

Multi-Satellite Volcanic Sulfur Dioxide (SO₂) Database Long-Term L4 Global**Overview**

This document describes the long-term database of volcanic SO₂ emissions derived from ultraviolet (UV) satellite measurements between October 1978 and the present (MSVOLSO2L4 v3.00). The database is primarily designed as a volcanic forcing dataset for use in atmospheric chemistry and climate model simulations of recent volcanic activity. The database provides SO₂ mass loadings for all significant global volcanic eruptions detected from space since October 1978, and will be regularly updated as new eruptions occur and old eruptions are reanalyzed. Thus, users of the data are *strongly encouraged* to contact the database curators listed at the end of this document for advice on any recent database updates.

SO₂ measurements listed in the database are derived primarily from three space-borne UV sensors. Eruptions between October 1978 and August 2004 were measured by the Total Ozone Mapping Spectrometer (TOMS) instruments that flew on the Nimbus-7 (N7; Oct 31, 1978 – May 6, 1993), Meteor-3 (M3; Aug 21, 1991 – Dec 28, 1994), ADEOS (AD; Sep 11, 1996 – Jun 29, 1997) and Earth Probe (EP; Jul 15, 1996 – Dec 31, 2005) spacecraft between October 1978 and December 2005 [Bluth *et al.*, 1993, 1997; Krueger *et al.*, 1995, 2000; Carn *et al.*, 2003]. Note that no TOMS instrument was operational between December 28, 1994 and July 15, 1996, resulting in a ~18 month UV measurement data gap. The Ozone Monitoring Instrument (OMI) on NASA's Aura satellite has measured eruptions since September 6, 2004 [Carn *et al.*, 2013], although the EP-TOMS mission continued until December 2005, providing some overlap with OMI. Since 2012, UV SO₂ measurements from the Ozone Mapping and Profiler Suite (OMPS) Nadir Mapper (NM) aboard the Suomi National Polar-Orbiting Partnership (NPP) satellite have also supplemented the OMI measurements [Carn *et al.*, 2015, 2016], particularly for eruptions impacted by the OMI 'row anomaly' data gap [Carn *et al.*, 2013]. More recently, we have begun to use new UV SO₂ measurements from the Tropospheric Monitoring Instrument (TROPOMI) aboard the Copernicus Sentinel-5 Precursor (S5P) satellite [Theys *et al.*, 2017] to quantify volcanic SO₂ emissions. Infrared (IR) satellite measurements from sensors including the High-resolution Infrared Radiation Sounder (HIRS/2; 1978 – present; Prata *et al.*, 2003), Atmospheric Infrared Sounder (AIRS; 2002 – present; Prata and Bernardo, 2007), Moderate Resolution Infrared Spectroradiometer (MODIS; 1999 - present) and Infrared Atmospheric Sounding Interferometer (IASI; 2007 – present; Clarisse *et al.*, 2012) are also used to validate and refine SO₂ mass loadings based on UV data, particularly for high latitude eruptions in the winter months.

Explanation of column headings

Columns in the MSVOLSO2L4 data file contain the information shown in Table 1. Volcano parameters (name, latitude, longitude, and altitude) are derived from the Smithsonian Institution Global Volcanism Program (GVP) database (<http://www.volcano.si.edu>).

Eruption type (explosive or effusive) is provided to distinguish explosive eruption plumes, which have the potential for stratospheric injection of SO₂, from effusive eruption plumes, which typically attain maximum altitudes in the upper troposphere or below. Note that some eruptions may feature characteristics of both explosive and effusive eruptions; in such cases the database attempts to indicate the dominant eruptive style. For effusive or explosive eruptions lasting

