2019 CIDER Summer Program – Volcano Science

Tutorial on Satellite Data Access, Visualization and Analysis

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Introduction

Vast quantities of satellite data pertinent to volcano science are now publicly available at no cost to users, from sources such as NASA and the European Union's Copernicus Earth Observation program. Although access to satellite datasets is relatively straightforward, processing satellite data to extract volcanological information (e.g., mass of sulfur dioxide, SO_2) can be a challenge using commercially available software packages. Hence, most users of satellite data write their own codes for analysis (e.g., in IDL, Matlab, Python etc.). The most common satellite data formats are Hierarchichal Data Format (HDF, HDF4, HDF5, etc.) and the related Network Common Data Form (NetCDF) and most programming languages have extensive libraries to manipulate these formats.

This tutorial will introduce you to several online and offline satellite data visualization tools, that require no programming skills to use. These tools can be used to check whether a given volcanic event has been detected in satellite imagery and roughly estimate the magnitude (e.g., based on SO_2 or ash emissions), identify/download the specific datasets required for further analysis, and produce images of volcanic plumes. As examples we will use the eruptions of Kelut (Indonesia) in February 2014 and Ambae (Vanuatu) in July 2018, but in the materials folder you will also find copies of current satellite-based inventories of volcanic SO_2 emissions listing many other eruptions for further exploration.

Required Downloads

Download NASA's Panoply Data Viewer from here: https://www.giss.nasa.gov/tools/panoply/

Panoply also requires that your computer has the Java SE 8 (or later) runtime environment installed (https://www.java.com/en/download/).

Provided materials

MSVOLSO2L4_Jun2019.txt: current inventory of SO_2 emissions by volcanic eruptions detected by satellite sensors since 1978 (text file – can be imported into Excel). Source: NASA

NASA Ozone Mapping and Profiler Suite (OMPS) SO_2 data files (orbits) for the July 2018 Ambae eruption (HDF5 format):
OMPS-NPP_NMSO2-PCA-L2_v1.1_2018m0726t235126_o34953_2018m0727t015115.h5
OMPS-NPP_NMSO2-PCA-L2_v1.1_2018m0727t013256_o34954_2018m0727t060604.h5

Satellite data sources

NASA – Earthdata: https://earthdata.nasa.gov/ (requires free account)

ESA Sentinel-5P – Copernicus Open Access Hub: https://s5phub.copernicus.eu/dhus/#/home (guest username/password for data access: s5pguest/s5pguest)

NASA Global SO_2 Monitoring: https://so2.gsfc.nasa.gov/ (daily SO_2 maps of volcanic regions from UV satellite instruments and a portal to various other sources of volcanic SO_2 data)

1. Web-based satellite data visualization with NASA Worldview

This first exercise is a simple visualization of satellite data using NASA's Worldview interface (https://worldview.earthdata.nasa.gov/). Worldview is an excellent tool for browsing and visualizing available global satellite data for a given volcanic eruption (decades of satellite data are available, updated within 3 hours of observation), though only minimal quantitative analysis is possible. Apart from visualization, its main utility is to identify available datasets which can then be downloaded directly from Worldview or other source(s) for further analysis, if needed.

a) Open NASA Worldview in a web-browser. This should open a global basemap for the current day (change the date using the year/month/day counters in the lower left of the window, or the time slider along the bottom). The default base layers are 'true-color' visible satellite images from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the NASA Terra (~10:30 am and ~10:30 pm local time overpass; available since 2000) and Aqua (~1:30 pm and ~1:30 am local time overpass; available since 2002) satellites, and the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi-NPP (or Joint Polar Satellite System, JPSS; ~1:30 pm and ~1:30 am local time overpass; available since late 2015) satellite. Coastlines and place labels can be overlaid on these base images. Click and drag to move around and zoom in/out to focus on regions of interest.

b) For this example, we will use the 13 February 2014 explosive eruption of Kelut (Java, Indonesia; lat: 7.93ºS, lon: 112.308ºE), although feel free to explore any other eruption of interest (e.g., from the Smithsonian Institution Global Volcanism Program database or the supplied MSVOLSO2L4 database). The Smithsonian GVP report of the February 2014 Kelut eruption, which started at ~2300 local time (~1600 UTC) on February 13, is here. You can also download a GRL paper describing some analysis of satellite data for the Kelut eruption.

