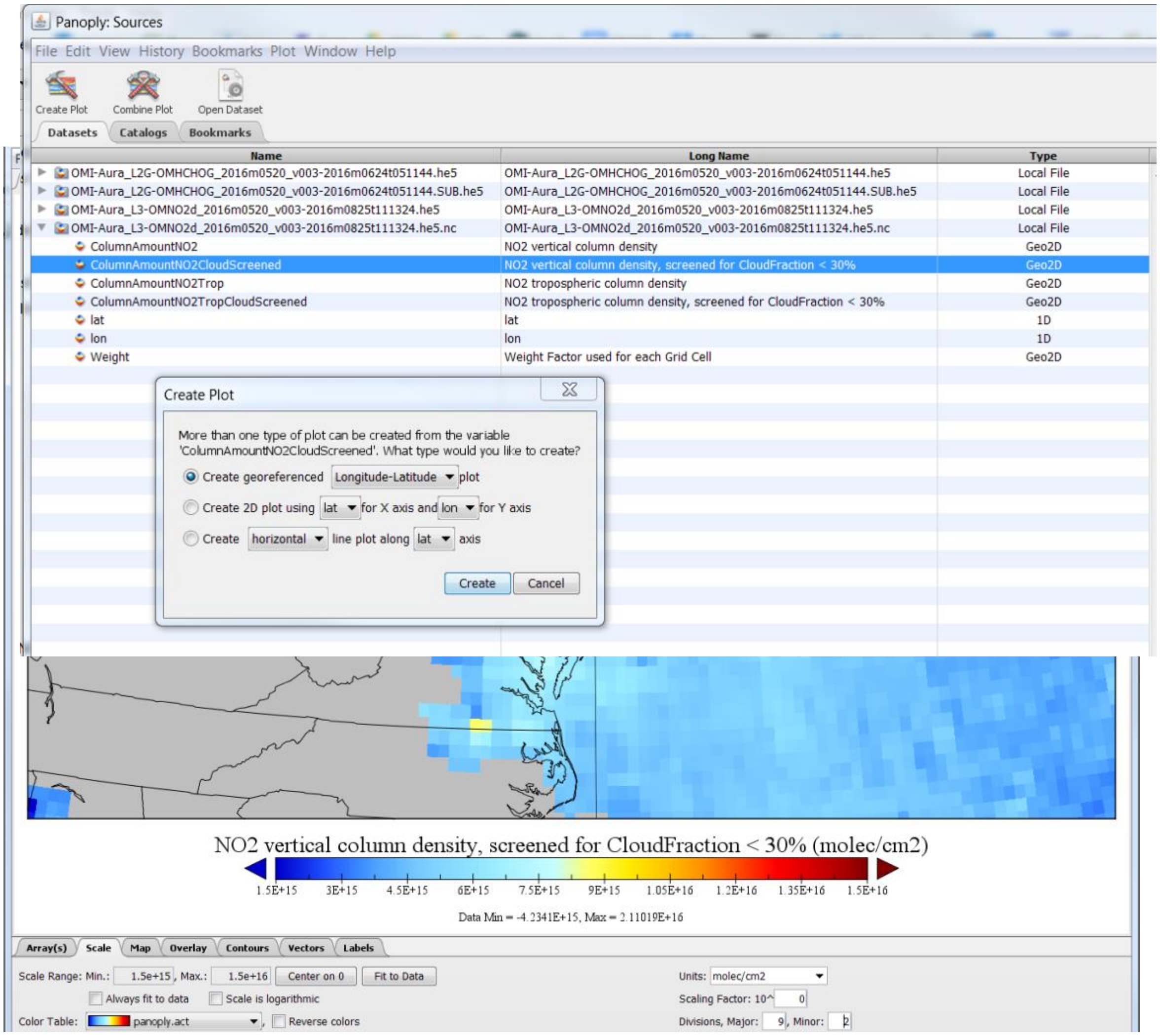
<InstrumentID> = OMI-Aura
<DataType> = L2-OMNO2
<ObservationDateTi = 2011m1010t23
<Orbit#> = 38499
<Collection#> = 003
<ProductionDateTim = 2011m1011t15
<Suffix> = he5

2d2. Reading ‘.he5’ format files

The he5 files can be then plotted using a viewer such as this offered by NASA: https://www.giss.nasa.gov/tools/panoply/. Panoply plots geo-referenced and other arrays from netCDF, HDF, GRIB, and other datasets.

