Anthropogenic and Volcanic Emission Inventories: Methodologies and Error Estimates, Using AeroCom as an Example

Thomas Diehl$^{1,2}$

David Streets, Tami Bond, Steven Baughcum, Nick Krotkov, Simon Carn, Lee Siebert, Xiaohua Pan, Mian Chin

1: NASA Goddard Space Flight Center
2: Universities Space Research Association

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Outline

- Part I: Anthropogenic emissions (BC, OC, SO$_2$)
  - Methodology
  - Trends
  - Error Estimates
  - Evaluation with Observations

- Part II: Volcanic Emissions (SO$_2$)
  - Types of Eruptions
  - Emission Estimates
  - Plume Heights

- Final Remarks
AeroCom Emissions

- AeroCom is an international initiative to improve our knowledge of aerosols and specifically to reduce the uncertainty of the aerosol climate forcing.
- It conducts multi-model experiments and uses a large number of observations to evaluate parameterizations in models.
- About 14 models are participating in this project.
- Experiments have well defined protocols (output format etc.). For some experiments a common set of emissions is recommended.

AeroCom I: Specified emissions for 1750 and 2000
AeroCom II: Emissions for a hindcast run from 1980 to 2010
AeroCom Phase II Anthropogenic Emissions

   Compiled from a technology based inventory from D. Streets, aircraft emissions from NASA’s AEAP project, and ship emissions based on work from V. Eyring

   SO2 emissions replaced with emissions from EDGAR 4.1 to fix overestimate in HCA0-v1 over Europe.

3. Updated emissions for China and India available (1996-2010)

   ACCMIP is a technology based inventory which was created by Lamarque et al. for IPCC AR5 experiments in 10 year increments from 1850 to 2000; years after 2000 derived from RCP8.5; linear interpolation applied for years in between (MACC-City).
## General Features

<table>
<thead>
<tr>
<th></th>
<th>A2-HCA0-v1</th>
<th>A2-HCA0-v2</th>
<th>China/India</th>
<th>A2-ACCMIP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td>1x1</td>
<td>1x1</td>
<td>0.1x0.1</td>
<td>0.5x0.5</td>
</tr>
<tr>
<td><strong>Temporal Resolution</strong></td>
<td>Yearly</td>
<td>Yearly</td>
<td>Monthly</td>
<td>Yearly</td>
</tr>
</tbody>
</table>

**China/India:** Residential sector with monthly variation per province.

**Aircraft emissions:** 1x1, monthly, 1976-2010
Land-based Anthropogenic Emissions

Wide variation of emission rates for different types of processes and control technologies:

In rapidly developing countries (China, India) new technologies cause significant changes in emission factors.

⇒ Technology-based methodology advantageous.

5 major emission sectors: power generation, industry, residential, transport.

More than 120 sector/fuel(product)/technology combinations.

Emissions per region/country/province $i$ and per species $j$:

$$E_{i,j} = \sum_{l} \sum_{m} A_{i,l,m} \left[ \sum_{n} X_{i,l,m,n} EF_{i,j,l,m,n} \right]$$

$EF$ is the net emission factor and is given by:

$$EF_{BC(OC)} = EF_{PM} \cdot F_{1.0} \cdot F_{BC(OC)} \cdot F_{\text{control}}$$

$$EF_{SO_2} = 2 \cdot S \cdot (1 - SR) \cdot (1 - \eta_k)$$

- $A_{i,l,m}$: activity rates (fuel consumption rates).
- $X_{i,l,m,n}$: fraction of fuel (product) that is consumed by a specific technology.
- $EF_{PM}$: bulk particulate emission factor.
- $F_{1.0}$: fraction with $d < 1 \mu m$.
- $F_{BC(OC)}$: fraction of BC (OC).
- $F_{\text{control}}$: unfiltered fraction of PM.
- $\eta_k$: removal efficiency of technology $k$.
- $S$ and $SR$: sulfur content and sulfur retention in...
Ship Emissions

Bottom-up: Based on detailed local data, i.e. ship- and route-specific emissions

Most common: **Top down**: Calculate global speciated emissions and distribute them via spatial proxies

AeroCom: **Top down** based on Eyring et al. [2005] for 2001

- Engine types
- Installed Engine Power
- Average Engine Load
- Annual Engine Running Hours
- Power-dependent fuel consumption rates
- Total Fuel Consumption
- Emission Factors
- Data from Lloyd’s Maritime Information System (LMIS), engine manufacturers, and field measurements.

