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

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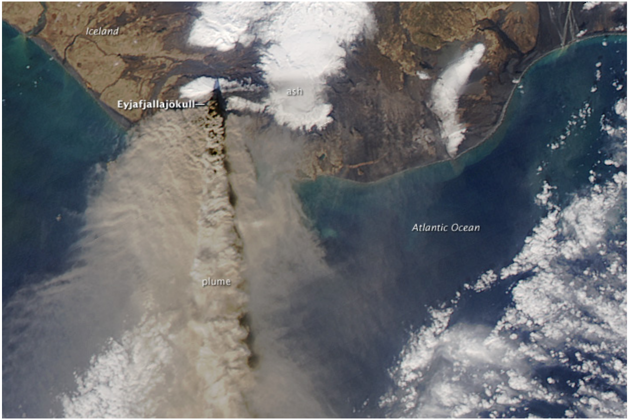
Eyjafjallajökull eruption

MODIS, NASA Earth Observatory Image of the Day



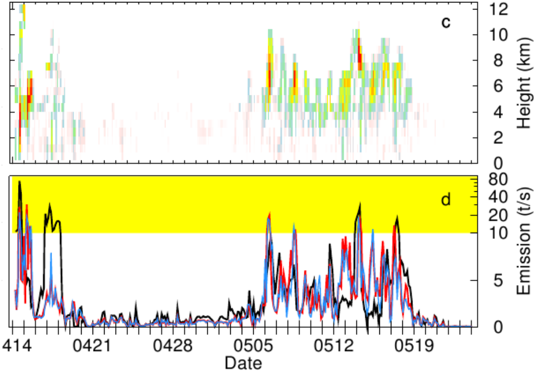
- Two eruption episodes in April and May 2010
- Disruption of air traffic. Small but unique impact on climate.

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.

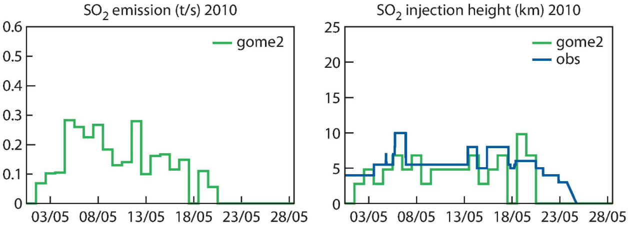
Ash emissions (*Stohl et al.*, 2011)



- Total injected tephra mass:
    - $8.3 \pm 4.2\,\mathrm{Tg}$ as "fine" ash ($2.8 - 28\,\mu\mathrm{m}$ diameter)
    - $\sim 12\,\mathrm{Tg}$ in $2.5 - 250\,\mu\mathrm{m}$ size range
- Global annual black carbon emissions: $\sim 8\,\mathrm{Tg}$

SO_2 emissions

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



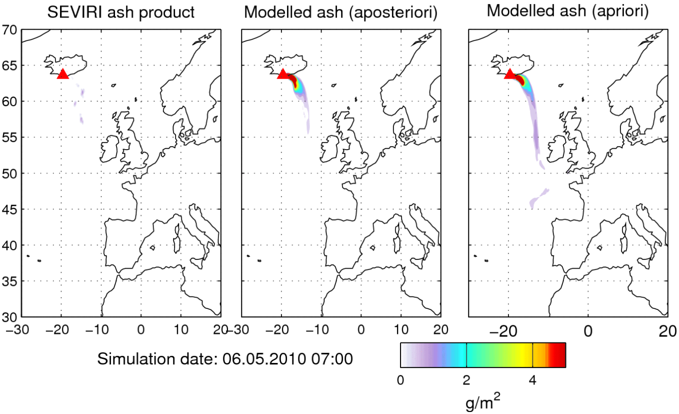
- Total SO_2 emissions: $0.25\,(0.13 - 0.43)$ Tg, also from *Heard et al.* (2012)
- Only $\sim 3\%$ of SO_2 emissions occurred during April event (not shown)
- Very little injection of SO_2 into stratosphere

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
  - $r < 0.56\,\mu\text{m}$, $0.56 < r < 1.0\,\mu\text{m}$, $1.0 < r < 2.5\,\mu\text{m}$, $r > 2.5\,\mu\text{m}$
- 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)

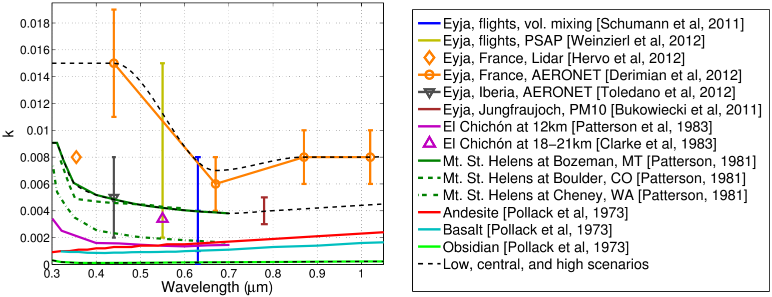
- Ash transport, wet+dry deposition simulated with the Lagrangian transport model FLEXPART, met fields from ECMWF and NCEP
- Forward dispersion modeling and satellite observations combined with inversion scheme to determine time-resolved ash emissions



