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Air quality and climate effects of tropospheric volcanic sulfur emissions

Anja Schmidt[1],

K. Carslaw, G. Mann, S. Leadbetter, N. Theys, E. Carboni, C.S. Witham, J.A. Stevenson, C.E. Birch, and T. Thordarson

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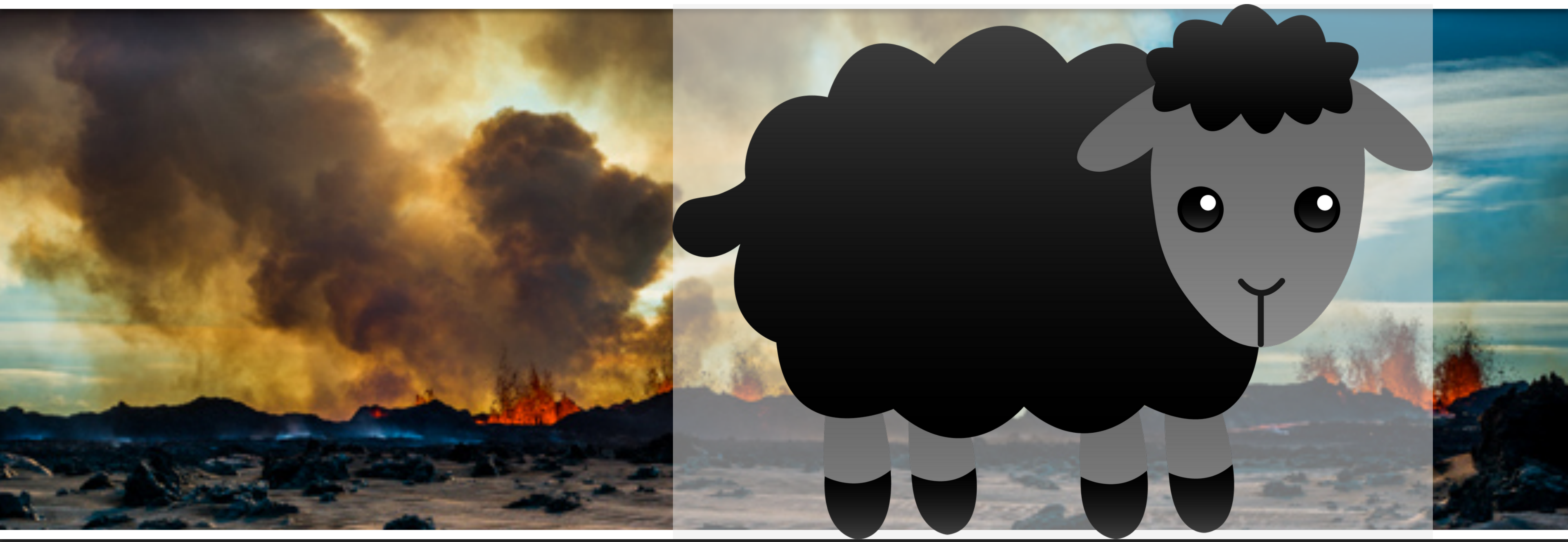
Air quality and climate effects of tropospheric volcanic sulfur emissions



