Overview

- Motivation for volcanic gas measurements
- Development of satellite remote sensing of SO$_2$
- Remote sensing theory (focus on SO$_2$ measurements)
- Survey of space-based SO$_2$ sensors
  - UV sensors: OMI, TOMS, GOME-2
  - IR sensors: MODIS, ASTER, TOVS, AIRS, IASI
- Application of Aura/OMI SO$_2$ data to volcano monitoring
  - SO$_2$ burden calculations
  - Burdens vs. emission rates
- Satellite sensor synergy: NASA’s A-Train
- Web access to near-real time data
- Lab exercise: SO$_2$ emissions from Latin American volcanoes
Motivation for volcanic SO$_2$ measurements

- SO$_2$ is the most abundant gas in volcanic emissions that can be easily measured by remote sensing techniques
  - Low background concentrations (cf. H$_2$O, CO$_2$)
  - No other major sources above the planetary boundary layer (PBL)
  - Well-characterized spectral absorption bands (UV, IR, microwave)
- Released from magma at high temperature and low pressure
  - Signature of magmatic eruptions with potential for high altitude eruption columns
  - H$_2$S (hydrogen sulfide) is the more stable sulfur species at high pressures and low temperatures (e.g., fumarole fields)
- Environmental, health and climate impacts (sulfate aerosol)
## Volcanic gas compositions

<table>
<thead>
<tr>
<th>mol%</th>
<th>Nyiragongo (DR Congo) RIFT</th>
<th>Kilauea* (Hawaii) HOTSPOT</th>
<th>Merapi* (Indonesia) SUBDUCTION</th>
<th>Etna* (Sicily) SUBDUCTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>70</td>
<td>37</td>
<td>91</td>
<td>48</td>
</tr>
<tr>
<td>CO₂</td>
<td>24</td>
<td>49</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>SO₂</td>
<td>5</td>
<td>12</td>
<td>1</td>
<td>31</td>
</tr>
<tr>
<td>CO</td>
<td>1</td>
<td>2</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>HCl</td>
<td>0.3</td>
<td>0.08</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>HF</td>
<td>0.1</td>
<td>-</td>
<td>0.04</td>
<td>-</td>
</tr>
</tbody>
</table>

Trace constituents: CH₄, N₂, BrO, Zn, Cu, Hg, Au, As, Re, He, Ne, Ar.....

*Symonds et al. [1994]
Temperature and pressure effects on volcanic gas species

\[ \text{SO}_2 + 3\text{H}_2 = \text{H}_2\text{S} + 2\text{H}_2\text{O} \]

\[ \log (\text{SO}_2/\text{H}_2\text{S}) = \log K_T - 3 \log (\text{H}_2/\text{H}_2\text{O}) - \log P \cdot X_{\text{H}_2\text{O}} \]

[Symonds et al., Rev. Mineral., 1994; Aiuppa et al., 2004]
Pre-eruptive volcanic degassing

[Daag et al., 1996]

- Increase in SO$_2$ emissions prior to a major eruption
SO$_2$ flux and LP seismicity at Galeras (Colombia)

FIG. 2 SO$_2$ flux in metric tons per day (●) and durations of recorded long-period ($\geq$ 22 s) events (vertical bars) plotted against time, also showing the eruptions during the same time period. The SO$_2$ flux is measured using correlation spectrometer (COSPEC) methodology$^{15}$. Uncertainty depends mostly on recorded wind speeds. The error at

[Galeras is assumed to be ±20%, in general, and ±40%, in the worst case. True SO$_2$ flux is likely to be higher than the calculated value. The three phases reflect changes in fluid dynamics along pathways through which gases flow, as interpreted from seismic and gas flux data.

[Fischer et al., Nature, 1994]
SO$_2$ emissions and RSAM at Fuego (Guatemala)

[Nadeau et al., GRL, 2011]
Aviation hazards from volcanic clouds

• Immediate hazards
  – Engine failure due to melted ash
  – Abrasion of windshield

• Secondary hazards
  – Corrosion by ash, sulfuric acid

• Mitigation
  – Immediate detection of fresh volcanic clouds – SO\(_2\) data valuable
  – Tracking/forecast of cloud position and altitude – SO\(_2\) valuable for cloud tracking

Effects of volcanic emissions on the climate system

Stratospheric aerosols (Lifetime ≈ 1-3 years)
- \( \text{H}_2\text{S} \oplus \text{H}_2\text{SO}_4 \)
- \( \text{HCl}, \text{BrO}, \text{ClO} \)
- \( \text{CO}_2 \)
- \( \text{H}_2\text{O} \)
- Explosive

Tropospheric aerosols (Lifetime ≈ 1-3 weeks)
- \( \text{SO}_2 \oplus \text{H}_2\text{SO}_4 \)
- Passive

Gas scavenging?