Simulation date: 06.05.2010 07:00

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

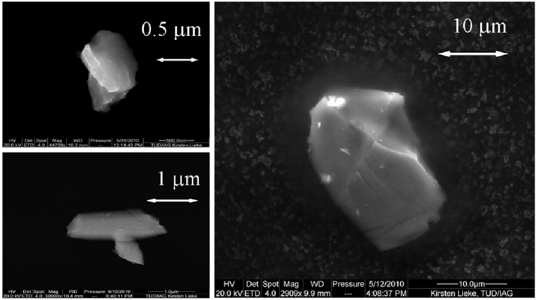
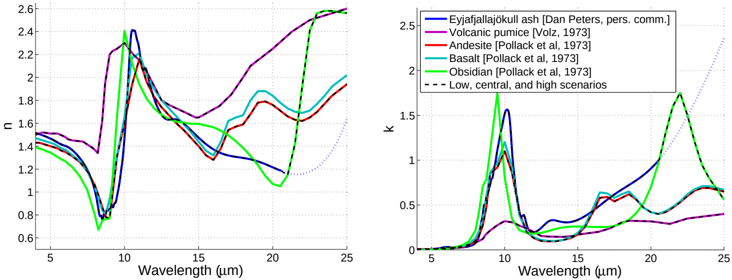


Figure: Schumann et al (2011), ACP

- 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

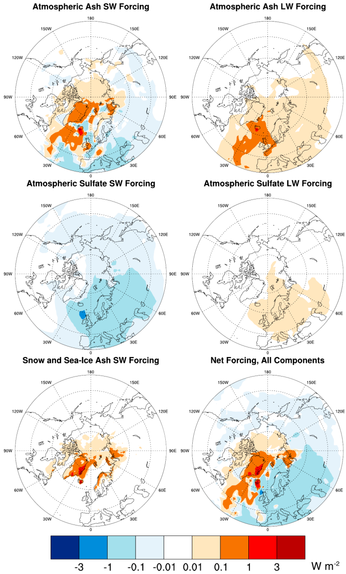
- Variability in ash refractive index in longwave spectrum:



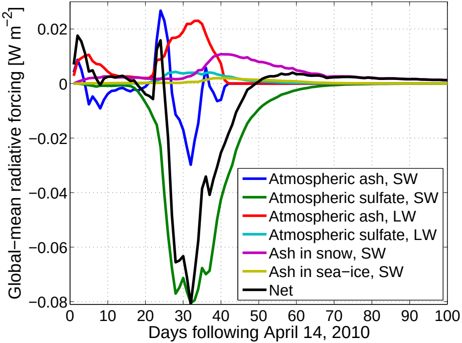
- Sulfate optical properties derived for three size distributions: $r_e = 0.17, 0.27, 0.43\,\mu\text{m}$ (*Rasch et al.*, 2008; *O'Dowd et al.*, 2011)

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)

Aerosol forcing components: Means

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

Instantaneous top-of-atmosphere forcings								
	Ash SW	Ash LW	Ash in snow	Ash in sea-ice	Sulfate SW	Sulfate LW	**Net**	**Net Effective**
Variable optical properties, central emissions								
Low	−4.1	0.7	0.0	0.0	−4.1	0.2	−7.3	−7.2
Central	−0.3	1.1	0.8	0.1	−3.8	0.2	−1.9	−0.5
High	+2.7	1.2	1.3	0.2	−3.0	0.2	+2.8	+4.9
Variable emissions, central optical properties								
Low	−0.1	0.5	0.4	0.1	−6.1	0.4	−4.9	−4.3
Central	−0.3	1.1	0.8	0.1	−3.8	0.2	−1.9	−0.5
High	−0.6	2.1	1.5	0.3	−2.1	0.1	+1.2	+4.5

- 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 atmsopheric 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 [$\mathrm{mW\,m^{-2}}$]

Ensemble Member	Ash SW	Ash LW	Sulfate SW	Sulfate LW
E1	−0.29	1.06	−3.83	0.24
E2	−0.59	1.07	−3.73	0.24
E3	−0.45	1.03	−3.56	0.22
E4	−0.20	1.07	−3.62	0.22
E5	−0.28	1.05	−3.57	0.22
Mean	−0.36	1.06	−3.66	0.23

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)?