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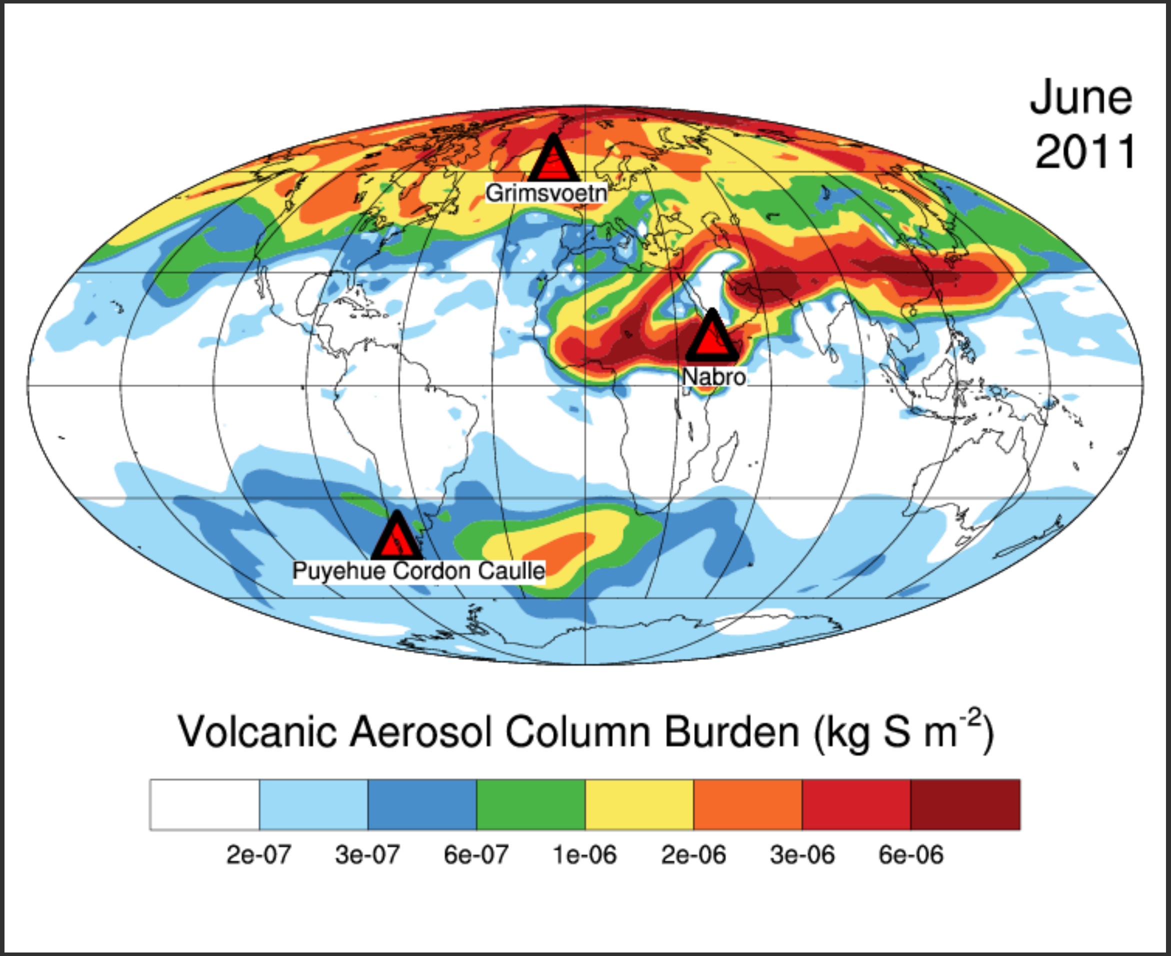
Volcanic eruptions …

- More recently recognition of small- to moderate-magnitude eruptions
  - 2009 Sarychev Peak = VEI 4 → 1 eruption per year on average
    - 50+ papers

Talk by Mike Mills



Volcanic eruptions …

- More recently recognition of small- to moderate-magnitude eruptions
  - 2009 Sarychev Peak = VEI 4 → 1 eruption per year on average
    - 50+ papers

  - 1991 Mt. Pinatubo = VEI 6 → 1 eruption every 50 yrs on average
  - ~500 publications

Why should we care about tropospheric volcanic aerosol?