Indirect Effects on Clouds

Forward scatter

Absorption (near IR)

Heterogeneous \( \text{O}_3 \) depletion

Less Solar Heating

Effects on cirrus clouds

Enhanced Diffuse Flux

Reduced Direct Flux

Less Total Solar Flux

More Reflected Solar Flux

More Downward IR Flux

Less Upward IR Flux

Net Heating

Net Cooling

Geoengineering

Tropopause (8-17 km)

TROPOSPHERE

STRATOSPHERE
Volcanic gas monitoring techniques

- Chemical sensors
- Mini UV spec
- FTIR
- Satellite
- UV imaging
- Direct sampling

COSPEC
Electromagnetic spectrum – SO$_2$ absorption

<table>
<thead>
<tr>
<th>Daytime only</th>
<th>Daytime or nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV</td>
<td>Vis</td>
</tr>
<tr>
<td>Near-Infrared (NIR)</td>
<td>Thermal Infrared (TIR)</td>
</tr>
</tbody>
</table>

- **Daytime only**: UV, Vis, Near-Infrared (NIR)
- **Daytime or nighttime**: Thermal Infrared (TIR)

- **OMI, GOME-2, SCIAMACHY**: 0.3-0.35 µm
- **IASI, SEVIRI, MODIS, AIRS, HIRS, ASTER**: 4 µm, 7.3 µm, 8.6 µm
- **MLS**: Microwave, ~1 mm

![Graph showing transmittance vs. wavelength with absorption bands at 0.3-0.35 µm, 4 µm, 7.3 µm, 8.6 µm]
UV and IR remote sensing

- **UV**
- **IR**

OMI

AIRS

T = 6000 K

T = ~300 K

Ultraviolet (UV)

Thermal Infrared (TIR)

T < 300 K
UV SO$_2$ and O$_3$ absorption spectra and instrument bands

- Spectral resolution affects sensitivity

- TOMS, SBUV
  Discrete bands

- GOME-2, SCIA, OMI, OMPS
  Full spectrum

- COSPEC masks
- UV camera filter bandpass
IR-active trace gases and instrument channels

~2300 AIRS channels
What about $\text{H}_2\text{S}$?

SO$_2$ + 3H$_2$ = H$_2$S + 2H$_2$O

• May be a significant component of total S budget at some volcanoes
• Mid-UV absorption bands require active source
• IR absorption bands are very weak

[O’Dwyer et al., GRL, 2003]
A-Train observations: Kasatochi, August 9, 2008

[Graph and data visualization showing atmospheric measurements and observations related to Kasatochi, August 9, 2008.]
GOSAT: Measuring CO$_2$ from space

- NASA Orbiting Carbon Observatory (OCO) – failed at launch
- Japanese Greenhouse Gas Observing Satellite (GOSAT)
  - Launched January 2009; polar orbit with 1300 LECT
  - Fourier Transform Spectrometer (FTS) and Cloud-Aerosol Imager (CAI)
  - TANSO-FTS sensor measures CO$_2$ and CH$_4$ columns and profiles in SWIR/TIR
  - 0.2 cm$^{-1}$ spectral resolution, 10.5 km diameter FOV
  - 56,000 observation points over land; sunglint obs over oceans
  - Special observation ‘stare’ mode
  - ppm-level sensitivity to changes in CO$_2$ column
  - Evaluation of GOSAT data for volcanic CO$_2$ detection underway
Forward-model SO$_2$ retrieval (e.g., TOMS, OMI)

- Simulate at-satellite UV radiances as a function of viewing geometry, latitude, column O$_3$ and SO$_2$ amounts, surface pressure and reflecting surface conditions, using a radiative transfer model.

- Compare measured normalized radiances with theoretical radiances calculated for the conditions of the measurement.

- Derive column O$_3$ and SO$_2$ amounts in the scene by finding the values that give a computed radiance equal to the measured radiance.

- Errors: highest in the presence of significant ash or sulfate aerosol, and at scan edges.
Differential Optical Absorption Spectroscopy (DOAS)

Measured UV-visible spectra contain overlapping structures due to the solar spectrum (Fraunhofer lines), elastic scattering, trace gas absorption, aerosol absorption and the Ring effect (inelastic Raman scattering).

