# Revision History

| ***Revision Date*** | ***Changes*** | ***Author*** |
|---|---|---|
| 2/02/2024 | Extended data time series range to 29 January, 2024 | Simon Carn, Can Li, Nickolay A. Krotkov and Peter J.T. Leonard |

**MSVOLSO2L4 README File v4**

**Multi-Satellite Volcanic Sulfur Dioxide ($SO_2$) Database Long-Term L4 Global**

**Overview**

This document describes the long-term database of volcanic $SO_2$ emissions derived from ultraviolet (UV) satellite measurements between October 1978 and the present (MSVOLSO2L4 v4). The database is primarily designed as a volcanic forcing dataset for use in atmospheric chemistry and climate model simulations of recent volcanic activity, and as a record of global eruptive volcanic emissions for the volcano science community. The database provides $SO_2$ 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. A complementary NASA database (MSAQSO2L4; *Fioletov et al.*, 2019, 2023) provides estimates of continuous $SO_2$ emissions from passively degassing volcanoes and anthropogenic $SO_2$ sources [*Fioletov et al.,* 2016; *Carn et al.*, 2017] and should be used in conjunction with MSVOLSO2L4 to fully represent global volcanic $SO_2$ emissions in model simulations.

$SO_2$ measurements listed in the database are derived primarily from 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 $SO_2$ measurements from the Ozone Mapping and Profiler Suite (OMPS) Nadir Mapper (NM) aboard the Suomi National Polar-Orbiting Partnership (SNPP) satellite have also supplemented the OMI measurements [*Carn et al.*, 2015, 2016; *Li et al.*, 2017], particularly for eruptions impacted by the OMI 'row anomaly' data gap [*Carn et al.*, 2013]. Since 2018, we have also been using UV $SO_2$ measurements from the Tropospheric Monitoring Instrument (TROPOMI) aboard the Copernicus Sentinel-5 Precursor (S5P) satellite [*Theys et al.,* 2017, 2021] and OMPS aboard the NOAA-20 (N20) satellite [*Li et al.*, 2023] to quantify volcanic $SO_2$ emissions. Infrared (IR) satellite measurements from sensors including the High-resolution Infrared Radiation Sounder (HIRS/2; 1978 – 2007; *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 $SO_2$ mass loadings based on UV data, or measure $SO_2$ emissions not detected by UV instruments, 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 (https://volcano.si.edu/).

**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) |

*) Eruption type (explosive or effusive) is provided to distinguish explosive eruption plumes, which have the potential for stratospheric injection of $SO_2$, 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 longer than one day, the database provides estimated $SO_2$ loadings for each day on which new eruptive $SO_2$ emissions were detected. Note that the database does not include $SO_2$ 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 $SO_2$ altitude retrievals [*e.g.*, *Yang et al.*, 2009b, 2010; *Clarisse et al.*, 2014; *Hedelt et al.*, 2019; *Fedkin et al.*, 2021]. 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 $SO_2$ injection.

TOMS $SO_2$ measurements are mostly derived using the $SO_2$ retrieval algorithm described by *Krueger et al.* [1995, 2000], with updated $SO_2$ retrievals for the largest eruptions (e.g., 1982 El Chichón, 1991 Pinatubo) from the MS_SO2 algorithm described by *Fisher et al.* [2019]. Most OMI $SO_2$ measurements prior to 2014 were derived using the linear fit (LF) $SO_2$ algorithm described by *Yang et al.* [2007]. More recent OMI and OMPS volcanic $SO_2$ measurements use a newer, low-noise Principal Component Analysis (PCA) $SO_2$ algorithm [*Li et al.*, 2013] which is used to generate the current operational OMI $SO_2$ product (OMSO2 V2.0) produced from global mode UV OMI measurements [*Li et al.*, 2020], and is also used to produce operational SNPP and N20/OMPS $SO_2$ data [*Li et al.*, 2017; 2023]. For some larger eruptions prior to 2014 that produced higher $SO_2$ column amounts (>100-200 Dobson Units [DU; 1 DU = $2.69\times10^{16}$ molecules $cm^{-2}$]; exceeding the valid range of the LF $SO_2$ algorithm), such as the 2008 Kasatochi eruption (Alaska, USA), advanced offline retrieval algorithms [e.g., *Yang et al.* 2009a, 2009b, 2010] or the PCA algorithm [*Li et al.*, 2017] have been used to calculate more accurate $SO_2$ loadings.