1. **Continuously degassing volcanoes**
2. **Icelandic flood lava eruptions**

Observed volcanic impacts on low-level clouds

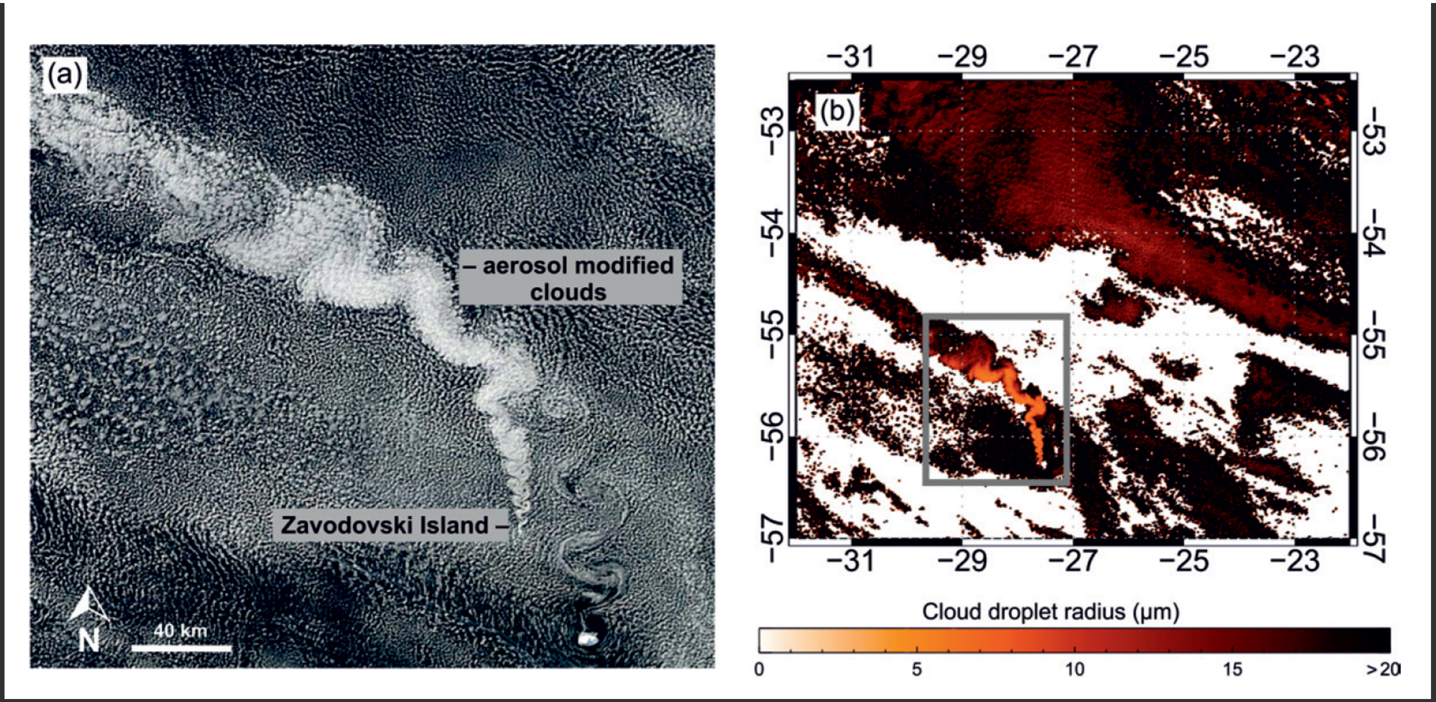
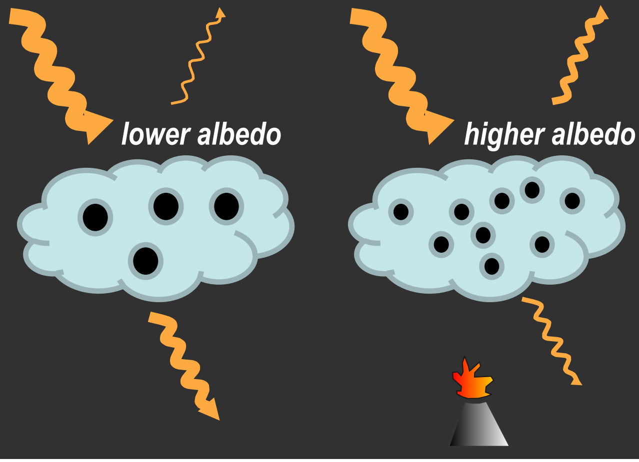
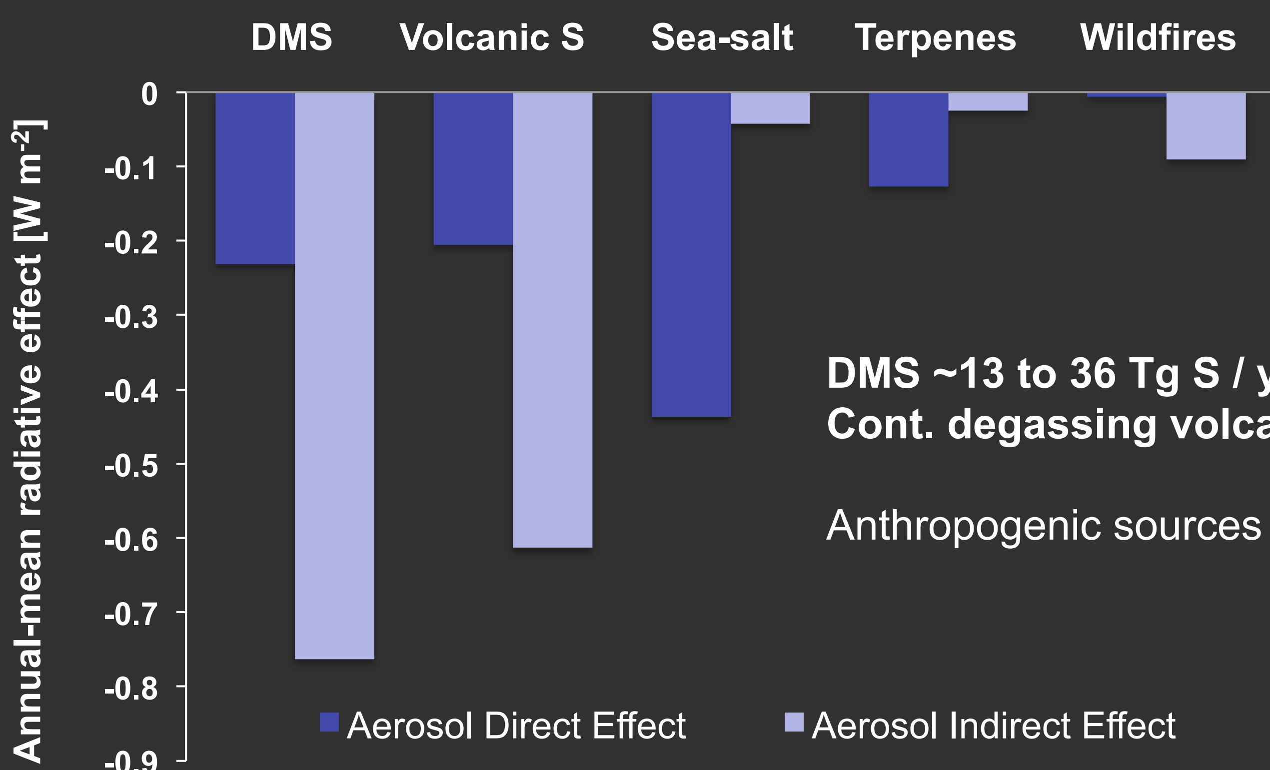