PM is split into BC, OC, SO₄ as 3%, 8%, and 47%, based on measurements.
Regions in HCA0-v1/v2

Choice of 17 regions is from the IMAGE 2.2 model
Spatial Allocation

Gridding of emissions per region/country/province based on spatial proxies, e.g.:

Population distribution from LandScan Global Population Dataset (ORNL)

Urban and rural population data from the Global Rural-Urban Mapping Project (GRUMP (CIESIN, Columbia University)

Road networks from the Defense Mapping Agency (DMA)

Point Source information for power plants in some cases

Shipping routes:
International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (freely available; AMVER (Automated Mutual-assistance Vessel Rescue system) (confidential)
BC Land-based Emissions

Decline in residential fuel use and transport sector from 1995 to 1996 in U.S.
OC Land-based Emissions
SO2 Land-based Emissions

V1 trend probably overestimated; SO2 reduction measures not accurate
Total Anthropogenic Emission over China by Sector: SO2 [Gg/month]
Uncertainty Estimates for China/India

Determine probability distribution for each input parameter. Run \( \approx 6000 \) Monte Carlo simulations to generate 95% CIs.

SO2 parameters: mostly normal distribution
BC/OC emission factors: lognormal

Sulfur contents and SO2 activity rates: lower uncertainty
BC/OC: combustion conditions have high uncertainty

<table>
<thead>
<tr>
<th></th>
<th>SO2</th>
<th>BC</th>
<th>OC</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>-16% to 17%</td>
<td>-43% to 93%</td>
<td>-43% to 80%</td>
</tr>
<tr>
<td>India</td>
<td>-15% to 16%</td>
<td>-41% to 87%</td>
<td>-44% to 92%</td>
</tr>
</tbody>
</table>

BC uncertainty in China decreases over time: decreasing share of residential and industry sect
SCIAMACHY/GOME Observations

After 2007 drop due to FGD
But: slight increase in 2010
Non-power sources dominant

Richter (2011)
OMI SO2 observations

Mean OMI observations over Eastern US 2005-2007 vs. 2008-2010
Emission sources from the top 40 list (EPA)
Mostly coal-burning power plants
Direct stack measurements using CEMS
Reduction due to FGD units ("scrubbers")
Threshold for detection: about 70 kt SO2/yr

Ratio of the sum as a function of distance.
Ratio ≈ 0.6,
i.e. 40% reduction.
EPA reports 46%.

Fioletov et al., 2011
EPA Coal Controls for SO2 (and NOX)

Mostly “tall” stacks (> 500 ft)

2005

2010
Linear Trends AOD from SeaWiFS 1997-2008 over Europe and South China (Yoon et al.)

Benelux and Po-Valley spring and summer: Mostly anthrop., downward trend

Eastern Europe and Mediterranean summer: Mix of aerosols, no significant trend

Winter: Cloud contamination; drier conditions?

Pearl River Delta: Upward trend (except summer) Summer: cloud contaminated; misclassification of aerosols and clouds?