Absorption cross-sections of trace gases in the 200-700 nm wavelength range
Beer-Bouguer-Lambert (Beer’s) Law

For a gaseous absorber, the absorption coefficient ($\beta$) is written as the product of an absorption cross-section ($\sigma$, cm$^2$) and the number density of absorbers ($N$, molecules cm$^{-3}$):

$$I = I_0 e^{-\sigma N d}$$

- Beer’s Law applies to direct beam only
- Deviations from Beer’s Law occur at high concentrations
Motivation for space-based volcanic gas measurements

- During intense activity (safe)
- Cover remote and/or unmonitored volcanoes
- Ground-based or airborne instruments unavailable
- Cloud cover obscures plume from below
- Independent of wind direction
- Aircraft hazards (use SO$_2$ as a proxy for ash)

Carn et al., 2009
Detection of April 1982 El Chichon SO\textsubscript{2} cloud with the Total Ozone Mapping Spectrometer (TOMS)

[Krueger, Science, 1983]
Volcanic $\text{SO}_2$ clouds measured by TOMS
Volcanic SO$_2$ Emissions Inventory

El Chichon

Pinatubo

OMI

[Bluth et al., 1993; Carn et al., 2003]
Exploiting A-Train synergy for volcanic cloud studies

Aura
- OMI: SO$_2$, O$_3$, NO$_2$, BrO
- TES: SO$_2$
- MLS: strat. SO$_2$, HCl, O$_3$

CloudSat
- CPR: precipitation, hydrometeors

CALIOP
- cloud altitude, aerosol phase/type

CALIPSO

Aqua
- MODIS: SO$_2$, ash, sulfate
- AIRS: UTLS SO$_2$, aerosols, SO$_2$ profile?

The A-Train
Aura - Ozone Monitoring Instrument (OMI)

- UV/VIS sensor that succeeded TOMS
- Dutch/Finnish contribution to NASA’s EOS/Aura mission (launched July 2004)
- Daily contiguous global coverage
- 13 x 24 km nadir footprint - best ever for UV measurements from space
- Overpass at 1:30-2:00 pm local time
- Data publicly available and free
- Row anomaly since August 2008 – some data gaps
- The first space-borne sensor to provide daily, global \( \text{SO}_2 \) measurements with sensitivity to the lower troposphere (i.e., passive degassing)
MetOp-A satellite

- Europe-US collaboration
- First in series of 3 MetOp satellites
- Launched 19 October 2006
- Polar, sun-synchronous orbit
- 9:30 am local time equator crossing
- 11 instruments
- Sensors of volcanological interest:
  - Global Ozone Monitoring Experiment 2 (GOME-2) – SO₂, ash
  - Infrared Atmospheric Sounding Interferometer (IASI) – SO₂, ash
  - High-resolution Infrared Radiation Sounder-4 (HIRS/4) – SO₂, ash
  - Advanced Very High Resolution Radiometer (AVHRR) – ash, IR hot spots
Global Ozone Monitoring Experiment-2 (GOME-2)

- UV-visible wavelengths
- 1920 km swath width
- 80 x 40 km ground pixel size
- Data gaps at Equator
- 9:30 am local time equator crossing
- High SO$_2$ sensitivity
- Can detect small eruptions and strong degassing
Infrared Atmospheric Sounding Interferometer (IASI)

- 3.4 – 15 µm (infrared) wavelengths
- High spectral resolution, Fourier transform interferometer
- Mapping and vertical profiling of SO$_2$ possible
- 25 km horizontal resolution, 1 km vertical resolution
- Covers 3 SO$_2$ absorption bands in the IR
- Measurements at 9:30 am and 9:30 pm local time (IR)
- High sensitivity to eruptions; degassing may be detectable
Up to 7 daily $\text{SO}_2$ measurements from UV/IR sensors