Figure from Schmidt et al. (2012)



Graf et al. (1998)
Gassó (2008)
Yuan et al. (2011)
Schmidt et al. (2010, 2012)
Ebmeier et al. (2014)
McCoy and Hartmann (2015)

Continuously degassing volcanoes



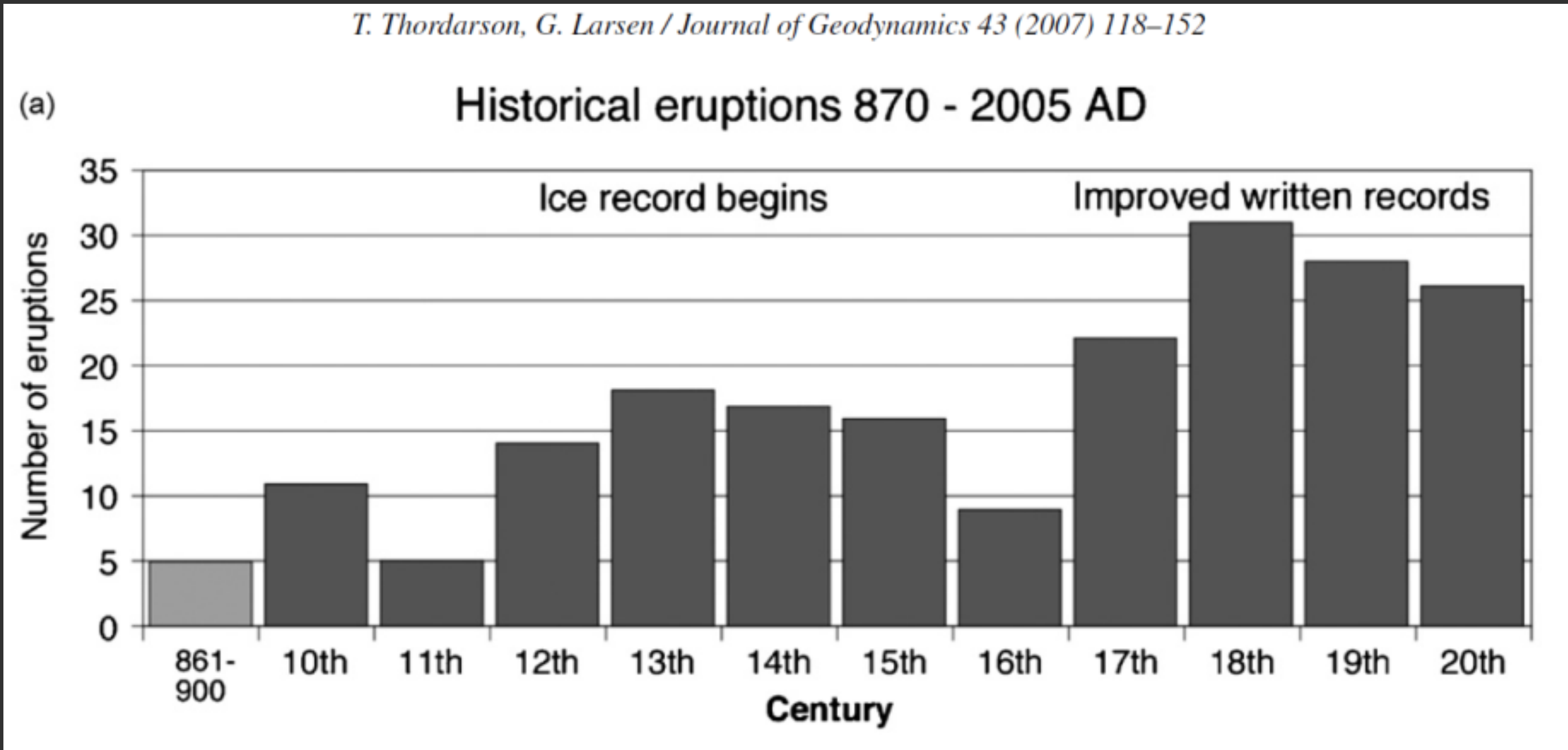
DMS ~13 to 36 Tg S / yr
Cont. degassing volcanoes ~12.5 Tg S / yr

Anthropogenic sources year 2005 ~58 Tg S / yr

- **Need to account for volcanic S when quantifying PI-PD forcing**
- **Source strength and variability not well constrained**

