A decade of volcanic observations from Aura and the A-Train

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Volcano team: Nick Krotkov, Kai Yang, Arlin Krueger, Eric Hughes, Jun Wang, Verity Flower, Jennifer Telling
Volcanic SO$_2$ clouds measured by TOMS

- Low sensitivity
- Low spatial resolution
- No altitude information
- No ‘monitoring’ capability

TOMS: Total Ozone Mapping Spectrometer

1978-2005
A time-averaged inventory of subaerial volcanic sulfur emissions

R.J. Andres and A.D. Kasgnoc
Institute of Northern Engineering, University of Alaska Fairbanks

Abstract. A time-averaged inventory of subaerial volcanic sulfur (S) emissions was compiled primarily for the use of global S and sulfate modelers. This inventory relies upon the 25-year history of S, primarily sulfur dioxide (SO₂), measurements at volcanoes. Subaerial volcanic SO₂ emissions indicate a 13 Tg/a SO₂ time-averaged flux, based upon an early 1970s to 1997 time frame. When considering other S species present in volcanic emissions, a time-averaged inventory of subaerial volcanic S fluxes is 10.4 Tg/a S. These time-averaged fluxes are conservative minimum fluxes since they rely upon actual measurements. The temporal, spatial, and chemical inhomogeneities inherent to this system gave higher S fluxes in specific years. Despite its relatively small proportion in the atmospheric S cycle, the temporal and spatial distribution of volcanic S emissions provide disproportionate effects at local, regional, and global scales. This work contributes to the Global Emissions Inventory Activity.

Motivation:
• Climate impact of volcanic emissions
• Global fluxes of other volatile species
• Field sites for volcanic gas studies

[Graf et al., 1997; Andres & Kasgnoc, 1998; Halmer et al., 2002; Smith et al., 2011]
OMI monitors SO$_2$ emissions in South America

- SO$_2$ emissions in Ecuador and Colombia from Tungurahua, Reventador, Galeras and Huila volcanoes
- Volcanic emissions from Ubinas volcano (Peru) drift over Ilo region in 2006-2007
- Upgraded sulfur capture technology at Ilo reduces SO$_2$ emissions
- Shut-down of La Oroya smelter in mid-2009; reduction expected

Volcanic SO₂ emissions inventories are inaccurate

- OMI measurements indicate deficiencies in current ‘bottom up’ volcanic SO₂ emission inventories used in CTMs

REMOTE model simulation of annual mean SO₂ columns over Indonesia [Pfeffer et al., ACP, 2006]
Identification of global volcanic SO$_2$ sources

- SO$_2$ index defined using OMI ozone algorithm residuals (sensitive to SO$_2$)
- Rank top 1000 values of SO$_2$ index on each day (lat 65°S – 80°N)
- Locate active volcanoes within 50 km radius of these OMI pixels (using modified Smithsonian Global Volcanism Program database)
- Record unique volcanic sources for each day
- Repeat for each day of OMI measurements (>3200 from Sep 2004 – Dec 2013)
Persistent volcanic SO$_2$ sources (2004-2013; ~3200 days)

<table>
<thead>
<tr>
<th>Volcano</th>
<th>SO$_2$ flux (t/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etna</td>
<td>4000</td>
</tr>
<tr>
<td>Bagana</td>
<td>3300</td>
</tr>
<tr>
<td>Lascar</td>
<td>2400</td>
</tr>
<tr>
<td>Ruiz</td>
<td>1900</td>
</tr>
<tr>
<td>Sakura-jima</td>
<td>1900</td>
</tr>
<tr>
<td>Manam</td>
<td>920</td>
</tr>
<tr>
<td>Yasur</td>
<td>900</td>
</tr>
<tr>
<td>Kilauea</td>
<td>800</td>
</tr>
<tr>
<td>Masaya</td>
<td>790</td>
</tr>
<tr>
<td>Stromboli</td>
<td>730</td>
</tr>
</tbody>
</table>

[Andres and Kasgnoc, 1998]
Most persistent volcanic SO$_2$ sources in 2013

- POPOCATEPETL
- NYIRAGONGO
- AMBRYM
- RUIZ
- KILAUEA
- AOBA
- TURRIALBA
- TOLBACHIK
- KLIUČEVEŠKII
- ULAWUN
- IJEN
- DUKONO
- BAGANA
- GAUA
- COPAHUE
- TUNGURAHUA
- YASUR
- HUILA
- KIZIMEN
- MANAM
- KERINCI
- TENGGER_CALDERA
- SHIVELUCH
- SANTIAGUITO
- KARYMSKY
- LEWOTIOBI
- GALERAS
- SUWANOSE-JIMA
- SAKURA-JIMA
- ETNA

Number of days with detected SO$_2$ degassing

Average SO$_2$ Index

Reuters
SO₂ emission rate estimation from satellite data

\[ Q_{\text{meas}} = \left[ \frac{vM}{L} \right] \]

- Similar approach used to estimate smoke and NO₂ emissions from fires [Ichoku and Kaufman, 2005; Mebust et al., 2011]
- Note that asymmetry of OMI pixel affects plume detection
- Chemistry correction [Mebust et al., 2011] can be applied if SO₂ lifetime is known

\[ Q_{\text{meas}} = Q_{\text{init}} \tau t_c^{-1} \left[ 1 - \exp(-\tau^{-1} t_c) \right] \]

\[ t_c = L v^{-1} \]

\[ M = \text{SO}_2 \text{ mass in pixel (kg)} \]
\[ v = \text{wind speed (m s}^{-1}) \]
\[ L = \text{length of plume (m)} \]
\[ Q = \text{SO}_2 \text{ flux (kg s}^{-1}) \]
Estimated $\text{SO}_2$ fluxes (2004-2013; ~3200 days)

- New volcanic $\text{SO}_2$ emissions database for CTMs
- Jun Wang’s talk (Tuesday)

<table>
<thead>
<tr>
<th>Volcano</th>
<th>$\text{SO}_2$ flux (t/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambrym</td>
<td>32800</td>
</tr>
<tr>
<td>Popocatepetl</td>
<td>13000</td>
</tr>
<tr>
<td>Etna</td>
<td>5500</td>
</tr>
<tr>
<td>Nyiragongo</td>
<td>3280</td>
</tr>
<tr>
<td>Miyake-jima</td>
<td>3000</td>
</tr>
</tbody>
</table>

[Oppenheimer et al., 2011]
Validation with ground-based SO$_2$ measurements

Good agreement with long-term, ground-based datasets

Chemistry correction:
$\sim 20\%$ for $\tau_{SO2} = 2$ hrs

Sporadic
Continuous (NOVAC; Galle et al., 2010)

$y = 0.3333x + 869.33$
$R^2 = 0.70436$
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/20/2006 17:00-18:41 UT

Mass: 135.133 kt; Area: 202457 km²; SO₂ max: 146.85 DU at lon: 64.79 lat: 15.72

~0.2 Tg SO₂

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/21/2006 17:40-19:25 UT

Mass: 195.725 kt; Area: 1400753 km²; SO₂ max: 32.71 DU at lon: -74.40 lat: 11.42

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/22/2006 16:48-20:08 UT

Mass: 188.536 kt; Area: 1890299 km²; SO₂ max: 23.66 DU at lon: -61.33 lat: 14.47

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006


Mass: 171.187 kt; Area: 241000 km²; SO₂ max: 19.89 DU at lon: -93.38 lat: 13.66

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/24/2006 16:33-21:35 UT

Mass: 159.341 kt; Area: 2532097 km²; SO$_2$ max: 20.18 DU at lon: -107.02 lat: 12.14

Normalised SO$_2$ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/25/2006 14:03-22:18 UT

Mass: 168,052 kt; Area: 3126612 km²; SO₂ max: 18.41 DU at lon: -114.18 lat: 13.47

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/26/2006 16:19-23:02 UT

Mass: 146,936 kt; Area: 346,046 km²; SO₂ max: 12.14 DU at lon: -121.13 lat: 13.78

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/28/2006 00:22-22:50 UT

Mass: 108.896 kt; Area: 2279174 km²; \( \text{SO}_2 \) max: 8.11 DU at lon: -135.54 lat: 13.82

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/29/2006 01:07-23:33 UT

Mass: 98.493 kt; Area: 17014.11 km²; \( \text{SO}_2 \) max: 6.22 DU at lon: -145.52 lat: 12.46

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 05/30/2006 00:11-22:37 UT

Mass: 107.076 kt; Area: 2034.725 km²; SO₂ max: 6.74 DU at lon: -146.34 lat: 13.83

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Carn et al., 2007; Prata et al., 2007

~0.2 Tg SO$_2$

Aura/OMI - 05/31/2006 00:54-23:21 UT

Mass: 96.573 kt; Area: 2063998 km$^2$; SO$_2$ max: 6.10 DU at lon: -156.59 lat: 11.76

Normalised SO$_2$ column

[Carn et al., 2007; Prata et al., 2007]
SOuflière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/02/2006 00.00-24.00 UT

Mass: 92.692 kt; Area: 2247222 km²; SO₂ max: 5.54 DU at lon: -165.01 lat: 9.94

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/03/2006 00:41-04:04 UT

Mass: 82.835 kt; Area: 2209377 km²; SO₂ max: 3.85 DU at lon: -175.63 lat: 9.17

[NASA/KMI/NVI/FMI]

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/04/2006 01:25-06:23 UT

Mass: 79.103 kt; Area: 2352265 km²; SO₂ max: 3.01 DU at lon: 155.20 lat: 11.69

[Carn et al., 2007; Prata et al., 2007]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Carn et al., 2007; Prata et al., 2007

~0.2 Tg SO2
Soufrière Hills volcano (Montserrat) eruption, May 2006

Carn et al., 2007; Prata et al., 2007

~0.2 Tg SO$_2$
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/07/2006 03:34-08:34 UT

Mass: 45.726 kt; Area: 1734106 km²; SO₂ max: 2.12 DU at lon: 126.13 lat: 4.70

No volcanic SO₂ cloud of similar size tracked for more than 7 days by TOMS
New insights into volcanic SO$_2$ plume dispersion

OMI SO$_2$

Kasatochi eruption, Aug 2008

- New constraints on SO$_2$ lifetime in UTLS
- Improve sulfur chemistry scheme in CTMs

[Krotkov et al., JGR, 2010; Wang et al., ACP, 2013]
CALIPSO first light – 7 June 2006

Stratospheric aerosol

OMI SO$_2$ – 7 June 2006

SO$_2$ column 15 km [DU]
A-Train data for February 2014 Kelut eruption

Color Enhanced Infrared Imagery (11μm)

Aqua MODIS (02/13/2014 – 18:10 UTC)

MODIS image courtesy of NOAA/CIMSS
A-Train data for February 2014 Kelut eruption

Credit: S.A. Cam, Michigan Tech (scarn@mtu.edu)
Direct retrieval of SO$_2$ altitude from UV radiances

- SO$_2$ altitude directly retrieved from hyperspectral UV radiances
- Validate with CALIPSO, MLS
- Critical for climate impact, aviation hazards and CTM source term

- SO$_2$ altitude retrievals for 2008 Kasatochi eruption

[Yang et al., JGR, 2010]
UV satellite volcanic SO$_2$ inventory (1978 – 2014)

333 eruptions; 94 Tg total SO$_2$; mean 0.28 Tg; 1$\sigma$ = 1.3 Tg

$\sim$6 eruptions/yr (1979-2004); $\sim$19 eruptions/yr (2004-2014)
Stratospheric AOD and the global warming ‘hiatus’

Increase linked to influence of tropical volcanic eruptions

Vernier et al., GRL, 2011
Solomon et al., Science, 2011
Santer et al., Nature Geosci., 2014
Santer et al., Nature Geosci. [2014]

Increase in tropical stratospheric AOD since 2000

- Eruptions filtered using Volcanic Explosivity Index (VEI)
- VEI not a good proxy for climate impact (i.e., SO$_2$ emissions)
- VEI no longer needed -> use satellite observations
Volcanic SO$_2$ and stratospheric aerosol since 2002

Carn et al., in prep.
OMI SO$_2$ validation - Okmok (Aleutian Is) eruption

Aura/OMI - 07/17/2008 00:00-24:00 UT

SO$_2$ mass: 67.350 kt; Area: 968738 km$^2$; SO$_2$ max: 23.27 DU at lon: -143.54 lat: 40.71; 22:19 UTC

Spinei et al., JGR [2010]
MFDOAS-OMI comparison

- OMI SO$_2$ – ISF
- OMI SO$_2$ – Operational
- WSU MFDOAS SO$_2$
- MLDPO model (1 m$^2$s$^{-2}$)
- MLDPO model (0.5 m$^2$s$^{-2}$)
- MLDPO model data from Environment Canada, Montreal

Spinei et al., JGR [2010]
Extreme SO$_2$ columns in volcanic clouds

- SO$_2$ in fresh eruption clouds – highest trace gas columns measured
- Challenge to validate extreme SO$_2$ column amounts – UAVs, balloons?
- More volc. SO$_2$ validation needed in general
- Complex radiative transfer (ash, hydrometeors)

[Yang et al., GRL, 2009]

~800 DU

Sierra Negra – October 2005

~1100 DU
Request from Icelandic Meteorological Office: ‘We are getting very nice OMI images of the SO$_2$ rich eruption cloud from the Holuhraun eruption. Could you help us to set up a way of turning the OMI observations into daily SO$_2$ mass and daily SO$_2$ emission rates? It's possible this eruption will last weeks or months and so we need such a technique to be automated and fast.’

OMI SO$_2$ data used in: U.S., Mexico, Guatemala, El Salvador, Costa Rica, Montserrat, Ecuador, Colombia, Peru, Chile, New Zealand, Vanuatu, Indonesia, Papua New Guinea, Philippines, DR Congo, Ethiopia, Russia, France
Summary

• Science contributions and applications of Aura/OMI SO$_2$
  – Identification of new volcanic and anthropogenic SO$_2$ sources
  – Updated volcanic SO$_2$ emissions inventory
  – Effect of small volcanic eruptions on climate
  – Radiative forcing of volcanic sulfate aerosol
  – Volcanic aerosol enhancement of lightning activity
  – Cloud seeding by volcanic aerosol downwind of volcanoes
  – Lifetime of SO$_2$ in upper troposphere and lower stratosphere
  – Sulfur gas scavenging in eruption columns
  – Improving sulfur chemistry in CTMs
  – Volcanic plume tracking for aviation hazard mitigation
  – Detection of eruptions in remote regions

• Future developments in satellite SO$_2$ observations
  – Improved spatial resolution (e.g., TROPOMI) -> better monitoring capability
  – Direct assimilation of volcanic SO$_2$ observations into CTMs
Thanks to:
the Aura Science and OMI SIPS Teams
NASA for support from the Aura Validation program, Aura Science Team, ACMAP program, MEaSUREs program

Ambrym volcano (Vanuatu) – one of the strongest SO$_2$ sources on Earth
OMI - $\text{SO}_2$, $\text{NO}_2$, BrO
TES - $\text{SO}_2$
MLS - strat. $\text{SO}_2$, $\text{HCl}$

CloudSat (2006-)
CPR (radar) – precipitation, hydrometeors

Aqua (2002-)
MODIS - $\text{SO}_2$, ash, sulfate
AIRS - UTLS $\text{SO}_2$, ash

Volcanic $\text{CO}_2$?

Aura (2004-)

The A-Train

OMPS, VIIRS, CrIS - $\text{SO}_2$, ash

CALIPO (lidar) - cloud altitude, aerosol phase