http://sacs.aeronomie.be/nrt/
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite(s)</th>
<th>Data coverage dates</th>
<th>Daily global coverage?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Ozone Mapping Spectrometer (TOMS)</td>
<td>Nimbus-7, Meteor-3, ADEOS, Earth Probe</td>
<td>Nov 78 – Dec 94 Jul 96 – Dec 2005</td>
<td>Yes</td>
</tr>
<tr>
<td>Global Ozone Monitoring Experiment (GOME)</td>
<td>European Remote Sensing Satellite (ERS-2)</td>
<td>July 95 – present</td>
<td>No</td>
</tr>
<tr>
<td>Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY)</td>
<td>European Environmental Satellite (Envisat-1)</td>
<td>Sept 03 – present</td>
<td>No</td>
</tr>
<tr>
<td>Ozone Monitoring Instrument (OMI)</td>
<td>NASA EOS Aura</td>
<td>Sept 2004 – present</td>
<td>Yes (until late 2008)</td>
</tr>
<tr>
<td>Ozone Mapping and Profiler Suite (OMPS)</td>
<td>National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP)</td>
<td>2011?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Operational SO$_2$ data products
# Satellite instruments – Microwave & IR

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite(s)</th>
<th>Data coverage dates</th>
<th>Daily global coverage?</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Resolution Infrared Radiation Sounder (HIRS, HIRS/2)</td>
<td>TIROS-N, NOAA-6-14</td>
<td>Oct 78 – present</td>
<td>Yes (day/night)</td>
</tr>
<tr>
<td>Moderate Resolution Imaging Spectroradiometer (MODIS)</td>
<td>EOS Terra, Aqua</td>
<td>Feb 2000 –</td>
<td>Yes (day/night)</td>
</tr>
<tr>
<td>Advanced Spaceborne Thermal Emission &amp; Reflection Radiometer (ASTER)</td>
<td>EOS Terra</td>
<td>Feb 2000 – (request only)</td>
<td>No</td>
</tr>
<tr>
<td>Atmospheric Infrared Sounder (AIRS)</td>
<td>EOS Aqua</td>
<td>Sept 2002 –</td>
<td>No</td>
</tr>
<tr>
<td>Spinning Enhanced Visible and Infrared Imager (SEVIRI)</td>
<td>Meteosat Second Generation (MSG)</td>
<td>2004 –</td>
<td>No</td>
</tr>
<tr>
<td>Infrared Atmospheric Sounding Interferometer (IASI)</td>
<td>MetOp A, B, C</td>
<td>Oct 2006 -</td>
<td>No</td>
</tr>
</tbody>
</table>
### UV instrument SO$_2$ sensitivity

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Footprint area (km$^2$)</th>
<th>Sensitivity (DU) $1\sigma$</th>
<th>Smallest cloud detection limit (tons) 5 pixels at $5\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stratosphere 20 km</td>
<td>Troposphere &lt;5 km</td>
</tr>
<tr>
<td>EP TOMS</td>
<td>1521 (39×39)</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>GOME</td>
<td>12800 (40×320)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>SCIAMACHY</td>
<td>1800 (30×60)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>GOME-2</td>
<td>3200 (40×80)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>OMI</td>
<td>312 (13×24)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>OMPS</td>
<td>2500 (50×50)</td>
<td>0.2</td>
<td>0.4</td>
</tr>
</tbody>
</table>
## IR instrument SO$_2$ sensitivity

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Footprint area (km$^2$)</th>
<th>Sensitivity (DU)*$_{1\sigma}$</th>
<th>Smallest cloud detection limit (tons) 5 pixels at $5\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stratosphere 20 km</td>
<td>Troposphere &lt;5 km</td>
</tr>
<tr>
<td>MODIS</td>
<td>1 (1×1)</td>
<td>9</td>
<td>250</td>
</tr>
<tr>
<td>ASTER</td>
<td>0.008</td>
<td>9</td>
<td>250</td>
</tr>
<tr>
<td>AIRS</td>
<td>143</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>SEVIRI</td>
<td>23 (4.8×4.8)</td>
<td>9</td>
<td>250</td>
</tr>
</tbody>
</table>

*Based on Realmuto [1999], AGU Geophysical Monograph 116, p101-115 (except AIRS)
Units for SO$_2$ column amount measurements

- **Satellites provide measurements of ‘column amount’ or ‘total column’ SO$_2$**
  - US units: Dobson Unit (DU)
  - 1 DU = $2.69 \times 10^{16}$ molecules cm$^{-2}$ = 0.0285 g m$^{-2}$ SO$_2$
  - European units: molecules cm$^{-2}$
  - *Milli atm cm* also used (same as DU)

- **Typical values in volcanic clouds**
  - Fresh eruption cloud: 100s – 1000+ DU
  - Non-eruptive degassing: <20 DU
  - Measured column amount depends on spatial resolution of sensor
  - Can be converted to mass or concentration (if cloud thickness is known)