   The first step is to navigate to the relevant date in Worldview and find Java (Indonesia) on the map. Note that, since the eruption started late on February 13 (after the Terra/Aqua MODIS daytime overpasses), the eruption cloud does not appear on the February 13 MODIS visible images. To visualize the eruption cloud in this case we can use nighttime infrared (IR) Brightness Temperatures (also available from MODIS, VIIRS and many other satellite instruments).

c) To add a new data layer in Worldview, click '+ Add Layers' and a menu will appear listing available layers by 'Hazards and Disasters' or 'Science Discipline'. The 'Ash Plumes' collection provides access to several datasets useful for visualizing volcanic plumes, including sulfur dioxide (SO_2) data, aerosol data (for volcanic ash) and thermal anomalies (sensitive to active lava).

To add a Brightness Temperature layer, start typing 'Brightness Temperature' in the search field and many options will appear. Check the 'Brightness Temperature (Band 31-Night)' layer from Aqua/MODIS to add it to the display. This layer should now appear in the list of 'Overlays' in the top left of the window; these can be switched on or off using the 'eye' icon, and the order of the layer 'stack' can also be changed by dragging layers up or down (it is useful to have the coastlines and place labels at the top so they are overlaid on all other layers). The thresholds and color palette for the layer can also be changed.

With the Brightness Temperatures displayed (which are from Aqua/MODIS at ~1:30 am local time on February 14, ~2.5 hrs after the Kelut eruption), the volcanic umbrella cloud should be visible as a large, dark (i.e., low temperature) feature over East Java (other similar features in the region are probably thunderstorm clouds). The cold temperatures are consistent with an opaque cloud at high altitudes. By moving the mouse over the cloud you can view the actual temperatures recorded on the scale bar. One way of estimating volcanic cloud altitude is to compare the IR brightness temperatures with the closest (in time and location) radiosonde atmospheric temperature sounding (e.g., obtained from the University of Wyoming). *Do you notice anything unusual about the temperature distribution in the volcanic cloud (especially over the location of Kelut), relative to other cold clouds in the region?*

d) Other useful layers to add for this nighttime case are accessed under 'Ash Plumes' -> 'Sulfur Dioxide':

i. Aqua/AIRS Sulfur Dioxide (Night, Prata Algorithm)
ii. Aura/MLS Sulfur Dioxide (147 hPa, Night)

The IR Atmospheric Infrared Sounder (AIRS on NASA's Aqua satellite) and Microwave Limb Sounder (MLS) instruments can detect volcanic SO_2 at night (unlike the UV sensors, OMI and OMPS). Note the unusual 'ring-like' SO_2 distribution in the AIRS SO_2 data which is due to high opacity (probably due to ice/ash) preventing SO_2 retrieval in the center of the volcanic cloud (cloud transparency is required for SO_2 retrieval). MLS provides a coarse vertical profile of SO_2 in the upper troposphere and stratosphere along the Aura satellite track – the MLS data in Worldview are for just one layer (147 hPa pressure; ~14 km altitude).

e) You can also add orbit tracks from various satellites to the data stack. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite (https://www-calipso.larc.nasa.gov/), which carries a space-borne Light Detection and Ranging (LiDAR) instrument, can measure the altitude of volcanic clouds directly if the satellite track intersects the plume. Although CALIPSO LiDAR data cannot be visualized in Worldview, the CALIPSO satellite tracks can be viewed to check for plume intersection, since the CALIPSO, Aqua, and Aura satellites orbit in NASA's A-Train constellation and have very similar overpass times (within ~10 minutes).

   To add CALIPSO Orbital Tracks, click '+ Add Layers' and search for 'CALIPSO', then check 'CALIPSO Orbital Track & Overpass Time (Descending/Night)' to display the nighttime CALIPSO track (roughly coincident with the Aqua MODIS and AIRS data). Note that the CALIPSO track cuts directly through the young Kelut eruption cloud, which is a rare occurrence!