2d2a. Using Panoply to view/extract NO_2 data

Unlike TEMIS, the NASA EARTHDATA Level 3 data downloads for NO_2 are not processed for monthly means, but the data is readily displayed in Panoply. Using this service will require you to register free with EARTHDATA. The following is a screen shot of the menu tree in Panoply for plotting the May 20, 2016 cloud screened NO_2 data parameter:



Name	Long Name	Type
OMI-Aura_L2G-OMHCHOG_2016m0520_v003-2016m0624t051144.he5	OMI-Aura_L2G-OMHCHOG_2016m0520_v003-2016m0624t051144.he5	Local File
OMI-Aura_L2G-OMHCHOG_2016m0520_v003-2016m0624t051144.SUB.he5	OMI-Aura_L2G-OMHCHOG_2016m0520_v003-2016m0624t051144.SUB.he5	Local File
OMI-Aura_L3-OMNO2d_2016m0520_v003-2016m0825t111324.he5	OMI-Aura_L3-OMNO2d_2016m0520_v003-2016m0825t111324.he5	Local File
OMI-Aura_L3-OMNO2d_2016m0520_v003-2016m0825t111324.he5.nc	OMI-Aura_L3-OMNO2d_2016m0520_v003-2016m0825t111324.he5.nc	Local File
ColumnAmountNO2	NO2 vertical column density	Geo2D
ColumnAmountNO2CloudScreened	NO2 vertical column density, screened for CloudFraction < 30%	Geo2D
ColumnAmountNO2Trop	NO2 tropospheric column density	Geo2D
ColumnAmountNO2TropCloudScreened	NO2 tropospheric column density, screened for CloudFraction < 30%	Geo2D
lat	lat	1D
lon	lon	1D
Weight	Weight Factor used for each Grid Cell	Geo2D

Create Plot

More than one type of plot can be created from the variable 'ColumnAmountNO2CloudScreened'. What type would you like to create?

● Create georeferenced Longitude-Latitude plot

○ Create 2D plot using lat for X axis and lon for Y axis

○ Create horizontal line plot along lat axis

NO2 vertical column density, screened for CloudFraction < 30% (molec/cm2)