- **Emission rate not directly measured**
UV backscatter measurements

Air Mass Factor (AMF) = SC/VC

Image courtesy Matt Patrick (HVO)
UV radiation penetrates clouds

- IR cloud top ≠ UV cloud pressure

(Joiner et al., ATMD, 2009)

(Ziemke et al., ACP, 2009)
OMI data products – SO$_2$

2600 km

60 pixels across-track

16 day repeat cycle

Row anomaly

SO$_2$ mass: 5.46 kt; Area: 589600 km$^2$; SO$_2$ max: 7.91 DU at lon: -84.49 lat: 10.55; 18:47 UTC
OMI data products – Aerosol Index

Aura/OMI - 03/10/2010 18:44-18:50 UT - Orbit 30064

Aerosol Index

NSF PASI, San José, Costa Rica, Jan 2011
OMI data products – Cloud fraction
Detection of passive $\text{SO}_2$ degassing with OMI

Mariana Is
Papua New Guinea
Solomon Is
Vanuatu
3 year global average SO$_2$ from IASI (without large eruptions)

Okmok  Popocatepetl  Eyjafjallajokull  Etna  Dalaffila

Kliuchevskoi/Shiveluch/Koryaksky

Chaiten, Llaima  Soufrière Hills  Nyamuragira  Jebel at Tair  Souptan

Pacaya  Lascar  Ubinas

Courtesy of L. Clarisse, ULB
Global \( \text{SO}_2 \) emissions measured by OMI
Plume extent relative to size of satellite FOV constrains detection of degassing plumes from space.
Effect of volcanic plume altitude on SO$_2$ retrievals

- OMI SO$_2$ product
- 4 *prescribed* SO$_2$ profiles:
  - PBL (<3 km)
  - TRL (0-5 km)
  - TRM (5-10 km)
  - STL (15-20 km)
- 2 SO$_2$ algorithms
  [Krotkov *et al.*, 2006; Yang *et al.*, 2007]

- Knowledge of SO$_2$ cloud altitude is critical for accurate SO$_2$ retrieval
- Satellite sensitivity increases with altitude in the troposphere
  [Krotkov *et al.*, IEEE TGRS, 2006; Yang *et al.*, JGR, 2007]
Relative sensitivity of UV and IR measurements

- IR channels at ~4 µm and ~8.6 µm can detect lower tropospheric SO$_2$

*Courtesy of L. Clarisse, ULB*

*Prata and Bernardo, 2007*
Direct retrieval of $\text{SO}_2$ altitude from UV radiances

- Midlatitude $\text{O}_3$ profile, 325 DU, nadir, clear sky, SZA=45º

[Yang et al., GRL, 2009]
Retrieval of large SO$_2$ columns in volcanic clouds

Figure 3. Comparison of ISF and LF SO$_2$ columns in the Sierra Negra eruption cloud on October 23, 2005. The LF retrievals saturate at about 200 DU in this case. [Yang et al., GRL, 2009]
Daily OMI SO$_2$ measurements for Central America

http://so2.umbc.edu/omi

- Satellites measure column amounts of gases, NOT emission rates
Daily OMI SO$_2$ measurements for Kilauea

http://so2.umbc.edu/omi

SO$_2$ burden in plume
Max. SO$_2$ column, location and time (UT)
SO$_2$ plume area
Hawaii measurement domain
Construction of SO$_2$ mass time-series

Daily OMI measurements

Calculate SO$_2$ burdens
- Threshold (e.g., >0.6 DU = volcanic)
- Background subtraction
- Noise statistics in SO$_2$-free region

Ambrym 2004-2005

Daily SO$_2$ burdens (not fluxes)
OMI SO$_2$ data for Costa Rica
OMI SO$_2$ time-series for Costa Rica

Verano

Invierno
Kilauea plume SO$_2$ burdens: 2004-2009

Halema’uma’u eruption begins (Mar 08)

Summit SO$_2$ emissions increase (Jan 08)
Kilauea plume $\text{SO}_2$ burdens: 2004-2009

Halema’uma’u eruption begins (Mar 08)

Summit $\text{SO}_2$ emissions increase (Jan 08)
Kilauea plume SO$_2$ burdens: 2008-2009

- Reduced incandescence (Nov 08)
- Rockfalls block summit vent (Jul 09)
Reventador (Ecuador) seismicity and OMI SO$_2$ data