   If you want to then go and find the corresponding CALIPSO browse image showing the LiDAR backscatter data, you need to note the CALIPSO overpass time from Worldview (~18:15 UTC on Feb 13 in this case), go to the CALIPSO website (https://www-calipso.larc.nasa.gov), and browse to Products -> LIDAR Browse Images -> Version 4 (Go) -> Select date (Feb 13, 2014) -> Search for the image panel corresponding to the ~18:15 UTC overpass (orbital track maps are available to aid navigation). *See if you can locate the Kelut volcanic cloud feature in the CALIPSO data and obtain an approximate altitude.*

f) Note that all layers added to the stack are preserved as you navigate forward or backward in time in Worldview. To visualize the dispersion of the Kelut eruption cloud in subsequent days, you need to add other data layers available in daytime under 'Ash Plumes' including:
   i. Aura/OMI UV Aerosol Index (for volcanic ash)
   ii. Aqua/AIRS Sulfur Dioxide (Day, Prata Algorithm)
   iii. Aura/MLS Sulfur Dioxide (147 hPa, Day)
   iv. Aura/OMI Sulfur Dioxide (Upper Troposphere and Stratosphere)

   Note that Aura/OMI, Aura/MLS and Aqua/AIRS (daytime) measurements are roughly coincident in time. Comparing these datasets provides some insight into the different sensitivity to volcanic SO_2 in the UV (OMI) and IR (AIRS).

g) Finally, many of the visualized satellite datasets can be downloaded for further offline analysis using the 'Data' tab at the top left of the screen. Satellite datasets are typically packaged as entire satellite orbits (~14-15 orbits per day for a typical polar-orbiting asset) or as 'granules' covering smaller geographic regions.

2. Satellite data visualization/extraction with NASA Panoply

This exercise uses NASA's free Panoply Data Viewer to visualize data. Panoply is less user-friendly than Worldview, but provides more control over plotting parameters and access to the full range of variables provided in satellite data files (HDF or netCDF). As with Worldview, minimal quantitative analysis is possible with Panoply (its main function is to produce images) but data can be extracted for further analysis if needed.

Panoply is a Java application that enables the user to plot raster images of geo-gridded (geo-referenced) data from datasets in netCDF or HDF format. Depending on the type of data available, Panoply can be used to create displays in a variety of ways:

• Plot longitude-latitude data as global maps or zonal averages, using any of over 40 global map projections
• Overlay continent outlines or masks on longitude-latitude plots, or just plot a particular region
• Display specific latitude-longitude or latitude-vertical arrays from larger multidimensional variables as slices

Panoply also functions as a tool for graphical data analysis and reporting of results by allowing the user to:

• Combine two arrays in one plot by differencing, summing or averaging
• Use any of the 30 scale colorbars provided, or add a custom colorbar
• Save plots to disk as PNG or GIF images

For this example, we will use the 26-27 July 2018 eruption of Ambae (or Aoba, Vanuatu; lat: 15.389ºS, lon: 167.835ºE), which produced significant SO_2 emissions. This exercise uses two current satellite SO_2 datasets, from the ESA/Sentinel-5P TROPOMI instrument and the NASA Suomi-NPP OMPS instrument. These are both UV instruments, but TROPOMI has higher spatial resolution and hence greater sensitivity to volcanic SO_2. As before, feel free to explore any other eruption of interest (e.g., from the Smithsonian Institution Global Volcanism Program database or the supplied MSVOLSO2L4 database).

To locate the relevant TROPOMI orbit covering the Ambae volcanic cloud and load it into Panoply:

a) Go to the Sentinel-5P Hub: https://s5phub.copernicus.eu/dhus/#/home
b) Drag the map to the area of interest (Vanuatu) and draw a box over and to the east of Vanuatu (to do this you need to activate 'area mode' using the box icon at top right of the window).
c) Click the bars on the left of the Search window (top left) to bring up Advanced Search options, and enter the following:
    a. Sensing period: start: 2018/07/27; stop: 2018/07/27
    b. Product Type: L2__SO2___
    c. Timeliness: Reprocessing

Then click the magnifying glass icon to search. You will be prompted to login using the username/password: s5pguest/s5pguest, then you may need to hit search again.