Data Min = -4.2341E+15, Max = 2.11019E+16

Scale Range: Min.: 1.5e+15, Max.: 1.5e+16

☐ Always fit to data ☐ Scale is logarithmic

Color Table: panoply.act, ☐ Reverse colors

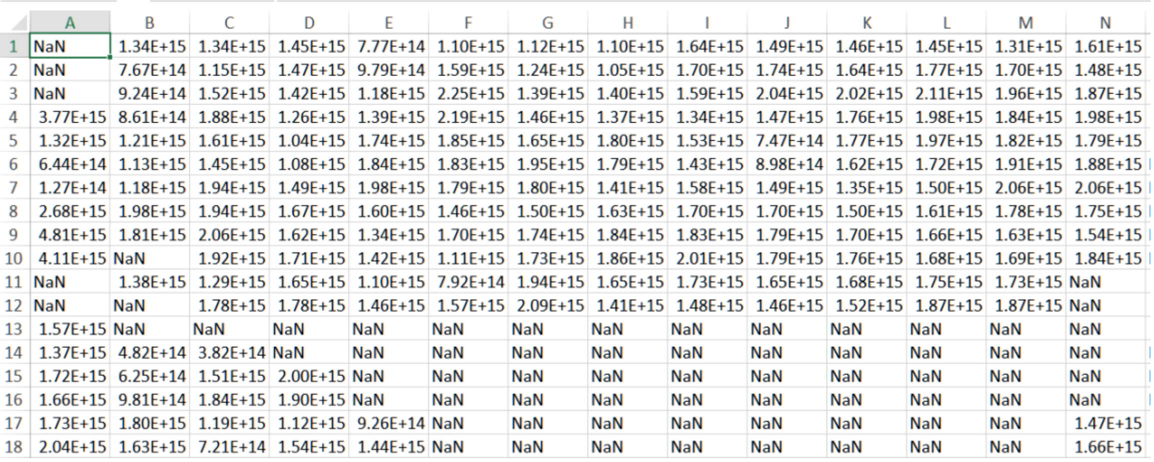
Units: molec/cm2

Scaling Factor: 10^ 0

Divisions, Major: 9, Minor: 2

It is important that you choose the GEO2D file type for plotting, otherwise there will be no geo-reference for the map that is produced. The following map was easily produced after changing the map projection and adjusting the color scale ranges:

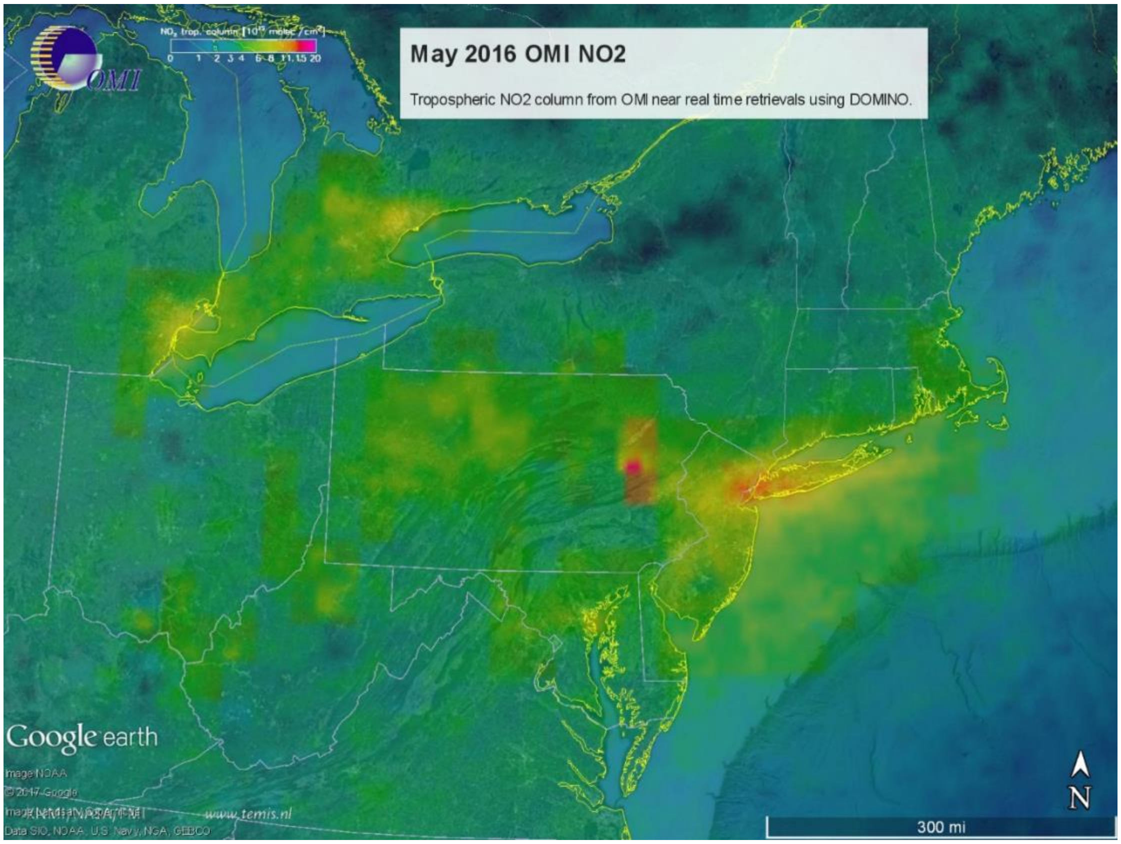
Panoply also allows you to download the gridded data as a .csv file, which is readily viewed in a spreadsheet:



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	NaN	1.34E+15	1.34E+15	1.45E+15	7.77E+14	1.10E+15	1.12E+15	1.10E+15	1.64E+15	1.49E+15	1.46E+15	1.45E+15	1.31E+15	1.61E+15
2	NaN	7.67E+14	1.15E+15	1.47E+15	9.79E+14	1.59E+15	1.24E+15	1.05E+15	1.70E+15	1.74E+15	1.64E+15	1.77E+15	1.70E+15	1.48E+15
3	NaN	9.24E+14	1.52E+15	1.42E+15	1.18E+15	2.25E+15	1.39E+15	1.40E+15	1.59E+15	2.04E+15	2.02E+15	2.11E+15	1.96E+15	1.87E+15
4	3.77E+15	8.61E+14	1.88E+15	1.26E+15	1.39E+15	2.19E+15	1.46E+15	1.37E+15	1.34E+15	1.47E+15	1.76E+15	1.98E+15	1.84E+15	1.98E+15
5	1.32E+15	1.21E+15	1.61E+15	1.04E+15	1.74E+15	1.85E+15	1.65E+15	1.80E+15	1.53E+15	7.47E+14	1.77E+15	1.97E+15	1.82E+15	1.79E+15
6	6.44E+14	1.13E+15	1.45E+15	1.08E+15	1.84E+15	1.83E+15	1.95E+15	1.79E+15	1.43E+15	8.98E+14	1.62E+15	1.72E+15	1.91E+15	1.88E+15
7	1.27E+14	1.18E+15	1.94E+15	1.49E+15	1.98E+15	1.79E+15	1.80E+15	1.41E+15	1.58E+15	1.49E+15	1.35E+15	1.50E+15	2.06E+15	2.06E+15
8	2.68E+15	1.98E+15	1.94E+15	1.67E+15	1.60E+15	1.46E+15	1.50E+15	1.63E+15	1.70E+15	1.70E+15	1.50E+15	1.61E+15	1.78E+15	1.75E+15
9	4.81E+15	1.81E+15	2.06E+15	1.62E+15	1.34E+15	1.70E+15	1.74E+15	1.84E+15	1.83E+15	1.79E+15	1.70E+15	1.66E+15	1.63E+15	1.54E+15
10	4.11E+15	NaN	1.92E+15	1.71E+15	1.42E+15	1.11E+15	1.73E+15	1.86E+15	2.01E+15	1.79E+15	1.76E+15	1.68E+15	1.69E+15	1.84E+15
11	NaN	1.38E+15	1.29E+15	1.65E+15	1.10E+15	7.92E+14	1.94E+15	1.65E+15	1.73E+15	1.65E+15	1.68E+15	1.75E+15	1.73E+15	NaN
12	NaN	NaN	1.78E+15	1.78E+15	1.46E+15	1.57E+15	2.09E+15	1.41E+15	1.48E+15	1.46E+15	1.52E+15	1.87E+15	1.87E+15	NaN
13	1.57E+15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
14	1.37E+15	4.82E+14	3.82E+14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
15	1.72E+15	6.25E+14	1.51E+15	2.00E+15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
16	1.66E+15	9.81E+14	1.84E+15	1.90E+15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
17	1.73E+15	1.80E+15	1.19E+15	1.12E+15	9.26E+14	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.47E+15
18	2.04E+15	1.63E+15	7.21E+14	1.54E+15	1.44E+15	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	1.66E+15