Closed system

[Carn et al., JVGR, 2008]
• Combine space-based and ground-based $SO_2$ measurements to estimate total $SO_2$ budgets
Volcanic SO$_2$ flux measurements

SO$_2$ Emission Rate
= SO$_2$ Amount in a cross-section $\times$ Plume Velocity

UV COSPEC

Mini UV spec
Comparing OMI SO$_2$ burdens with SO$_2$ emission rates (Kilauea)

- Direct comparison of SO$_2$ emission rates (summit + ERZ) and OMI SO$_2$ burdens complicated by variability, meteorology and errors
- Broad positive correlation

_Offset of 1 day_
SO$_2$ flux estimation from satellite data

- Satellite ‘snapshots’ measure SO$_2$ burden, not flux
- To first order, SO$_2$ emission rates can be inferred using the SO$_2$ burden and an estimate of the SO$_2$ lifetime
  - SO$_2$ lifetime short (hours) at low altitudes and in humid environments
  - May be a few hours in tropical boundary layers

$$ Q = \frac{M}{\tau} $$

- Q = SO$_2$ emission rate (tons/day), M = SO$_2$ burden (tons), $\tau$ = SO$_2$ lifetime (days)
SO$_2$ flux estimation from satellite data

Wind speed ($v$)

Plume length across pixel ($L$)

SO$_2$ flux ($Q$)

Satellite pixel (SO$_2$ mass = $M$)

\[ Q = \left[ \frac{vM}{L} \right] \]

- Similar approach used to estimate smoke emissions from fires [Ichoku and Kaufman, 2005]
- Note that asymmetry of OMI pixel affects plume detection
SO$_2$ flux estimation from satellite data (Turrialba)

- Comparison between Turrialba SO$_2$ emission rates derived from ASTER, OMI and UV camera [Campion et al., in prep.]
Detection limit (3σ above background) of passive SO$_2$ flux from a 5000m volcano at various plume velocities; 1σ = 0.2 DU assumed for OMI

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Minimum detectable SO$_2$ flux (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plume velocity 1 m/s</td>
</tr>
<tr>
<td>Earth Probe TOMS (1σ = 3.5 DU)</td>
<td>1030</td>
</tr>
<tr>
<td>OMI (plume traverses 13 km pixel width)</td>
<td>36</td>
</tr>
<tr>
<td>OMI (plume traverses 24 km pixel length)</td>
<td>19</td>
</tr>
<tr>
<td>COSPEC</td>
<td>10</td>
</tr>
<tr>
<td>Typical volcano</td>
<td>100 - 5000</td>
</tr>
</tbody>
</table>
OMI SO$_2$ websites

http://so2.umbc.edu/omi_home_new2.html/
OMI SO$_2$ websites - NRT

Operational OMI SO$_2$ data from NASA Mirador

http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml
Near real-time OMI SO$_2$ data from NASA LANCE

http://lance.nasa.gov/data-producers/omi-sips/omi-sips-products/
(Registration required)
BIRA website

SCIAMACHY

OMI

GOME-2

http://sacs.aeronomie.be/nrt/
GOME-2 Near-Real-Time Service

GOME-2 level 3 products on SO2 are generated at DLR in near-real-time in the framework of the projects ESA/PROMOTE, EUMETSAT/AGORA and BMBF/EXUPERY.

GOME-2 NRT Products (level 3)

Latest Map

Map of Previous Day / Latest Available Data

Archive: Images (GIF, PS)

SO2 Navigation Tool

Select Region from List

Select Region from Map

From

To

http://wdc.dlr.de/data_products/SERVICES/GOME2NRT/so2.php
## AIRS NRT SO$_2$ website