AOD Trends from SeaWiFS from 1997 to 2010 (Hsu et al., 2012)
Ship Trends
- Based on gridded burnt fuel files from AEAP project for 1976, 1984, 1992, 1999, and a projection for 2015
- Emission index (EI) of 0.8 - 0.4 for SO₂; height dependent EI for BC (≈0.04)
- OC=1/3 BC; all hydrophilic
Part II: Volcanic SO2 Emissions

- Daily SO$_2$ emissions and plume heights for 1167 volcanoes from 1-1-1979 to 31-12-2009
- Emissions due to explosive and effusive eruptions as well as silent degassing taken into account
- Eruption data including the VEI is from the Smithsonian’s Global Volcanism Program (GVP)
- All volcanoes with historic subaerial eruptions in GVP are included
- For eruptive episodes, GVP provides dates and the VEI.
  - First approximation of SO$_2$ and plume height by the VEI/VSI
VEI/VSI classification

- VEI is based on amount of tephra and/or plume height
- VSI assigns range of SO2 emissions to each VEI
- Observed SO2 from TOMS (1979 – 1993)
- VSI for non-arc eruptions not statistically meaningful

<table>
<thead>
<tr>
<th>Arc volcano SO2, kt</th>
<th>&lt;0.5</th>
<th>0.5–4</th>
<th>4–30</th>
<th>30–200</th>
<th>0.2–1 x 10^3</th>
<th>1–8 x 10^3</th>
<th>0.8–6 x 10^4</th>
<th>0.6–5 x 10^5</th>
<th>&gt;5 x 10^5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonarc volcano SO2, kt</td>
<td>80–300</td>
<td>0.3–1 x 10^5</td>
<td>1–4 x 10^5</td>
<td></td>
<td></td>
<td></td>
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</table>

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<thead>
<tr>
<th>General description</th>
<th>nonexplosive</th>
<th>small</th>
<th>moderate</th>
<th>moderate large</th>
<th>large</th>
<th>very large</th>
<th>very large</th>
<th>very large</th>
<th>very large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud column height, km</td>
<td>&lt;0.1</td>
<td>0.1–1</td>
<td>1–5</td>
<td>3–15</td>
<td>10–25</td>
<td>&gt;25</td>
<td>&gt;25</td>
<td>&gt;25</td>
<td>&gt;25</td>
</tr>
<tr>
<td>Volume of tephra, m^3 (arc only)</td>
<td>&lt;10^4</td>
<td>10^4–10^6</td>
<td>10^6–10^7</td>
<td>10^7–10^8</td>
<td>10^8–10^9</td>
<td>10^9–10^10</td>
<td>10^10–10^11</td>
<td>10^11–10^12</td>
<td>&gt;10^12</td>
</tr>
</tbody>
</table>
Distribution of Emitting Volcanoes 1979-2009

- Mostly located along arcs of subduction zones
  - More frequent, violent and short-lived eruptions
- Fewer hot spot and rift volcanoes
  - Longer lasting eruptions, more effusive
Volcano Settings
Methodology

- SO$_2$ amount iteratively refined for individual eruptions by satellite (e.g. TOMS, OMI) and COSPEC (Correlation Spectrometer) observations, and more detailed analyses from publications

- For some eruptions with known Lava and/or Tephra volumes, the SO$_2$ is estimated from these amounts

- Data for quasi-continuously erupting volcanoes is from Andres & Kasgnoc (1998)

- Silent degassing estimates for non-eruptive periods are based on Berresheim & Jaeschke (1983) and Stoiber et al. (1987)
Currently re-processed with retrieval algorithm used for OMI
Example from OMI - Kasatochi

Aura/OMI - 08/09/2008 00:56-01:03 UT - Orbit 21636

SO₂ mass: 882.092 kt; Area: 641791 km²; SO₂ max: 246.15 DU at lon: -171.85 lat: 50.32 ; 01:02UTC
# Volcanic SO2 Measurement Aspects

