Remote Sensing of NO₂, OMI Data Products, and Tools

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Webinar Agenda

Session 1: Remote sensing of NO₂, OMI Data Products, and Tools

Session 2: Introducing TROPOMI - High Resolution NO₂ Observations from Space

Session 3: Python Tools - TROPOMI

Session 2 Image Credit: TROPOMI
Learning Objectives

By the end of this presentation, you will be able to:

• Describe existing satellite capabilities for global NO$_2$ observations
• Describe the current NO$_2$ data products available from the Ozone Monitoring Instrument (OMI)
• Identify various air quality monitoring applications utilizing OMI NO$_2$ observations
• Perform a data download of OMI and/or TROPOMI data
What do Satellites Measure?

- Remote sensing: collecting information about an object without being in direct physical contact with it
- The intensity of reflected and emitted radiation to space is influenced by the surface and atmospheric conditions
- Satellite measurements contain information about the surface and atmospheric conditions
Measuring Trace Gases from Space

- Satellites detect backscattered UV, visible, and/or emitted thermal radiation.
- We know the distinct absorption spectra of each trace gas.
- We can identify a “spectral fingerprint” for each atmospheric constituent.
- Retrieval algorithms (a model) infer physical quantities such as number density, partial pressure, and column amount.
A Spectral Signature of a Trace Gas is Unique like a Fingerprint

- One fingerprint on a drink can allows the owner to be identified.
- If a lot of people touch the drink can, it can be very difficult to identify any one person. This is the case for trace gases as spectral signatures often overlap.

Image Credits (left to right): Walmart Canada; Wikimedia Commons, The Photographer
A Spectral Signature of a Trace Gas is Unique Like a Fingerprint

- Two wavelengths ($\lambda$) are used in retrievals
  - $\lambda_1$ is NOT absorbed by trace gas
  - $\lambda_2$ is absorbed by trace gas
Vertical Distribution

- Very little information can be obtained on the vertical distribution of trace gases in the troposphere from a nadir view.

- Some information on vertical distribution can be inferred by taking the altitude of the trace gas source and its lifetime into account.

- Examples:
  - NO$_2$ is short-lived and primarily emitted from fossil fuel combustion (e.g., cars, power plants), so most NO$_2$ is found near the surface.
### Data Formats & Resolutions

<table>
<thead>
<tr>
<th>Data Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 0</strong></td>
<td>Raw data at full instrument resolution</td>
</tr>
<tr>
<td><strong>Level 1A</strong></td>
<td>Raw data that have been time-referenced and supplemented with information such as radiometric and geometric calibration coefficients and geo-referencing parameters. These are computed and appended, but not applied to Level 0 data.</td>
</tr>
<tr>
<td><strong>Level 1B</strong></td>
<td>Level 1A data that has been processed to sensor units (not all instruments have Level 1B source data)</td>
</tr>
<tr>
<td><strong>Level 2</strong></td>
<td>Derived geophysical variables at the same resolution and location as Level 1 source data</td>
</tr>
<tr>
<td><strong>Level 2G &amp; 3</strong></td>
<td>Variables mapped on uniform space-time grid scales, usually with some completeness and consistency</td>
</tr>
<tr>
<td><strong>Level 4</strong></td>
<td>Model output or results from analyses of lower level data (e.g. variables derived from multiple measurements)</td>
</tr>
</tbody>
</table>
Trace Gases: Using Level 3 vs. Level 2 Data

• Advantages
  – Uniform grid
  – One file per day
  – Smaller sized files
  – Quality flags and filtering criteria have been applied

• Limitations
  – Can be coarser resolution than L2
  – L2 observation typically at the same location as the L1 source data
Spatial Resolution: Trace Gases

- Spatial resolution of current satellite instruments (10s to <10 km diameter)
  - good enough to map tropospheric concentration fields on local to regional scales
  - fine enough to resolve individual power plants and large cities
- For species with short atmospheric lifetimes (e.g. NO₂), averaging over larger satellite pixels can lead to significant dilution of signals from point sources, complicating quantitative analysis and separation of emission sources
- For quantitative analysis: Level 2 and high resolution gridded Level 3 data are optimal

Source: Richter, 2010
Perspective...

Spatial Resolution

OMI 24x13 km²  Approx. GOME-2 72x39 km²

Mexico City, Jan. 20, 2005
TROPOMI: Impact of Resolution

OMI NO$_2$

TROPOMI data courtesy of ESA

TROPOMI NO$_2$

Spatial Resolution = 3.5 x 7.0 km$^2$

November 28, 2017
Global Pollution Monitoring Constellation (2020-2022)

Policy-relevant science and environmental services enabled by common observations

- Improved emissions over industrialized Northern Hemisphere
- Improved air quality forecasts and assimilation systems
- Improved assessment, e.g., observations to support the United Nations Convention on Long Range Transboundary Air Pollution

Image Credit: Courtesy Jhoon Kim, Andreas Richter
NASA’s Applied Remote Sensing Training Program
Ozone Monitoring Instrument (OMI)