2c3. Viewing Satellite data from TEMIS

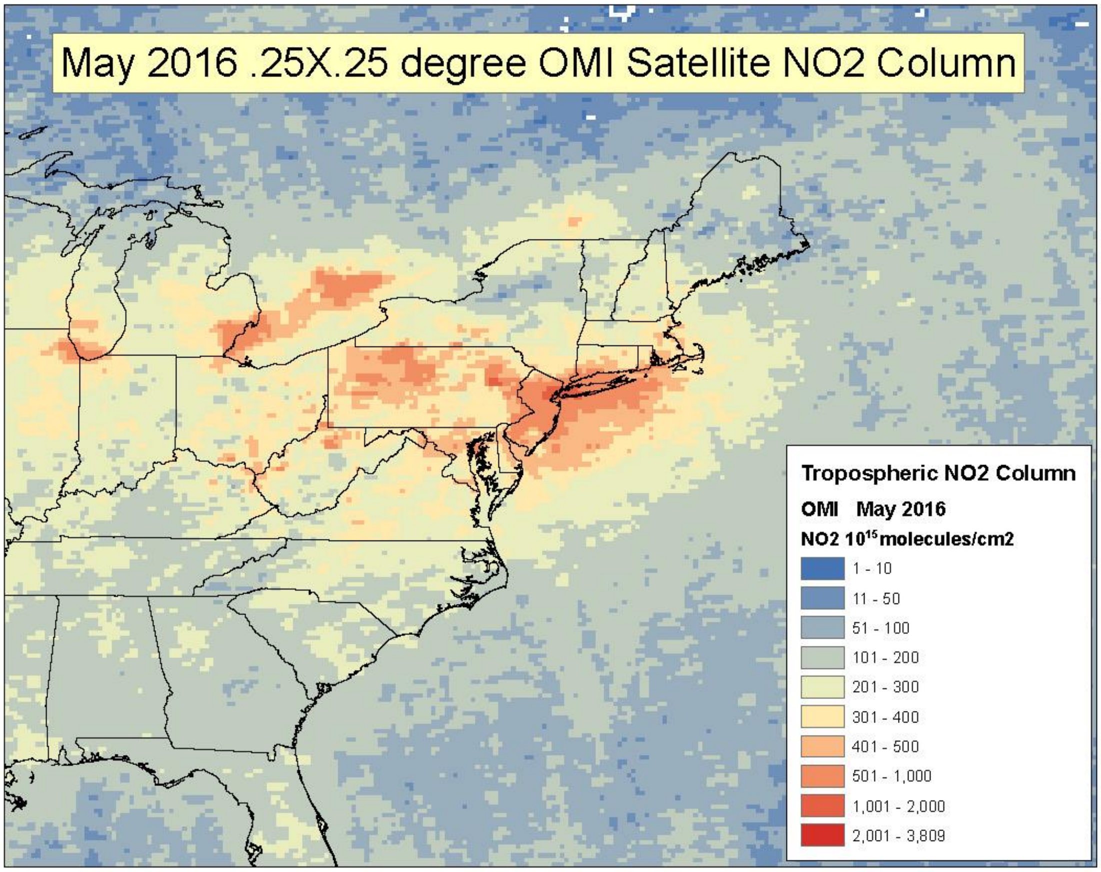
As mentioned before, the TEMIS web site provides downloads for monthly average KML files, and zip-ed ASCII data files in TOMS and ESRI grid formats. These are not readily viewable in Panoply, but the ASCII data file in TOMS format can be viewed in a spreadsheet (as above). The kml file can be saved and viewed in Google Earth, but that is of limited usefulness. The following is a map that was downloaded as a kml for May, 2016:



May 2016 OMI NO2

Tropospheric NO2 column from OMI near real time retrievals using DOMINO.

If the ESRI ArcGIS products are at your disposable, then the ESRI Gridded formatted data can be plotted. This data needs to be georeferenced within ArcCatalog before it can be plotted. This is what the OMI May 2016 looks like in ArcMAP after the data intervals have been manually selected and the colors changed:



For comparison, this is the downloaded the GOME-2 ESRI gridded data for the same period and plotted in ArcMAP (below). GOME satellite pixels have a coarser resolution than OMI, which is apparent in the image and it is also noted that the NO_2 concentrations tend to be higher.

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