<table>
<thead>
<tr>
<th>Instrument (Algorithm)</th>
<th>Detection Limit [kt SO2] (Emission Limit)</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOMS Nimbus-7 1978-1993</td>
<td>10.4 (range: 2 - 20)</td>
<td>OBS: 5 DU [Extrapolation: 15%-30% for 95% CI]</td>
</tr>
<tr>
<td>TOMS Earth Probe 1996-2005</td>
<td>3.8</td>
<td>5 DU</td>
</tr>
<tr>
<td>OMI (TRL LF)</td>
<td>0.125 (100 t/d)</td>
<td>0.6</td>
</tr>
<tr>
<td>OMI (TRM LF)</td>
<td>0.06 (50 t/d)</td>
<td>0.3</td>
</tr>
<tr>
<td>OMI (STL LF)</td>
<td>0.02 (17 t/d)</td>
<td>0.2</td>
</tr>
<tr>
<td>COSPEC</td>
<td>0.01 – 0.1</td>
<td>Up to 40%</td>
</tr>
</tbody>
</table>
SO$_2$ related to ejected magma

Correlation of TOMS SO$_2$ data with erupted magma yields:

$$M_{SO_2} (\text{in Mt}) = 1.77 \left( M_{magma} (\text{in Gt}) \right)^{0.64} \quad (r^2=0.67) \quad (\text{Blake 2003})$$
Plume Height

Column altitudes impact transport and residence time of derived SC. They are also important for aviation.

Plume heights are typically estimated from ground or airplane observations, with errors up to 50%. For well observed sites like Etna, reported errors are about 20%.

In some cases they can be derived from the analysis of satellite images (MISR, OMI).

For Plinian eruptions (VEI ≥ 4), the height can often be approximated as a function of the volume discharge rate $Q$. $H = f(Q)$
Plume Height Estimation in AeroCom

In our inventory, the height default is based on the VEI/height relationship. Data from the weekly or monthly reports from GVP has been added over time. Plume heights for major eruptions are from analyses in the literature.

SO2 is evenly distributed over all levels located in the top 1/3 of the column.

Silently degassing volcanoes emit at the elevation of the volcano. No flank degassing is considered.
MISR provides multispectral and multiangle measurements.

Plume height of Etna in October 2002 estimated by Scollo et al. using MISR stereo height retrieval algorithm.

Mean uncertainty of height: ± 0.5 km
MISR: Vertical Distribution of Plume

Eruption of Etna on 2002-10-27
Index 1 = location of volcano

Histogram of MISR Stereo product plume height at the site of the volcano. In this case the aerosols are not uniformly distributed within the column (Kahn et al.).
Yang et al. have estimated SO2 plume heights from the eruption of Jebel al Tair (Yemen) on September 30, 2007. Plume height from the major eruption is about 16 km ASL, reaching the UTLS. Another plume top is at around 3 km, probably from an effusive eruption.
Total SO$_2$ per Year

About 11-13 Tg/year from silent degassing included

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total SO$_2$/year</td>
<td>22 Tg</td>
<td>52 Tg</td>
<td>27 Tg</td>
<td>26 Tg</td>
</tr>
</tbody>
</table>
Total $\text{SO}_2$ per Volcano

Emitted $\text{SO}_2$ during 1979-2009 [Tg]
Strongest Emitters

Top ten $\text{SO}_2$ emitters for 1979 - 2009 [Tg]

1: Etna
2: Bagana
3: Lascar
4: Miyake-jima
5: Nyamuragira
6: Nevado del Ruiz
7: Sakura-jima
8: Pinatubo
9: Kilauea
10: Manam
Largest 20 Explosive Eruptions

12 Volcanoes:
Kasatochi
Alaid, Sarychev Peak, Chikurachki
St. Helens
Mauna Loa, El Chichon, Sierre Negra, Nevado del Ruiz
Nyamuragira, Pinatubo
Cerro Hudson

triangles = approx. tropopause for given latitude
OMI very fast delivery

- OMI vfd by FMI provides near-real time SO2 images in [DU] over the NH
- Available about 15 m after overpass
- URL: http://omivfd.fmi.fi/volcanic.html

Grimsvotn eruption 2011
Final Remarks

- There are still large uncertainties associated with global emission inventories.

- A detailed knowledge of technology changes is required to accurately represent emission trends.

- For individual events and small regions the uncertainty can be reduced using measurements, but this requires a time-consuming manual analysis and is typically not possible in NRT.

- Need to implement and improve NRT products, specifically for volcanic eruptions.