- Launched July 15, 2004
- NASA EOS Aura Satellite
- Nadir-viewing UV/Visible
  - 264 – 311 nm at 0.63 nm
  - 307 – 383 nm at 0.42 nm
  - 349 – 504 nm at 0.63 nm
- 1:45 p.m. equatorial crossing time
- 13x24 km² at nadir
- Daily global coverage

- Products
  - Total Column O₃
  - Tropospheric Column O₃
  - Aerosol optical depth (in UV)
  - Column Formaldehyde
  - Column NO₂
  - Tropospheric column NO₂
  - Column SO₂
Data Granule

- **Product File**
  - covers sunlit portion of the orbit with an approx. 2,600 km wide swath
  - contains 60 binned pixels or scenes per viewing line
- **14 or 15 granules are produced daily, providing fully contiguous coverage of the globe**
Effect of the OMI Row Anomaly

• Began in 2007 with only two rows
• Grew until 2012, at which point was affecting almost 50% of the data
• Affects all OMI products
Nitrogen Dioxide (NO₂)

• Why measure NO₂?
  – NO₂ is an ozone precursor and health irritant
  – Sources: Fires, industrial and transportation sources, stationary sources (e.g. power plants), but emissions can vary depending on fuel type and conditions
  – High concentrations in the planetary boundary layer (PBL)

Image Credit: NASA SVS
OMNO$_2$ Level 2 Product - Native Resolution

Aura OMI OMNO2 (17:53UTC August 8, 2006)

Column NO2 Amount in Troposphere (10$^{15}$ molecule/cm$^2$)
OMNO2G L2 Gridded Product (0.25° x 0.25°) - No Pixel Averaging

Aura OMI OMNO2G May 29, 2006

Column NO2 Amount in Troposphere $10^{15} \text{ cm}^{-2}$
OMNO2d L3 Gridded Product (0.25° x 0.25°) - Pixel Averaging

Aura OMI OMNO2d October 2, 2006
Understanding an OMI File Name

OMNO2, OMSO2

HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data
### OMI NO₂ Parameter Information (OMNO₂)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Unit</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ColumnAmountNO₂Trop</td>
<td>Tropospheric Column NO₂</td>
<td>Molec / cm²</td>
<td>• Use only scenes with: radiative cloud fraction &lt; 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>solar zenith angle &lt; 85°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>terrain reflectivity &lt; 0.3</td>
</tr>
<tr>
<td>TerrainReflectivity</td>
<td>Unitless</td>
<td>Scale factor: 0.001</td>
<td></td>
</tr>
<tr>
<td>CloudRadianceFraction</td>
<td>Unitless</td>
<td>Scale factor: 0.001</td>
<td></td>
</tr>
<tr>
<td>SolarZenithAngle</td>
<td>Deg</td>
<td>In geolocation fields</td>
<td></td>
</tr>
</tbody>
</table>

- All fill values are high negative numbers: \((-2.100 \approx -1.26765 \times 10^{30})\)
OMNO2_HR Gridded High Resolution OMI NO₂ (0.1° x 0.1°)

• Based on NASA standard product

• Daily:
  – https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L3/OMNO2D_HR/OMNO2D_HRD/
  – Available in hdf5 format

• Monthly:
  – https://avdc.gsfc.nasa.gov/pub/data/satellite/Aura/OMI/V03/L3/OMNO2D_HR/OMNO2D_HRM/
  – Available in ASCII (text) and NetCDF format
Applications and Research Using OMI data
OMI Detects NO$_2$ Changes in Pollution Over Time

2005 - 2016
OMI Detects NO$_2$ Increases from ONG Activities

North Dakota

Texas

Suomi NPP VIIRS Lights at Night

Williston Basin

Permian Basin

Eagle Ford

Courtesy of: Bryan Duncan
OMI NO$_2$ Used to Update Inventory Trends

- Creating a bottom-up emissions inventory is time consuming and labor intensive
  - e.g., Currently the most up-to-date U.S. emissions inventory is the NEI 2017
- Satellite observations and trends can be used to update bottom-up emissions inventories until a new inventory is completed
- Example: Lamsal et al. 2011 used a chemistry transport model to estimate how changes in emissions related to changes in the atmospheric column
- Then they applied this relationship using post-inventory satellite observations

Image credit: Figure 5 from Streets et al. 2013
NASA's Applied Remote Sensing Training Program
Temporal Variations

- Satellite observations can also be used to detect potential short term and unexpected changes in trends, such as reductions in activity due to:
  - economic recession
  - natural disasters (e.g., Hurricane Katrina)
  - policy interventions (e.g., Beijing Olympics)
  - civil unrest

**NO₂ Trends from OMI**
- Damascus: -37.1 ± 10.9%
- Aleppo: -40.2 ± 13.6%

Image credit: Figure 11 from Duncan et al. 2016

NASA’s Applied Remote Sensing Training Program
Temporal Variations

- Examine finer temporal emissions cycles
  - Weekly cycles
  - Seasonal cycles of different sources
    - Anthropogenic – Winter
    - Soil – Summer
    - Biomass Burning – Dry Season

Image credit: Figures 3, 5, and 7 from van der A. et al. 2008
NASA’s Applied Remote Sensing Training Program
Model-Satellite Inter-Comparison

OMI NO₂

CMAQ Model NO₂
OMI Trends in NO₂ Correlate Well With Surface Trends

Image credit: Lamsal et al. (2015)
NASA’s Applied Remote Sensing Training Program
Estimating Surface NO$_2$ From the Tropospheric Column

Satellites measure backscattered radiation, from which vertical column densities can be calculated.

