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\textsubscript{2} clouds measured by TOMS

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

1978-2005

TOMS: Total Ozone Mapping Spectrometer
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 (SO$_2$), measurements at volcanoes. Subaerial volcanic SO$_2$ emissions indicate a 13 Tg/a SO$_2$ 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:

- Volcanic S emission inventories ‘static’ and used ground-based data

[Graf et al., 1997; Andres & Kasgnoc, 1998; Halmer et al., 2002; Smith et al., 2011]
• SO\textsubscript{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\textsubscript{2} emissions
• Shut-down of La Oroya smelter in mid-2009; reduction expected
Volcanic SO$_2$ emissions inventories are inaccurate

- OMI measurements indicate deficiencies in current ‘bottom up’ volcanic SO$_2$ emission inventories used in CTMs

REMOTE model simulation of annual mean SO$_2$ columns over Indonesia [Pfeffer et al., ACP, 2006]
• **SO₂ index** defined using OMI ozone algorithm residuals (sensitive to SO₂)
• Rank top 1000 values of SO₂ 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>
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<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]

[Diagram showing number of days with detected SO$_2$ degassing vs. average SO$_2$ Index]
Most persistent volcanic SO$_2$ sources in 2013

- Popocatépetl
- Nyiragongo
- Ambrym
- Ruiz
- Turrialba
- Tolbachik
- Kliuchevskoi
- Ulawun
- Ijen
- Dukono
- Bagana
- Gaia
- Copahue
- Tungurahua
- Yasur
- Huila
- Kizimen
- Manam
- Kerinci
- Tengger Caldera
- Shiveluch
- Santiaguito
- Karymsky
- Lewotobi
- Galeras
- Suwanose-Jima
- Sakura-Jima
- Etna

Number of days with detected SO$_2$ degassing

Average SO$_2$ Index

Reuters
SO$_2$ emission rate estimation from satellite data

\[ Q_{meas} = \frac{vM}{L} \]

- Similar approach used to estimate smoke and NO$_2$ emissions from fires \cite{Ichoku2005, Mebust2011}
- Note that asymmetry of OMI pixel affects plume detection
- Chemistry correction \cite{Mebust2011} can be applied if SO$_2$ lifetime is known

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

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

\cite{Carn2013}
Estimated $SO_2$ fluxes (2004-2013; ~3200 days)

- New volcanic $SO_2$ emissions database for CTMs
- Jun Wang’s talk (Tuesday)

**Volcano** | **$SO_2$ flux (t/d)**
--- | ---
Ambrym | 32800
Popocatepetl | 13000
Etna | 5500
Nyiragongo | 3280
Miyake-jima | 3000

[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)
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: 2410000 km²; SO₂ max: 19.89 DU at lon: -93.38 lat: 13.66

[NASA/JPL/NCEP/NCMI]

[Norm Stock Carn (scarn@jpl.nasa.gov)]

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; SO₂ max: 20.18 DU at lon: -107.02 lat: 12.14

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

~0.2 Tg SO2

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

Normalised SO2 column

[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: 346,946 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

Aura/OMI - 05/27/2006 20:21-23:45 UT

Mass: 110.209 kt; Area: 2575001 km²; SO₂ max: 8.59 DU at lon: -128.96 lat: 14.21

Normalised SO₂ column

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

Mass: 108,896 kt; Area: 227,9174 km²; SO₂ 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: 1701411 km²; SO₂ max: 6.22 DU at lon: -145.52 lat: 12.46

[0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100]

Normalised SO₂ column

[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: 2034725 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

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

Mass: 96.573 kt; Area: 2063998 km²; SO₂ max: 6.10 DU at lon: -156.59 lat: 11.76

Normalised SO₂ column

[Carn et al., 2007; Prata et al., 2007]
Soufrière 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: 22,093,777 km²; SO₂ max: 3.85 DU at lon: -175.63 lat: 9.17

Normalised SO₂ column

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

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

~0.2 Tg SO$_2$

**Normalised SO$_2$ column**

[0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100]
Soufrière Hills volcano (Montserrat) eruption, May 2006

Aura/OMI - 06/05/2006 02:08-07:05 UT

Mass: 71.854 kt; Area: 2170677 km²; SO₂ max: 2.94 DU at lon: 151.98 lat: 8.57

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

Aura/OMI - 06/06/2006 02:50-07:53 UT

Mass: 54.517 kt; Area: 1996410 km²; SO₂ max: 2.67 DU at lon: 138.03 lat: 5.65

Normalised SO₂ column

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

Normalised SO₂ column

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]

Goddard Traj. Model (GTM)
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

Overshooting top

Umbrella cloud

Credit: S.A. Cam, Michigan Tech (scarn@mtu.edu)

Kristiansen et al., GRL, in prep.
Direct retrieval of SO₂ altitude from UV radiances

- SO₂ altitude directly retrieved from hyperspectral UV radiances
- Validate with CALIPSO, MLS
- Critical for climate impact, aviation hazards and CTM source term

- SO₂ 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

~6 eruptions/yr (1979-2004); ~19 eruptions/yr (2004-2014)

El Chichón Pinatubo

Nabro
Stratospheric AOD and the global warming ‘hiatus’

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

Increase linked to influence of tropical volcanic eruptions
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

Santer et al., Nature Geosci. [2014]
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

MLDP0 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)

Sierra Negra – October 2005

~800 DU

~1100 DU

[Yang et al., GRL, 2009]
Current Bardabunga/Holuhraun eruption (Iceland)

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 - SO$_2$, NO$_2$, BrO
TES - SO$_2$
MLS - strat. SO$_2$, HCl

Aura (2004-)

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

CloudSat (2006-)

Aqua (2002-)
MODIS - SO$_2$, ash, sulfate
AIRS - UTLS SO$_2$, ash

Volcanic CO$_2$?

The A-Train

CALIPSO (2006-)

Caliop (lidar) - cloud altitude, aerosol phase

OMPS, VIIRS, CrIS - SO$_2$, ash
2008

MLS
HCl

MLS
SO$_2$

OMI
SO$_2$

Kasatochi

Okmok