<table>
<thead>
<tr>
<th>Date, Granule</th>
<th>Image 1</th>
<th>Image 2</th>
<th>AIRS L1B (to get hdf data, email us)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007.11.24.118</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.11.24.118.L1B.AIRS_Rad.v4.0.9.0.N07328092701.hdf</td>
</tr>
<tr>
<td>2007.11.24.007</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.11.24.007.L1B.AIRS_Rad.v4.0.9.0.N07327220006.hdf</td>
</tr>
<tr>
<td>2007.10.15.163</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.15.163.L1B.AIRS_Rad.v4.0.9.0.N07288144427.hdf</td>
</tr>
<tr>
<td>2007.10.15.147</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.15.147.L1B.AIRS_Rad.v4.0.9.0.N07288130040.hdf</td>
</tr>
<tr>
<td>2007.10.04.217</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.04.217.L1B.AIRS_Rad.v4.0.9.0.N07277195643.hdf</td>
</tr>
<tr>
<td>2007.10.04.096</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.04.096.L1B.AIRS_Rad.v4.0.9.0.N07277063327.hdf</td>
</tr>
<tr>
<td>2007.10.04.080</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.04.080.L1B.AIRS_Rad.v4.0.9.0.N07277062356.hdf</td>
</tr>
<tr>
<td>2007.10.03.226</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.03.226.L1B.AIRS_Rad.v4.0.9.0.N07276203956.hdf</td>
</tr>
<tr>
<td>2007.10.03.105</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.03.105.L1B.AIRS_Rad.v4.0.9.0.N07276072757.hdf</td>
</tr>
<tr>
<td>2007.10.03.089</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.03.089.L1B.AIRS_Rad.v4.0.9.0.N07276071649.hdf</td>
</tr>
<tr>
<td>2007.10.02.236</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.02.236.L1B.AIRS_Rad.v4.0.9.0.N07275214657.hdf</td>
</tr>
<tr>
<td>2007.10.02.235</td>
<td><img src="example.png" alt="Image" /></td>
<td><img src="example.png" alt="Image" /></td>
<td>AIRS.2007.10.02.235.L1B.AIRS_Rad.v4.0.9.0.N07275214658.hdf</td>
</tr>
</tbody>
</table>

http://www.star.nesdis.noaa.gov/smcd/spb/iosspdt/iosspdt.php?so2=1#1
IASI NRT SO$_2$ alerts

MODIS Rapid Response website

http://rapidfire.sci.gsfc.nasa.gov/realtime/
CALIPSO website

http://www-calipso.larc.nasa.gov/products/lidar/browse_images/show_calendar.php
The fate of sulfur gases in the atmosphere

- $\text{SO}_2$ ($\text{S}^{+4}$) oxidizes to sulfuric acid (sulfate) aerosol ($\text{H}_2\text{SO}_4$)
  - Rapid in aqueous phase (hours) – clouds, fog
  - Slower in gas phase (days-weeks) – stratosphere
  - Sulfuric acid ($\text{S}^{+6}$) highly soluble in water – rapid removal in precipitation
  - $\text{SO}_2$ also scrubbed by $\text{H}_2\text{O}$ before emission

- $\text{H}_2\text{S}$ ($\text{S}^{-2}$) oxidizes to $\text{SO}_2$ (and sulfate) by reaction with OH, ozone ($\text{O}_3$)
  - Less water-soluble than $\text{SO}_2$ (lower oxidation state)
  - Less susceptible to scrubbing
  - Not easily detected using remote sensing techniques
Diurnal evolution of planetary boundary layer

OMI @ 1:30-1:45 pm

The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.
Aura/OMI - Aura/MLS: Anatahan (CNMI), April 7, 2005

- Daytime MLS track (coincident with OMI)
- Nighttime MLS track
- Tropospheric SO$_2$
- Stratospheric injection

OMI total column SO$_2$ [DU] vs. MLS strat column SO$_2$ [DU]
Aura/OMI – Aura/MLS: Manam (PNG), Jan 2005

• Estimate stratospheric chlorine input

MLS SO₂ profile

MLS HCl profile
• Sierra Negra (Galapagos) eruption, October 24, 2005
• OMI-AIRS synergy indicates SO$_2$ concentrated in the lower troposphere

F. Prata, NILU
Aura/OMI - CALIPSO lidar: Soufriere Hills, May 2006

- May 20 eruption on Montserrat
- SO$_2$ tracked for 3 weeks
- Cloud altitude ~20 km
- Aerosol layer non-depolarizing
- Sulfate dominant, not ash

[Carn et al., ACPD, 2007]
OMI - Aqua/AIRS - CALIPSO: Chaitén (Chile), May 2008

[Carn et al., EOS, in press]

Chaitén

OMSO2
May 6, 1925 UT

16 km

CALIPSO
May 7, 0430 UT

AIRS SO$_2$
May 7, 0442 UT

OMSO2
May 7, 1650 UT

Michigan Tech
Create the Future
Kilauea degassing – April 7, 2008

The A-Train

Aura/OMI SO₂

CALIPSO backscatter

Kilauea aerosol plume

Aqua/MODIS visible
Aura/OMI - Aqua/MODIS - Anatahan (CNMI), Feb 10, 2008

Aura OMI 03:55 UT
Aqua MODIS 03:40 UT
Earth Probe TOMS (11:00 am)

