Use of CESM to quantify aerosol forcing from the Eyjafjallajökull volcanic eruptions

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Eyjafjallajökull eruption

MODIS, NASA Earth Observatory Image of the Day

- Two eruption episodes in April and May 2010
- Disruption of air traffic. Small but unique impact on climate.
Aerosol climate impacts

- Atmospheric ash forcing:
  - longwave: +
  - shortwave: ?

- Atmospheric sulfate forcing:
  - longwave: +
  - shortwave: −

- Deposition of ash to snow and sea-ice:
  - shortwave: +

- Insulation of snow: −

- Aerosol–cloud indirect effects:
  - shortwave: − (?)
  - longwave: + (?)

Figure: 10 cm thick ash layer overlying snow in September 2010. Courtesy of Steve Warren.
Total injected tephra mass:
- $8.3 \pm 4.2 \text{Tg}$ as “fine” ash ($2.8 - 28 \mu m$ diameter)
- $\sim 12 \text{Tg}$ in $2.5 - 250 \mu m$ size range
- Global annual black carbon emissions: $\sim 8 \text{Tg}$
SO$_2$ emissions

- Estimates derived from OMI, SCIAMACHY, GOME-2, and ground radar (*Flemming and Inness*, 2013):

![SO$_2$ emission (t/s) 2010](image1)

![SO$_2$ injection height (km) 2010](image2)

- Total SO$_2$ emissions: 0.25 (0.13 – 0.43) Tg, also from *Heard et al.* (2012)

- Only ~ 3% of SO$_2$ emissions occurred during April event (not shown)

- Very little injection of SO$_2$ into stratosphere
Aerosol radiative forcing calculations

- CAM, CICE, and CLM employed in different capacities
- Modified CAM4 to accommodate 4 ash tracers and volcanic SO$_2$/SO$_4$ tracers with new optical properties
- Vertically-resolved daily SO$_2$ emission fluxes from Flemming and Inness, (2013), oxidation to SO$_4$ simulated with CAM4-BAM with prescribed 2010 SSTs/sea-ice
- Daily 3-D ash fields from Stohl et al. (2011), 25 size bins, re-partitioned into 4 size bins, prescribed in CAM
- Atmospheric RF calculations using RRTMG with prescribed ash and SO$_4$ fields in CAM
- Added 4 ash particle species to CLM/SNICAR and CICE/Delta-Eddington (pre-existing: 2 BC species, 4 dust).
  - Particle size ranges partitioned to have roughly equal surface area
  - $r < 0.56 \mu m$, $0.56 < r < 1.0 \mu m$, $1.0 < r < 2.5 \mu m$, $r > 2.5 \mu m$
- Daily ash deposition fluxes from Stohl et al., (2011) prescribed in CLM4 and CICE4 simulations with 2010 forcing data
Atmospheric ash (*Stohl et al.*, 2011)

- Ash transport, wet+dry deposition simulated with the Lagrangian transport model FLEXPART, met fields from ECMWF and NCEP
- Forward dispersion modeling and satellite observations combined with inversion scheme to determine time-resolved ash emissions

![Maps showing ash dispersion and simulation dates](image-url)
Ash optical properties

- Uncertainty in imaginary component of ash refractive index drives large uncertainty in forcing
- Low, central, and high absorptivity estimates derived from aircraft/PSAP measurements, sun photometer inversions, Lidar inversions, and measurements of previous events

Mie optical properties weighted into RRTMG SW and LW spectral bands, and provided as supplementary data
Optical properties

- Ash particles are often highly non-spherical

![Image of ash particles](image_url)

**Figure:** Schumann et al (2011), ACP

- Properties for equal-mass non-spherical particles simulated with T-Matrix code [*Mishchenko and Travis*, 1998]. MAC of Chebyshev particles, oblate/prolate spheroids, spheres differ by **16% at most**
Optical properties

- Variability in ash refractive index in longwave spectrum:

- Sulfate optical properties derived for three size distributions: \( r_e = 0.17, 0.27, 0.43 \mu m \) (Rasch et al., 2008; O’Dowd et al., 2011)
Aerosol forcing components: Daily animations
Aerosol forcing components: 2-month means
Aerosol forcing components: Timeseries of global means

- Atmospheric ash SW forcing is noisy because of variable plume/cloud/cryosphere co-location and short residence time.
- Ash LW forcing is substantial because particles are large.
- Ash-in-snow forcing persists for months.
- Negative SW forcing from sulfate dominates (in May).