Table 1. Data fields in the MSVOLSO2L4 product

Column header	Explanation
volcano	Name of volcano (from Smithsonian GVP database)
lat	Latitude of volcano (from Smithsonian GVP database)
lon	Longitude of volcano (from Smithsonian GVP database)
v_alt	Altitude of volcano (km; from Smithsonian GVP database)
yyyy	Eruption year
mm	Eruption month
dd	Eruption day
type	Eruption style: 'exp' = explosive eruption; 'eff' = effusive eruption
vei	Eruption Volcanic Explosivity Index, where known (from Smithsonian GVP database); nd = no data or undetermined
p_alt_obs	Observed plume altitude (km), where known (from Smithsonian GVP database, pilot reports, other satellite data such as CALIPSO or MLS, etc); Fill value is -999
p_alt_est	Estimated plume altitude (km). Fixed at 10 km above vent altitude for explosive eruptions and 5 km above vent altitude for effusive eruptions; Fill value is -999
so2(kt)	Measured SO ₂ mass in kilotons (kt; 1 kt = 10 ³ metric tons)

longer than one day, the database provides estimated SO₂ loadings for each day on which new eruptive SO₂ emissions were detected. Note that the database does not include SO₂ loadings for volcanic clouds that continue to drift in the atmosphere and remain detectable after an eruption has ended.

Where plume altitude observations are available, these are provided in the data file (p_alt_obs). Plume altitude information may be derived from a number of sources, including: satellite IR cloud-top brightness temperatures, plume trajectory modeling, direct (e.g., pilot) observations, space-borne or ground-based LiDAR or radar measurements, or UV/IR SO₂ altitude retrievals [e.g., Yang *et al.*, 2009b, 2010; Clarisse *et al.*, 2014]. In the absence of direct plume altitude observations, a fixed plume altitude above the vent is assumed (10 km for explosive eruptions, and 5 km for effusive eruptions). Users are cautioned that the vertical structure of volcanic eruption plumes can be complex and the database does not attempt to provide an accurate vertical emission profile; the plume altitude provided is an estimate of the altitude of peak SO₂ injection.

Most TOMS SO₂ measurements are derived using the SO₂ retrieval algorithm described by Krueger *et al.* [1995, 2000]. OMI SO₂ measurements are derived using the linear fit (LF) SO₂ algorithm described by Yang *et al.* [2007], which is used to generate the current operational OMI

SO₂ product (OMSO2) produced from global mode UV OMI measurements, and is also used to produce OMPS SO₂ data. For some larger eruptions producing higher SO₂ column amounts (>100-200 Dobson Units [DU; 1 DU = 2.69×10¹⁶ molecules cm⁻²]; exceeding the valid range of the LF SO₂ algorithm), advanced offline retrieval algorithms [e.g., *Yang et al.* 2009a, 2009b, 2010] have been used to calculate more accurate SO₂ loadings.

During normal operations, 14 or 15 OMSO2 granules are produced daily, providing fully contiguous coverage of the globe. Currently, OMSO2 products are not produced when OMI goes into ‘zoom mode’ for one day every 452 orbits (~32 days), hence there are no OMI SO₂ measurements on these days. Since June 25, 2007 signal suppression (anomaly) has been observed in Level 1B OMI Earth radiance data for some OMI scenes. This anomaly is also known as the OMI row anomaly since it affects some rows of the CCD detector. Since 2007, the row anomaly has expanded to affect more rows creating a significant data gap, particularly at low latitudes where there is no orbit overlap. More information about the OMI row anomaly can be obtained from KNMI (<http://www.knmi.nl/omi/research/product/rowanomaly-background.php>).

The principal difference between TOMS, OMI and OMPS SO₂ measurements is the lower detection limit of OMI and OMPS: the minimum volcanic SO₂ mass detectable by OMI/OMPS is about 1-2 orders of magnitude smaller than the TOMS detection threshold. This is due to the smaller OMI footprint and the use of wavelengths better optimized for distinguishing O₃ from SO₂ in OMI and OMPS measurements. Thus the detection rate for volcanic eruptions has significantly increased during the OMI and OMPS missions.

SO₂ mass loadings are calculated from the TOMS, OMI or OMPS retrievals of SO₂ column amount in DU using:

$$M_{SO_2} = 0.0285 \sum_{i=0}^n \Omega_i A_i$$

where M_{SO_2} is the total SO₂ mass (metric tons) in a volcanic cloud comprising n satellite pixels, and Ω_i and A_i are the SO₂ column amount (DU) and area (km²) for the i th satellite pixel, respectively. In regions with substantial overlap of adjacent satellite orbits, SO₂ data may be resampled (gridded) to avoid ‘double counting’ of SO₂ (in this case, M_{SO_2} is the sum over n grid cells), or individual orbits may be considered separately. The database typically reports the highest measured SO₂ mass on a single day for explosive eruptions, assuming a SO₂ plume altitude equal to the observed or estimated plume altitude (p_alt_obs or p_alt_est). Note that the calculated SO₂ mass increases as the assumed plume altitude decreases. For effusive eruptions involving continuous emissions, the database provides daily SO₂ loadings and plume altitudes for each day of the eruption.

Subsets of the long-term volcanic SO₂ database have been previously published in *Bluth et al.* [1993, 1997] and *Carn et al.* [2003, 2015], with a major review of the entire database provided by *Carn et al.* [2016]. However, SO₂ algorithm updates or reanalysis of specific volcanic eruptions will undoubtedly result in some changes to previously reported SO₂ amounts in future iterations of the database.

Changes from Prior Versions of the Database

As noted above, SO₂ retrieval algorithm improvements, reanalysis of specific volcanic eruptions or updated information (e.g., on plume altitude) may result in some changes to previously reported data. Some notable changes in the current release (v3.00) relative to the previous version (v2.00) include the addition of new data for volcanic eruptions since 2015, the insertion of several older eruptions omitted from the previous release (e.g., Colima in 2005, Oldoinyo Lengai in 2008, South Sarigan in 2010) and some refinement of SO₂ tonnage data and plume altitudes for old eruptions based on information from the scientific literature and new TOMS and OMI SO₂ data analysis. In particular, the SO₂ tonnage for the 1991 Pinatubo eruption has been revised based on new TOMS data analysis [Fisher *et al.*, 2019].

Data Quality Assessment and Errors

Satellite SO₂ measurements are optimized for low optical depths of SO₂ under cloud-free conditions in a Rayleigh scattering atmosphere. Errors on the TOMS, OMI and OMPS volcanic SO₂ measurements can be difficult to quantify, owing to the highly variable (and often poorly constrained) measurement conditions in volcanic clouds, which may contain aerosols (volcanic ash and sulfate) and hydrometeors in addition to SO₂ [Krotkov *et al.*, 1997]. A major source of uncertainty in the SO₂ mass loadings, particularly for volcanic plumes in the lower troposphere, is the assumed SO₂ altitude or vertical profile [Yang *et al.*, 2007]. In most cases, the altitude assumed in the SO₂ retrieval is given by p_alt_obs or p_alt_est. If the assumed altitude is below the true altitude of the volcanic SO₂, the SO₂ mass will be overestimated, and vice versa, all other factors being equal. The accuracy and precision of OMI and TOMS SO₂ measurements also vary significantly with observational geometry and slant column ozone. UV measurements become more sensitive to SO₂ above clouds and snow/ice, and less sensitive to SO₂ below clouds. Overall errors of ~20-30% are commonly assumed, though they may be higher for some eruptions. Both the TOMS and OMI SO₂ measurements have been validated to a limited extent with ground-based SO₂ measurements [e.g., Krueger *et al.*, 2000; Spinei *et al.*, 2010; Carn and Lopez, 2011]. Users are strongly encouraged to contact the database curators to discuss specific cases.

Product Description

The database is provided as an ASCII text file. The data file is available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) web site (doi: 10.5067/MEASURES/SO2/DATA404). For general assistance with the data archive, please contact the NASA GES DISC.

Contact Information

For questions and comments related to the MSVOLSO2L4 product and data quality please contact Nickolay Krotkov (Nickolay.A.Krotkov@nasa.gov), who has the overall responsibility for this product, with copies to Simon Carn (scarn@mtu.edu).

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