d) The results should list 1or 2 TROPOMI orbits that intersect your search box. 'Mousing over' the results will illuminate the corresponding orbit on the map. The results also show a Download URL for each orbit – rather than downloading the files (which are quite large), you can copy this URL and paste it in the 'Enter the URL of a remote dataset to open:' window in Panoply. You will be prompted to login to Sentinel Hub again (s5pguest/s5pguest) and then the remote dataset should load (may take some time depending on connection speed).

e) In case of problems, here's the direct link to TROPOMI orbit for Ambae on July 27, 2018 (Sentinel Hub): https://s5phub.copernicus.eu/dhus/odata/v1/Products('64ba1ebd-cb68-416e-a45d-8ca7e4dd059a')/$value

Once loaded into Panoply, the structure of the TROPOMI data files (HDF version 5) can be explored in the 'Datasets' tab. There are many parameters stored in the files, but to plot a map of SO_2 select:

$value -> PRODUCT -> SUPPORT_DATA -> DETAILED RESULTS -> sulfurdioxide_total_vertical_column_15km

Then click 'Create Plot' or right-click on the variable to create a plot. Select the option 'Create a georeferenced Longitude-Latitude plot', then 'Create'. Plotting may take some time as the data are being read remotely. A window should open with a plot of the TROPOMI orbit on a global map. To zoom in to the area of interest (Vanuatu) you need to hold 'Command' (on a Mac) and draw a new box; zoom out using 'Option-Command' (or use the Plot menu).

Tabs at the bottom of the plot window allow you to change various plotting parameters:

- Array(s) – checking the 'Interpolate' box produces a smoothed map; unchecking the box displays the actual sensor ground-pixels.
- Scale – change the range of the plotted data (e.g., remove negative values by setting Min to zero); change the color table and caption. *Note*: the units of TROPOMI SO_2 columns are moles m^{-2}; to convert these to the more commonly used Dobson Units (DU; 1 DU = 2.69×10^{16} molecules cm^{-2} = 0.0285 g m^{-2} SO_2) you would need to multiply by a scaling factor of 2241.15, but unfortunately it is not easy to do this in Panoply.
- Map – change map projection; re-center the map (note that the July 27, 2018 eruption cloud from Ambae straddles the International Date Line, so try centering on 180ºE); add a graticule and labels.
- Overlays – add coastlines and country borders (MWDB_Coasts_Countries_1.cnob is high-resolution data, useful for small regions).
- Contours – add contours to the data plot.
- Labels – Add/change plot title, footnotes etc.

When you are happy with the plot you can save it using File -> Save Image As.. (default format is PNG). You can also export the maps as KMZ files (e.g., for display in Google Earth or GIS software). To export the actual data (e.g., for use in a spreadsheet or other data analysis tool), highlight the variable of choice in the 'Datasets' tab (Panoply – Sources window) and use File -> Export Data.

You can now repeat this procedure to locate and load OMPS SO_2 data for the same Ambae eruption (hard copies of data files will also be provided):

f) To search for the OMPS data yourself, you can use the NASA Earthdata portal (https://search.earthdata.nasa.gov/search?q=OMPS_NPP_NMSO2_PCA_L2), which requires you to register for a free account to download data. Then choose a region and date of interest, search for corresponding data granules (OMPS-NPP_NMSO2*.h5 files) and either download the data files or copy the access URLs from the 'Information' tab for each granule for use in Panoply. Detailed instructions are not provided here but it is fairly intuitive.

g) Alternatively, here is the direct link to an OMPS SO_2 data file for the Ambae eruption that you can use in Panoply (this also requires an Earthdata account for download, however: https://measures.gesdisc.eosdis.nasa.gov/data/SO2/OMPS_NPP_NMSO2_PCA_L2.1/2018/208/OMPS-NPP_NMSO2-PCA-L2_v1.1_2018m0727t013256_o34954_2018m0727t060604.h5

h) Once you have the data file URL, you can paste it in the 'Enter the URL of a remote dataset to open:' window in Panoply as before. It will then appear in the 'Datasets' window under the TROPOMI data file. Alternatively, you can load a local data file from your hard disk using File -> Open…

i) To locate the SO_2 variable, select OMPS-NPP_NMSO2… -> SCIENCE_DATA -> ColumnAmountSO2_STL (stratospheric SO_2 column amount). Now you have two options: make a new plot window (-> Create Plot) or combine the OMPS SO_2 data with the previously plotted TROPOMI data (-> Combine Plot). In the latter case, you will be asked in which existing plot you should combine the variable. Then in the combined plot window, you can toggle between the TROPOMI and OMPS SO_2 data using the Array(s) tab:
   a. Plot Map of Array 1 Only – TROPOMI
   b. Plot Map of Array 2 Only – OMPS

   Again, unchecking 'Interpolate' shows the native satellite spatial resolution. This is useful for comparing the high resolution TROPOMI observations (3.5x7 km) with the lower resolution OMPS (50x50 km). However, due to the different units used in the TROPOMI (mol m^{-2}) and OMPS (DU) files, you need to change the scaling on the 'Scale' tab using 'Fit to Data'

j) You may find it easier to open the OMPS SO_2 data in a new plot window (-> Create Plot) for a side-by-side comparison. *Compare the sensitivity and extent of the Ambae SO_2 cloud* *as observed by TROPOMI and OMPS (which have similar overpass times at ~1:30 pm local time).*

Additional activities: try searching for and loading adjacent TROPOMI and/or OMPS orbits from the same day or subsequent days to increase spatial coverage (the Ambae SO_2 cloud spread over the southern Pacific Ocean in the 1-2 weeks after the eruption). You can also try visualizing the OMPS UV Aerosol Index data (sensitive to volcanic ash) in Panoply, or visualizing the OMPS data (and other datasets) for the Ambae eruption in NASA Worldview as described in (1) above. TROPOMI data are not currently available in Worldview but can be visualized (along with many other ESA Sentinel datasets) in the similar Sentinel EO Browser (https://apps.sentinel-hub.com/eo-browser).

More information on Panoply is available in these manuals:

https://earth.usc.edu/files/ge-labs/EdGCM/Documentation/Panoply_Manual.pdf
https://www.geo.uni-bremen.de/Interdynamik/images/stories/pdf/visualizing_netcdf_panoply.pdf
https://disc.gsfc.nasa.gov/information/howto?title=Quick%20View%20Data%20with%20Panoply

3. Online satellite data analysis using NASA Giovanni

In this final visualization exercise, we will explore the use of NASA's Giovanni application (https://giovanni.gsfc.nasa.gov/giovanni) for online satellite data analysis. In contrast to Worldview and Panoply, which are primarily data visualization tools, Giovanni can be used to analyze large amounts of satellite data online without downloading the files. Satellite data animations can also be generated. Here, we will use Giovanni to create a time-averaged map of satellite SO_2 data to detect and visualize passive volcanic degassing. The only relevant satellite SO_2 dataset currently available in Giovanni is from the NASA Ozone Monitoring Instrument (OMI). Some generic instructions are provided below, but you are encouraged to explore different volcanic regions and time periods to visualize the variability in volcanic degassing.

Note: although limited functionality in Giovanni is available as a 'guest user', a free NASA Earthdata account provides full access.

(a) From the Giovanni home page, various plot types are available under 'Select Plot' (e.g., time-averages, cumulative plots, comparisons, vertical profiles, etc). Select the first option: 'Maps: Time Averaged Map'.
(b) Next, Select Date Range (UTC) for the time-averaging. This is your choice, but you may want to experiment with annual, seasonal or monthly averages. Note that the OMI SO_2 dataset used for analysis is available from October 2004 to present. The stronger the volcanic SO_2 source, the less data averaging is required to 'detect' the source in satellite data, and vice versa.

(c) Next, Select Region (Bounding Box or Shape) for analysis, using the 'Draw bounding box on map' tool. Use the 'hand' to roam around the map, then zoom in to your region of interest and draw a box. The smaller the box, the faster the analysis will run. The choice of region is up to you, but some global volcanic SO_2 emission 'hotspots' include Vanuatu, Papua New Guinea, Hawaii (Kilauea), Mexico, Colombia/Ecuador, southern Peru, and Sicily (Etna). More details on volcanic SO_2 sources are here.

(d) Now, Select Variables. Under 'Measurements', check the SO_2 box. Four available datasets should appear in a Table. Select 'SO2 Column Amount (Planetary Boundary Layer) OMSO2e v003', which is the OMI SO_2 dataset. The other SO_2 datasets listed are model output from the MERRA-2 Model (not actual observations), but you could also try plotting these for comparison with the OMI SO_2 data. In the model data, SO_2 emissions are simulated using emissions inventories.

(e) Now hit 'Plot Data' in the bottom right of the window, and the data analysis will be launched. This may take some time, depending on the selected time-period and size of region.

(f) Once complete, a map of time-averaged OMI SO_2 columns will appear. Various aspects of the map can be changed using the 'Options' menu; e.g., change the scale, color palette, caption, title etc. Maps can also be downloaded as GeoTIFF, KMZ or PNG files. Unfortunately, volcano locations cannot be plotted – see which volcanoes you can identify based on their SO_2 emissions.

(g) Further analysis using Giovanni could include comparison of annual or monthly mean SO_2 maps for a particular volcano; e.g., Kilauea's SO_2 emissions increased significantly after the summit eruption in March 2008. You could also experiment with some other tools available in Giovanni (e.g., data animation).

Other exercises

Calculation of the sulfur budget for the 2011 Grimsvötn (Iceland) eruption

This exercise is an example of a common problem in volcanic emission studies: inferring the total volcanic sulfur budget based on measured emissions of only 1 or 2 sulfur species.

Goal: calculate the sulfur (S) budget of the May 2011 explosive eruption of Grimsvötn (Iceland) based on satellite remote sensing measurements of degassing and petrological data (S concentrations in the melt), and estimates of other sulfur sinks in the volcanic system.

Satellite remote sensing data and derived estimate of other sulfur species

The following sulfur gas species were measured or estimated in the Grimsvötn eruption cloud [*Sigmarsson et al.*, 2013]:

0.3 Tg SO_2 (OMI measurements)
29 Gg H_2S (IASI measurements)
15 Gg S_2 (estimated based on assumed gas ratios)

1 Tg = 10^{12} g
1 Gg = 10^{9} g

Ash leachate data

An estimated 118 Gg S was sequestered on volcanic ash in the eruption column [*Olsson et al.*, 2013]

Petrological estimate of Grimsvötn SO_2 emissions

Degassed SO_2 mass = $\frac{64}{32}\rho V_{DRE}(S_i - S_g)$

S_i = 0.1750 wt%
S_g = 0.0687 wt%
V_{DRE} = 0.25 km^3

Where 64/32 = ratio of molecular weights of SO_2 and S; ρ = 2750 kg m^{-3} (melt density); V_{DRE} = 0.25 km^3 (eruption volume, Dense Rock Equivalent); S_i = initial S concentration (from melt inclusions); S_g = residual S concentration after degassing (from groundmass).

Other sulfur sinks

Other potential sinks for S in the Grimsvötn system are:

S lost to hydrothermal system and caldera lake (S_{lake}) = 37 Gg S
S conserved in the magma as sulfide globules ($S_{sulfide\ globules}$). Sulfide globules were observed in the erupted products.

Total S mass balance for 2011 Grimsvötn eruption

$$S_i - (S_g + S_{satellite} + S_{leachate} + S_{lake} + S_{sulfide\ globules}) = 0$$

Step 1: calculate the total eruptive S emission (as SO_2, H_2S and S_2) based on satellite measurements.

Step 2: estimate the total S emission, accounting for the S scavenged in the eruption column. What proportion of the emitted S was scavenged and returned to the ground in ashfall?

Step 3: calculate the petrological estimate of SO_2 emissions, and compare this with the satellite observations.

Step 4: estimate the amount and proportion of the total S budget conserved in the magma as sulfide globules, according to the mass balance equation provided.

References

Olsson, J., S. L. S. Stipp, K. N. Dalby, and S. R. Gislason (2013), Rapid release of metal salts and nutrients from the 2011 Grímsvötn, Iceland volcanic ash, *Geochim. Cosmochim. Acta*, 123, 134–149, doi:10.1016/j. gca.2013.09.009.

Sigmarsson, O., B. Haddadi, S. Carn, S. Moune, J. Gudnason, K. Yang, and L. Clarisse (2013), The sulfur budget of the 2011 Grímsvötn eruption, Iceland, *Geophys. Res. Lett.*, 40, doi: 10.1002/2013GL057760.