Flanner, Gardner, Eckhardt, Stohl, Perket
Eyjafjallajökull Volcanic Aerosol Forcing in CESM
## Aerosol forcing components: Means

Table: Global annual-mean radiative forcings [mW m\(^{-2}\)]

<table>
<thead>
<tr>
<th></th>
<th>Ash SW</th>
<th>Ash LW</th>
<th>Ash in snow</th>
<th>Ash in sea-ice</th>
<th>Sulfate SW</th>
<th>Sulfate LW</th>
<th>Net</th>
<th>Net Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable optical properties, central emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-4.1</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td>-4.1</td>
<td>0.2</td>
<td>-7.3</td>
<td>-7.2</td>
</tr>
<tr>
<td>Central</td>
<td>-0.3</td>
<td>1.1</td>
<td>0.8</td>
<td>0.1</td>
<td>-3.8</td>
<td>0.2</td>
<td>-1.9</td>
<td>-0.5</td>
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<tr>
<td>High</td>
<td>+2.7</td>
<td>1.2</td>
<td>1.3</td>
<td>0.2</td>
<td>-3.0</td>
<td>0.2</td>
<td>+2.8</td>
<td>+4.9</td>
</tr>
<tr>
<td>Variable emissions, central optical properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-0.1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.1</td>
<td>-6.1</td>
<td>0.4</td>
<td>-4.9</td>
<td>-4.3</td>
</tr>
<tr>
<td>Central</td>
<td>-0.3</td>
<td>1.1</td>
<td>0.8</td>
<td>0.1</td>
<td>-3.8</td>
<td>0.2</td>
<td>-1.9</td>
<td>-0.5</td>
</tr>
<tr>
<td>High</td>
<td>-0.6</td>
<td>2.1</td>
<td>1.5</td>
<td>0.3</td>
<td>-2.1</td>
<td>0.1</td>
<td>+1.2</td>
<td>+4.5</td>
</tr>
</tbody>
</table>

- Central estimates yield weakly negative forcing
- High ash absorption assumption produces *positive* net forcing
- Forcing sign of atmospheric ash component is uncertain
- Uncertainty in emissions of ash and SO\(_2\) are both \(\sim 2\times\)
Uncertainty due to clouds

- Cloud variability in different ensemble members drives large variation in atmospheric ash SW forcing, but has little impact on the other forcing terms.

Table: Global annual-mean instantaneous top-of-atmosphere radiative forcings from different ensemble members [mW m$^{-2}$]

<table>
<thead>
<tr>
<th>Ensemble Member</th>
<th>Ash SW</th>
<th>Ash LW</th>
<th>Sulfate SW</th>
<th>Sulfate LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>−0.29</td>
<td>1.06</td>
<td>−3.83</td>
<td>0.24</td>
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<tr>
<td>E2</td>
<td>−0.59</td>
<td>1.07</td>
<td>−3.73</td>
<td>0.24</td>
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<td>E3</td>
<td>−0.45</td>
<td>1.03</td>
<td>−3.56</td>
<td>0.22</td>
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<tr>
<td>E4</td>
<td>−0.20</td>
<td>1.07</td>
<td>−3.62</td>
<td>0.22</td>
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<tr>
<td>E5</td>
<td>−0.28</td>
<td>1.05</td>
<td>−3.57</td>
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<tr>
<td>Mean</td>
<td>−0.36</td>
<td>1.06</td>
<td>−3.66</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Conclusions

- CESM is a useful tool for calculating RF of various volcanic aerosol components.
- Net aerosol forcing from Eyjafjallajökull was nearly climate neutral, marking an unusual volcanic event in present climate.
  - Negative sulfate forcing slightly exceeded positive ash forcing.
  - Ash-in-snow forcing persisted longer than atmospheric forcing, but operated over a smaller spatial domain.
  - Ash longwave forcing is non-negligible.
- Ash absorptivity and emissions are largest sources of uncertainty. Ash/cloud covariance is large source of uncertainty for atmospheric ash SW forcing.
- Beyond RF: Did large positive forcing over Arctic and Greenland enhance summer melt in 2010?
- Did latitudinal gradient in forcing alter atmospheric dynamics in a meaningful way (e.g., weakened westerlies)?