During normal operations, 14 or 15 OMSO2 granules are produced daily, providing fully contiguous coverage of the globe. OMSO2 products are not produced when OMI goes into ‘zoom mode’ for one day every 452 orbits (~32 days), hence there are no OMI $SO_2$ 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. After 2007, the row anomaly expanded to affect more rows creating a significant data gap, particularly at low latitudes where there is no orbit overlap [*Schenkeveld et al.*, 2017].

The principal difference between TOMS, OMI and OMPS $SO_2$ measurements is the lower detection limit of OMI and OMPS: the minimum volcanic $SO_2$ 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 $O_3$ from $SO_2$ in OMI and OMPS measurements. Thus, the detection rate for volcanic eruptions has significantly increased during the OMI and OMPS missions, as smaller $SO_2$ emissions can be detected. Note that the TROPOMI $SO_2$ detection limit [*Theys et al.*, 2021] is even lower than OMI and OMPS due to its higher spatial resolution (3.5×5.5 km) .

$SO_2$ mass loadings are calculated from the satellite retrievals of $SO_2$ column amount in DU using:

$$M_{SO2} = 0.0285 \sum_{i=0}^{n} \Omega_i A_i$$

where $M_{SO2}$ is the total $SO_2$ mass (metric tons) in a volcanic cloud comprising *n* satellite pixels, and $\Omega_i$ and $A_i$ are the $SO_2$ column amount (DU) and area ($km^2$) for the *i*th satellite pixel, respectively. In regions with substantial overlap of adjacent satellite orbits, $SO_2$ data may be resampled (gridded) to avoid 'double counting' of $SO_2$ (in this case, $M_{SO2}$ is the sum over *n* grid cells), or individual orbits may be considered separately. The database typically reports the highest measured $SO_2$ mass on a single day for explosive eruptions, assuming a $SO_2$ plume altitude equal to the observed or estimated plume altitude (p_alt_obs or p_alt_est). Note that the calculated $SO_2$ mass increases as the assumed plume altitude decreases. For effusive eruptions involving continuous emissions, the database provides daily $SO_2$ loadings and plume altitudes for each day of the eruption.

Subsets of the long-term volcanic $SO_2$ 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, $SO_2$ algorithm updates or reanalysis of specific volcanic eruptions will undoubtedly result in some changes to previously reported $SO_2$ amounts in future iterations of the database.

## Changes from Prior Versions of the Database

As noted above, $SO_2$ 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 MSVOLSO2L4 release (v4) relative to the previous version (v3) include the addition of new data for volcanic eruptions detected since early 2019, the insertion of more detailed $SO_2$ data for some eruptions omitted from the previous release (*e.g*., Kilauea in 2018) and some refinement of $SO_2$ tonnage data and plume altitudes for old eruptions based on information from the scientific literature and new TOMS, OMI, TROPOMI, and OMPS $SO_2$ data analysis. In particular, the $SO_2$ mass for the 1991 Pinatubo eruption has been revised based on new TOMS data analysis [*Fisher et al*., 2019].

## Data Quality Assessment and Errors

Satellite $SO_2$ measurements are optimized for low optical depths of $SO_2$ under cloud-free conditions in a Rayleigh scattering atmosphere. Errors on the TOMS, OMI and OMPS volcanic $SO_2$ 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 $SO_2$ [*Krotkov et al*., 1997; Fisher et al., 2019]. A major source of uncertainty in the $SO_2$ mass loadings, particularly for volcanic plumes in the lower troposphere, is the assumed $SO_2$ altitude or vertical profile [*Yang et al.*, 2007; *Li et al.*, 2017]. In most cases, the altitude assumed in the $SO_2$ retrieval is given by p_alt_obs or p_alt_est. If the assumed altitude is below the true altitude of the volcanic $SO_2$, the $SO_2$ mass will be overestimated, and vice versa, all other factors being equal. The accuracy and precision of OMI, OMPS, TROPOMI, and TOMS $SO_2$ measurements also vary significantly with observational geometry and slant column ozone. UV measurements become more sensitive to $SO_2$ above clouds and snow/ice, and less sensitive to $SO_2$ below clouds. Overall errors of ~20-30% are commonly assumed, though they may be higher for some eruptions. Both the TOMS and OMI $SO_2$ measurements have been validated to a limited extent with ground-based $SO_2$ 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/DATA405). For general assistance with the data archive, please contact the NASA GES DISC: gsfc-dl-help-disc@mail.nasa.gov .

## 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 the main database curator, Simon Carn (scarn@mtu.edu).

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