- Courtesy of Randall Martin
Estimating Surface NO₂ From the Tropospheric column

Use vertical information from an atmospheric chemistry model to estimate the relationship between the column and the surface.

\[ S = \Omega_{Sat} \times \left[ \frac{v S_{Model}}{v \Omega_{Model} - (v - 1) \Omega_{FT} (Model)} \right] \]

\[ v = \frac{\Omega_{Satellite}}{\Omega_{Model}} \]

Lamsal et al. (2008)

S = Surface Concentration
Ω = Tropospheric Column
FT = Free Troposphere

Courtesy of Randall Martin
Ground-Level Afternoon NO₂ Inferred from OMI for 2005

- Note: this is a research product and not an official NASA product

Source: Lok Lamsal
## Satellite-Based Surface NO₂ Datasets

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Available Product</td>
<td>Annual Mean, 3-Yr Running Mean</td>
<td>Annual Mean (North America and global)</td>
<td>Monthly Mean</td>
</tr>
<tr>
<td>Instruments</td>
<td>GOME, SCIAMACHY, GOME-2</td>
<td>OMI</td>
<td>OMI</td>
</tr>
<tr>
<td>Overpass Time</td>
<td>~9:30-10:30</td>
<td>~13:30</td>
<td>~13:30</td>
</tr>
<tr>
<td>Product Resolution</td>
<td>0.1° x 0.1°</td>
<td>0.1° x 0.1°</td>
<td>0.1° x 0.1°</td>
</tr>
</tbody>
</table>
Satellite-Derived Surface NO₂ Used in Health Applications

• Anenberg et al. (2018) used annual average surface NO₂, along with annual average PM₂.₅ and annual average ozone from a model
• Used to estimate the number of global asthma-related emergency room visits due to PM₂.₅, O₃, and NO₂ exposure
• Noted that NO₂ impacts are likely underestimated because of the relatively coarse OMI resolution
Data Access
Step 1: Visit [https://urs.earthdata.nasa.gov/users/new](https://urs.earthdata.nasa.gov/users/new)

Register for an Earthdata Login Profile

Profile Information

Username:

Password:

Password Confirmation:

- Required field

Username must:
- Be a Minimum of 4 characters
- Be a Maximum of 30 characters
- Use letters, numbers, periods and underscores
- Not contain any blank spaces
- Not begin, end or contain two consecutive special characters( ...)  

Password must contain:
- Minimum of 8 characters
- One Uppercase letter
- One Lowercase letter
- One Number
Step 2: Add NASA GESDISC to Your Applications

- Login to Earthdata
- Click on My Applications
- Click on Approve More Applications
- Look for NASA GESDISC DATA ARCHIVE in the list or search
- Add NASA GESDISC DATA ARCHIVE to your applications

You should see NASA GESDISC DATA ARCHIVE in list of approved applications.
Step 3: Login at https://disc.gsfc.nasa.gov/
Step 4: Enter Search Keywords (e.g. OMNO$_2$ or OMSO$_2$)
Step 5: Make a Product Selection
Step 6: Choose Data Access (We Will Use EARTHDATA)
Step 7: Select Product
Step 8: Select Time

To choose time, click on + or - to change the time resolution (e.g. Click - to change to year, and + to change to day)
Step 9: Select Swath

- Clicking on a swath will show you its location on the map.
Step 10: Download Single Granule by Clicking Gear Icon
Step 11: Choose “Direct Download” and Click “Submit”
Step 12: Click “View Download Link” to Download
Step 13: Download the Data

- [http://aura.gsdisc.cosdis.nasa.gov/data/Aura_OMI_Level2/OMSO2.003/2016/298/OMI-Aura_L2-OMSO2_2016m1024t0910-o05300_v003-2016m1024t174753.he5](http://aura.gsdisc.cosdis.nasa.gov/data/Aura_OMI_Level2/OMSO2.003/2016/298/OMI-Aura_L2-OMSO2_2016m1024t0910-o05300_v003-2016m1024t174753.he5)

Click on the provided link and save the data in your directory where you will run your python scripts.
Python Tools
ARSET Advanced Webinar


• This previous online training guided users through
  – Using available Python scripts to read, map, and analyze Level-2 data (OMI NO$_2$ and SO$_2$ and MODIS)
  – Modifying available scripts for future use
• All past webinar recordings, presentations, and Q&A transcripts are available for download
ARSET Advanced Webinar


• Example scripts:
  – Prints contents of HDF files
  – Plot and save a map
  – Extract data at a single point (e.g. the location of a ground station)
  – Extract variables to a text (.csv) file
References


References


OMI NO2 V3 paper: