Detection and Monitoring of Sulfur Dioxide from Satellite-based UV Sensors

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Abstract

Sulfur dioxide column amounts are retrieved from near-UV spectral radiance data with exceptional precision. The high sensitivity coupled with daily global coverage with unprecedented spatial resolution from Aura/OMI has provided a wealth of new information. Sulfur dioxide is a short-lived constituent of the atmosphere that is produced by volcanoes and from combustion of sulfur-containing fossil fuels. It is oxidized to sulfate aerosols at a rate that depends on altitude. Sulfate aerosols change the reflectance of the atmosphere, making sulfur dioxide an important climate constituent. While fossil fuel burning constitutes a large, broadly distributed source of sulfur dioxide, volcanic eruptions can inject very large sulfur dioxide clouds into the upper atmosphere in a few hours. Explosive eruptions also produce volcanic ash as frothy liquid magma freezes in the atmosphere. Ash clouds are a hazard to aviation but are sometimes difficult to discriminate from other clouds while sulfur dioxide is a unique marker. Volcanic clouds can drift global distances at aircraft cruise altitudes as they are carried by the upper air winds. Thus, satellite observations of sulfur dioxide are invaluable for locating fresh volcanic clouds. A near real-time data production capability has been developed for operational use at NOAA NESDIS where the data are distributed via internet to the Decision Support Systems. The UV algorithms are designed to operate with data from OMI and GOME-2 and future instruments like OMPS. The sensitivity is adequate to monitor pre-eruptive emissions from volcanoes for detection of new activity. In addition, large sources of sulfur dioxide from fossil fuel burning and from smelting of ores are being monitored.

INTRODUCTION

Satellite remote sensing of volcanic clouds began with the eruption of El Chichon in southern Mexico in 1982. Its globe-circling plume was tracked for three weeks as a tenuous aerosol cloud with visible AVHRR data (Robock and Matson, 1983) and as a sulfur dioxide cloud in the Nimbus 7 UV Total Ozone Mapping Spectrometer (TOMS) data (Krueger, 1983, Krueger et al., 2008). While the aerosol cloud was identified qualitatively by its hazy appearance and the distortion of underlying cloud edges, the sulfur dioxide cloud was retrieved quantitatively by column integral amounts in the TOMS pixels and as total mass by integrating over the cloud area. This newfound ability to measure the mass of eruption clouds was later applied to all the eruptions since 1978 in the TOMS dataset to produce a climate record of volcanic input that now extends for 30 years.

Only months after the El Chichon eruption, two Boeing 747 passenger jet airplanes were disabled after they flew into ash clouds from eruptions of Galunggung volcano in West Java, Indonesia. The thought of loss of hundreds of passengers lives and an expensive airplane due to a volcanic eruption has led to
development of satellite techniques to rapidly locate volcanic ash clouds directly and through a surrogate, sulfur dioxide. This information from research satellites is now made available in near real-time to the aviation and geophysical communities.

**TOMS VOLCANIC CLOUD DATA**

The TOMS instrument (Heath, et al., 1973) was designed to map the spatial distribution of total ozone using a total ozone retrieval scheme developed with the Nimbus 4 Backscatter UltraViolet (BUV) instrument (Dave and Mateer, 1967). Telemetry bandwidth restrictions on the Nimbus 7 satellite limited the instrument to six wavelengths and a spatial resolution of 50 km at nadir. The wavelengths were selected to accurately map ozone over the entire range of geophysical and geometric conditions from the sun synchronous satellite orbit. The swath width was designed for full contiguous daily global mapping to insure that no small ozone perturbations were missed between orbits. When El Chichon erupted an anomalous high ozone cloud appeared in the ozone data over the volcano and adjacent regions. The anomalous absorbing gas was identified as sulfur dioxide (Krueger 1983) and a new algorithm was developed to discriminate sulfur dioxide absorption from ozone absorption by spectral differences in the backscattered UV sunlight (Krueger et al., 1995). In addition, low temperature sulfur dioxide absorption cross sections were measured in the lab corresponding to stratospheric conditions where the volcanic cloud was located (McGee and Burris, 19xx). Figure 1 shows the cloud on the fifth day after the major eruption on April 4, 1982.

![Figure 1: The sulfur dioxide cloud produced by the eruption of El Chichon volcano in southern Mexico on April 4, 1982 as measured with the TOMS instrument on the Nimbus 7 satellite. This cloud continued to expand westward until the leading edge passed across Central America three weeks later.](image)

The sulfur dioxide amounts in the fresh El Chichon eruption clouds were found to be greater than the highest total ozone amounts. These amounts decreased fairly rapidly as the cloud dispersed and the sulfur dioxide was converted to sulfate molecules which do not absorb at UV wavelengths. However, the amounts were large enough that the cloud could be tracked as easterly stratospheric wind shear from 20 to 25 km separated the vertical eruption column into a banner that extended around the world after 3 weeks. The rate of loss of sulfur dioxide was consistent with a lifetime of about 30 days, which demonstrated that the conversion to sulfate did not use up hydroxyl and the chemistry was catalytic.
The retrieval noise level is determined by the inversion matrix properties that depended on the available wavelengths and corresponding ozone and sulfur dioxide cross sections (Gurevich and Krueger, 19xx). Nevertheless, every eruption since October 1978 was captured in the TOMS database except for an 18-month gap in 1994–1996 between TOMS missions. The contiguous daily spatial coverage became very important for monitoring volcanic eruptions because of the short (~1 day) lifetime of sulfur dioxide at low altitudes and the small size of some eruption clouds. A time series of the volcanic input from major eruptions were produced (Carn et al., 2003) for quantitative input to climate models (Figure 2).

![Figure 2: The time series of the input of sulfur dioxide from major volcanic eruptions into the atmosphere. The largest eruption was Mt Pinatubo in 1991 which produced 20 Mt (Tg) of sulfur dioxide. The only data gap was between the Meteor-3 TOMS mission and the ADEOS and Earth Probe TOMS missions. Data since the end of the Earth Probe mission in 2005 come from the EOS Aura/OMI instrument. Arc volcanoes erupt explosively to stratospheric altitudes while non-arc volcanoes erupt effusively and deliver the sulfur dioxide to the lower troposphere.](image)

**IMPROVED SO₂ DETECTION WITH HYPERSPECTRAL SATELLITE INSTRUMENTS**

In the 1990’s more telemetry bandwidth became available for data transfer to the ground. The first hyperspectral UV instrument flown was GOME on the ERS-2 satellite in 1995 (Burrows, et al. 1999). This instrument was not designed for mapping of spatial structure but its broad spectral coverage permitted detection of other species that absorb in the near UV and blue (NO₂, O₃Cl, BrO, OCHO). In addition, full spectral data led to a twenty-fold improvement in SO₂ sensitivity over TOMS (Eisinger and Burrows, 1998) and even air pollution sulfur dioxide was detected. This instrument was followed by the SCIAMACHY instrument on ENVISAT in 2002, which added nadir mapping that was time-shared with limb observations. The first hyperspectral instrument with contiguous spatial coverage that is essential for daily monitoring of volcanic sulfur dioxide emissions is the OMI instrument (Leveit, et al., 2006) on the EOS Aura platform. This Dutch/Finnish instrument provides continuation of volcanic SO₂ data after the TOMS series ended in 2005. In addition to a twenty-fold increase in sensitivity, the OMI ground resolution is improved over TOMS by a factor of eight to permit detection SO₂ clouds two orders of magnitude smaller (Krotkov et al., 2006, Yang et al., 2007). The SO₂ retrieval characteristics for the OMI instrument and the Earth Probe TOMS are shown in Table 1.
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<th>Aura/OMI</th>
<th>Earth Probe TOMS</th>
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<tr>
<td>Nadir footprint (km)</td>
<td>13 x 24</td>
<td>39 x 39</td>
</tr>
<tr>
<td>Spectral resolution (nm)</td>
<td>0.45</td>
<td>1.1</td>
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<tr>
<td>Wavelengths</td>
<td>780</td>
<td>6</td>
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<tr>
<td>SO2 retrieval noise, $1\sigma$ (DU) for a cloud at 15 km</td>
<td>0.2</td>
<td>5</td>
</tr>
<tr>
<td>SO2 detection limit (tons, 5 adjacent pixels &gt; 5$\sigma$)</td>
<td>50</td>
<td>7000</td>
</tr>
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Table 1: Comparison of sulfur dioxide cloud detection limits between OMI and TOMS. The OMI improvement is due to optimum wavelengths and smaller footprint size. The 25-fold decrease in retrieval noise results in detection of smaller extended areas clouds. The 140-fold decrease in detection limit results in detection of smaller point sources.

An example of an explosive eruption cloud monitored with OMI was from the Soufriere Hills volcano on Montserrat in the West Indies on May 20, 2006 (Figure 3). The eruption produced only 1% of the SO$_2$ in the Pinatubo eruption of 1991, but the cloud could be tracked nearly as long due to the decreased retrieval noise.

![Figure 3: The sulfur dioxide cloud from the eruption of the Soufriere Hills volcano on May 20, 2006. The figure is a composite showing the position of the cloud over the first two weeks after the eruption. The + marks show the trajectory at 20 km predicted by the HYSPLIT model. The initial sulfur dioxide amount is about 200 kt (0.2 Tg).](image)

**VOLCANIC DEGASSING AND AIR POLLUTION**

As with the GOME and SCIAMACHY instruments, OMI is able to detect passive degassing from volcanoes and from sulfate ore smelters. With the OMI contiguous coverage and small footprint, the emissions can be monitored on a daily basis and discriminated from nearby volcanoes (Figure 4).
Figure 4: Average $SO_2$ emissions from western South America measured with OMI over a one year period, together with time series of daily values. The emitting sources are two smelters in Peru and primarily 3 volcanoes in Ecuador and Columbia. Triangles show the location of active volcanoes.

Figure 5: Long term average OMI $SO_2$ over southeast Europe for 2005 and 2006. Mt Etna on Sicily at the tip of Italy is the largest source during this time period. Power plants across Bulgaria, Romania, Greece, and Turkey also produce detectable emissions.
Explosive magmatic volcanic eruptions produce fine ash as bubble-rich liquid magma expands, freezes, and fractures in the atmosphere during the eruption. Among the principal gases in the magma is sulfur dioxide. While ash is difficult to detect because it has only a weak spectral signature, sulfur dioxide has a distinct band structure at UV wavelengths that is easily detected from space. Thus, the UV mapping capability in TOMS, SCIAMACHY, and OMI has been utilized to locate fresh volcanic eruption clouds with sulfur dioxide as a marker for ash clouds (Carn, et al., 2008). While ash can also be located with these instruments, that signal is not unique and also occurs from dust and smoke. However, the only sources of large concentrations of sulfur dioxide are magmatic eruptions of volcanoes. Two programs are in place to produce sulfur dioxide data rapidly enough to be of use to the aviation community in air traffic control. In Europe, the PROMOTE project delivers SCIAMACHY data in near-real-time to the Toulouse and London Volcanic Ash Advisory Centers (VAAC) and the public via the web (http://www.oma.be/BIRA-IASB/Molecules/SO2nrt/alert/intro.php) and email alerts. In the US, a NASA-sponsored Cooperative Agreement between UMBC and NOAA is delivering OMI data to the Washington and Alaska VAAC’s and the US Geological Survey Volcano Observatories via the NOAA web site (http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html), as illustrated in Figure 7. In general, the data are available less than three hours after collection with the satellite instruments.

**Figure 6:** The NOAA near-real-time volcanic hazard website showing volcanic SO\textsubscript{2} clouds during the past 24 hours using OMI data. The most recent orbit is marked by a yellow outline on a global map projection for equatorial and subtropical latitudes. High latitude eruption clouds are shown on polar projections. This example, from August 15, 2008 shows streamers of SO\textsubscript{2} by the red bands across the northern hemisphere from the eruption of Kasatochi volcano in the Aleutian Islands.
Detailed maps of volcanic regions are provided to show degassing activity, which is useful for monitoring non-eruptive volcanic activity. For example, an image of SO₂ clouds from Kileaua volcano on Hawaii are shown in Figure 8. The ash distribution from OMI Absorbing Aerosol Index data are also provided. The NOAA link provides data in various formats for operational users.

**Figure 7**: An example of detailed OMI data over a volcanic region from the near real-time NOAA website. This shows degassing of SO₂ from Kileaua volcano on the island of Hawaii on June 17, 2008.

**Figure 8**: The trail of SO₂ on August 16, 2008 produced by the eruption of Kasatochi Volcano on August 7-8, 2008 and observed in OMI data. These streamers drifted very slowly in the late summer lower stratospheric circulation. Most of the ash from the eruption fell out in the first few days, leaving a plume of SO₂, sulfate and a small amount of ash that remained detectable until all the SO₂ was converted to sulfate.
The eruption of Kasatochi volcano in the Aleutian Islands on August 7-8, 2008 produced the most dramatic example of eruption cloud dispersal on record. This cloud was sheared into three fingers that were stretched into distinct trails across much of the northern hemisphere. Figure 8 illustrates the distribution across North America, the Atlantic Ocean and Western Europe on August 16th.

CONCLUSIONS

Quantitative mapping of volcanic eruption clouds was initiated in retrievals of sulfur dioxide with data from the Nimbus 7 TOMS instrument, a six-channel UV spectrometer designed to measure ozone. This led to a 25-year record of volcanic eruption sizes of interest to climate modelers. The volcanic images also found application in aviation safety as an easily detected proxy for ash clouds that can disable aircraft in flight. The introduction of hyperspectral instruments including GOME, SCIAMACHY, and OMI has improved the sensitivity for detection of SO$_2$ by an order of magnitude so that volcanic degassing and air pollution from smelters and fossil fuel burning can also be detected. The data are now being provided in near real-time to operational agencies responsible for aviation safety and volcano monitoring.

REFERENCES


