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

Simon Carn

Dept of Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, MI, USA

Currently at: National Museum of Natural History, Smithsonian Institution, Washington DC, USA

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

TOMS: Total Ozone Mapping Spectrometer

1978-2005

- Low sensitivity
- Low spatial resolution
- No altitude information
- No ‘monitoring’ capability
Pre-Aura view of global volcanic SO$_2$ emissions

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.

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

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]
SO₂ 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 SO₂ 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]
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 65ºS – 80ºN)
- 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)
Volcano SO$_2$ flux (t/d)

- Etna 4000
- Bagana 3300
- Lascar 2400
- Ruiz 1900
- Sakura-jima 1900
- Manam 920
- Yasur 900
- Kilauea 800
- Masaya 790
- Stromboli 730

[Andres and Kasgnoc, 1998]

Persistent volcanic SO$_2$ sources (2004-2013; ~3200 days)

Infrequently monitored
Most persistent volcanic SO$_2$ sources in 2013

- Rank
- Number of days with detected SO$_2$ degassing
- Average SO$_2$ Index

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

Reuters
SO₂ emission rate estimation from satellite data

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

- \( M \) = SO₂ mass in pixel (kg)
- \( v \) = wind speed (m s\(^{-1}\))
- \( L \) = length of plume (m)
- \( Q \) = SO₂ flux (kg s\(^{-1}\))

- 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

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

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

Estimated SO$_2$ fluxes (2004-2013; ~3200 days)

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

### Volcano SO$_2$ fluxes (t/d)

<table>
<thead>
<tr>
<th>Volcano</th>
<th>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

**Chemistry correction:**

~20% for $\tau_{SO2} = 2$ hrs

<table>
<thead>
<tr>
<th>City</th>
<th>OMI SO$_2$ flux (tons/day)</th>
<th>Ground-based SO$_2$ flux (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>~3500</td>
<td>~3500</td>
</tr>
<tr>
<td>Ga</td>
<td>~1500</td>
<td>~1500</td>
</tr>
<tr>
<td>Mi</td>
<td>~1000</td>
<td>~1000</td>
</tr>
<tr>
<td>Ao</td>
<td>~500</td>
<td>~500</td>
</tr>
<tr>
<td>Ra</td>
<td>~200</td>
<td>~200</td>
</tr>
<tr>
<td>So</td>
<td>~100</td>
<td>~100</td>
</tr>
<tr>
<td>Tr</td>
<td>~50</td>
<td>~50</td>
</tr>
<tr>
<td>Ma</td>
<td>~25</td>
<td>~25</td>
</tr>
<tr>
<td>Tn</td>
<td>~12.5</td>
<td>~12.5</td>
</tr>
<tr>
<td>Ba</td>
<td>~7</td>
<td>~7</td>
</tr>
<tr>
<td>La</td>
<td>~2.5</td>
<td>~2.5</td>
</tr>
<tr>
<td>Tr</td>
<td>~1.25</td>
<td>~1.25</td>
</tr>
</tbody>
</table>

*Good agreement with long-term, ground-based datasets*
Soufrière Hills volcano (Montserrat) eruption, May 2006

~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: -81.33 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: 2410030 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

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

~0.2 Tg SO₂

[Mass: 159,341 kt; Area: 253,2097 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

~0.2 Tg SO₂

[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

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

Mass: 146.936 kt; Area: 3468046 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

[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; SO₂ max: 8.11 DU at lon: -135.54 lat: 13.82

Normalised SO₂ column

[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; SO₂ max: 6.22 DU at lon: -145.52 lat: 12.46

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: 203,4725 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

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

*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

[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

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

Normalised SO₂ column

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

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

Mass: 71.854 kt; Area: 2170677 km$^2$; SO$_2$ max: 2.94 DU at lon: 151.98 lat: 8.57

Normalised SO$_2$ column

[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: 19964 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

No volcanic SO$_2$ 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)

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

Overshooting top
Umbrella cloud

Kristiansen et al., GRL, in prep.
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

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

Pinatubo

Ruiz

Aura
Increase in tropical stratospheric AOD since 2000

- Eruptions filtered using Volcanic Explosivity Index (VEI)
- VEI not a good proxy for climate impact (i.e., SO₂ 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: 966738 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)
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 - SO₂, NO₂, BrO
TES - SO₂
MLS - strat. SO₂, HCl

MODIS - SO₂, ash, sulfate
AIRS - UTLS SO₂, ash

CPR (radar) – precipitation, hydrometeors

Volcanic CO₂?

The A-Train

Aura (2004-)

CloudSat (2006-)

Aqua (2002-)

OMPS, VIIRS, CrIS - SO₂, ash

CALIPSO (2006-)

CALIOP (lidar) - cloud altitude, aerosol phase