Aura OMI (1:45 pm)

Aqua AIRS (1:30 pm)

- Independent SO$_2$ retrievals from 3 instruments (UV/IR)
- Volcanic cloud SO$_2$ burdens agree to within 20%
Strengths and weaknesses of SO$_2$ data

• **Strengths**
  - Unique marker of magmatic volcanic eruptions
  - Virtually no interference from other sources in most volcanic regions (apart from other volcanoes…)
  - Current UV/IR satellite sensors sensitive to low SO$_2$ amounts
  - UV sensors can detect SO$_2$ degassing prior to eruptions
  - Can map volcanic clouds when ash is encased in ice
  - UV sensors can detect SO$_2$ in opaque volcanic clouds
  - SO$_2$ measurements have been validated (but more is needed)
  - Could SO$_2$ be used to assess cumulative aircraft exposure to volcanic clouds?

• **Weaknesses**
  - Poor proxy for dense ash when SO$_2$ and ash clouds separate
  - No geostationary SO$_2$ data in NOPAC region (yet → GOES-R ABI)
  - UV techniques restricted during winter months
Summary

• Numerous satellite sensors now provide SO$_2$ measurements
• Some have standard SO$_2$ products, others require application of retrieval algorithms to yield quantitative SO$_2$ data
• Aura/OMI is an economical and effective tool for monitoring volcanic SO$_2$ degassing on a regional or local (single volcano) scale
• OMI’s high SO$_2$ sensitivity and global coverage allows detection of nearly all significant volcanic eruption clouds, assisting aviation hazard mitigation and improving our understanding of the atmospheric impacts of volcanism
• Detection of tropospheric SO$_2$ plumes by OMI depends on several factors, hence the lower detection limit in terms of SO$_2$ flux is variable (with latitude, vent altitude etc.)
• Altitude sensitivity must be considered when evaluation satellite SO$_2$ data
• New satellite constellations (A-Train) provide opportunities for sensor synergy and ‘3D’ analysis of volcanic clouds
Fourpeaked Volcano, AK: A long dormant volcano - last volcanic activity was prior to glaciation (>10,000 years ago). No known fumarolic areas around the volcano.

Eruption detection: Fourpeaked (AK) Sept 17, 2006 20:40 UTC

Fourpeaked (AK) eruption, Sept 2006

King Salmon NEXRAD [NEXRAD data courtesy AVO]
• Small magmatic intrusion at shallow depth?

Sept 17, 2006

Sept 18, 2006

20,000 ft
As of June 2007, seismic activity continued and a boiling lake occupied the crater.
Detection of ice-rich volcanic clouds

Aqua MODIS b721 composite

Aura OMI SO$_2$ data

Rabaul (PNG) eruption, 7 Oct 2006
Validation of trajectory/dispersion models

http://eer.cmc.ec.gc.ca/people/Alain/eer/exercises/okmok/exp_05/sig2v_0.5/FL350-FL600/anim.html

OMI SO$_2$ – July 19

MLDP0 simulation – July 19

MLDP0 data courtesy of René Servranckx and Alain Malo, Montreal VAAC

• Accurate dispersion models are essential for volcanic ash forecasting
• SO$_2$ better suited for model validation due to its much longer atmospheric residence time
Aviation encounters with dilute volcanic clouds

- Encounters over Micronesia, Nov 2002 and March 2003 [Tupper et al., 2006]
- ‘Gulfstream incident’: twin-engined flameout over PNG, July 2006 [Tupper et al., 2007]
- NASA DC8 encounter with Hekla volcanic cloud, Feb 2000

Mid-May 2006: Airbus 330 engines degraded during flight from Manila to Noumea

Redoubt eruption cloud over CA and NV on 16 Dec 1989 [Carn et al., 2009]
Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)

Cloud seeding?
Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)

Halema’uma’u (~1200 m)

Pu’u’O’o (~700 m)
Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)

Halema‘uma‘u (summit)

Pu‘u‘O‘o (ERZ)
OMI annual average $\text{SO}_2$ in 2005: W. Pacific/S.E. Asia

- China
- Anatahan
- Manam
- Bagana
- Ambrym
OMI annual average SO$_2$ in 2006: W. Pacific/S.E. Asia

- China
- Anatahan
- Rabaul
- Bagana
- Ambrym

SO$_2$ column [DU]

0.02 0.05 0.08 0.11 0.14 0.17 0.20 0.23 0.26 0.29 0.32