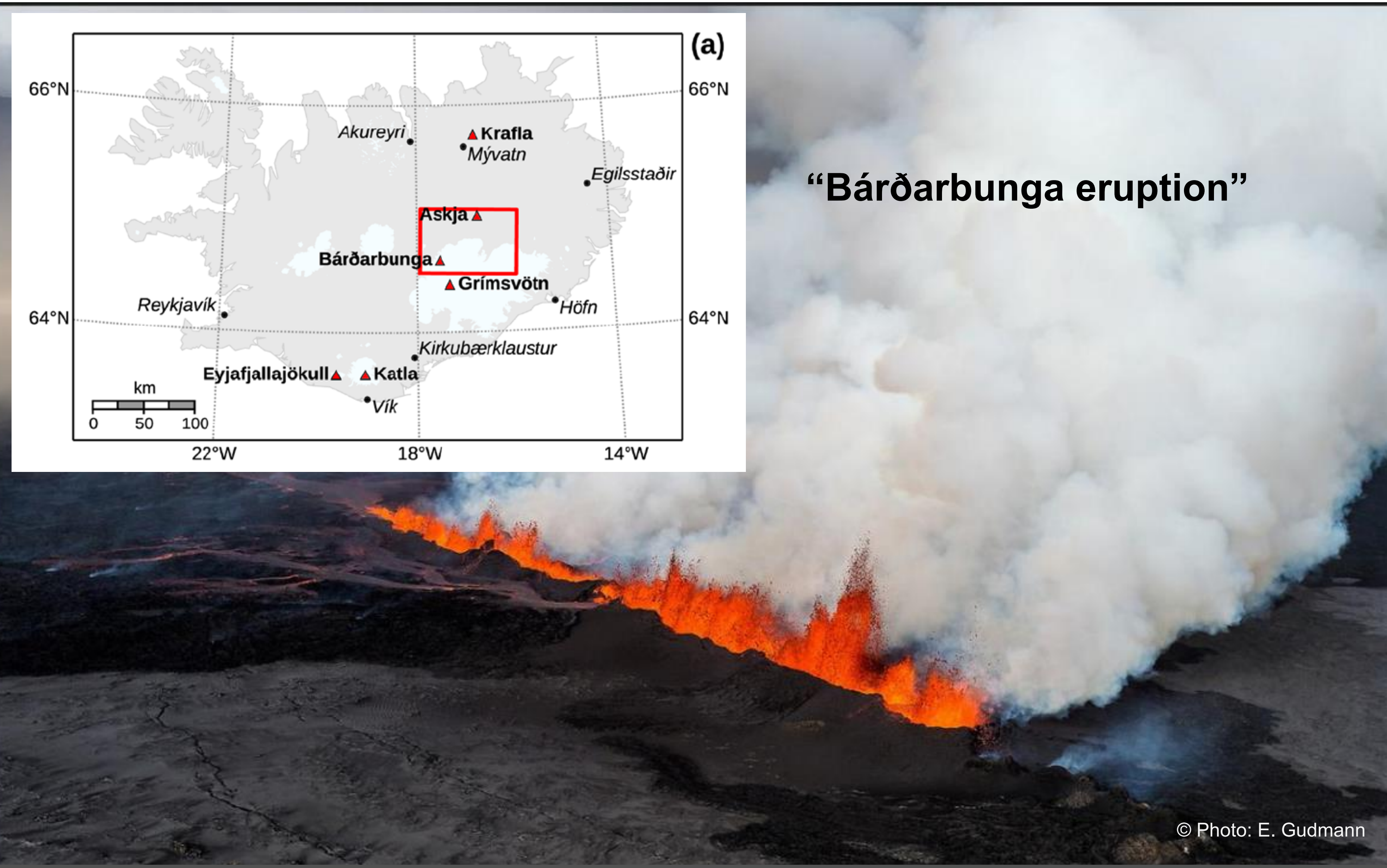
Schmidt et al., 2012, ACP
Rap et al., 2013, GRL

Record of eruptions in Iceland



- 205 historical eruptions in past 1150 years (on average one eruption every 5-6 years)
  - Hekla 2000, Grimsvötn 2004, Eyjafjallajökull 2010, Grimsvötn 2011, Holuhraun 2014-2015
- 78% are explosive, ash-producing eruptions
- Flood lava eruptions (> 1 km^3 of lava)

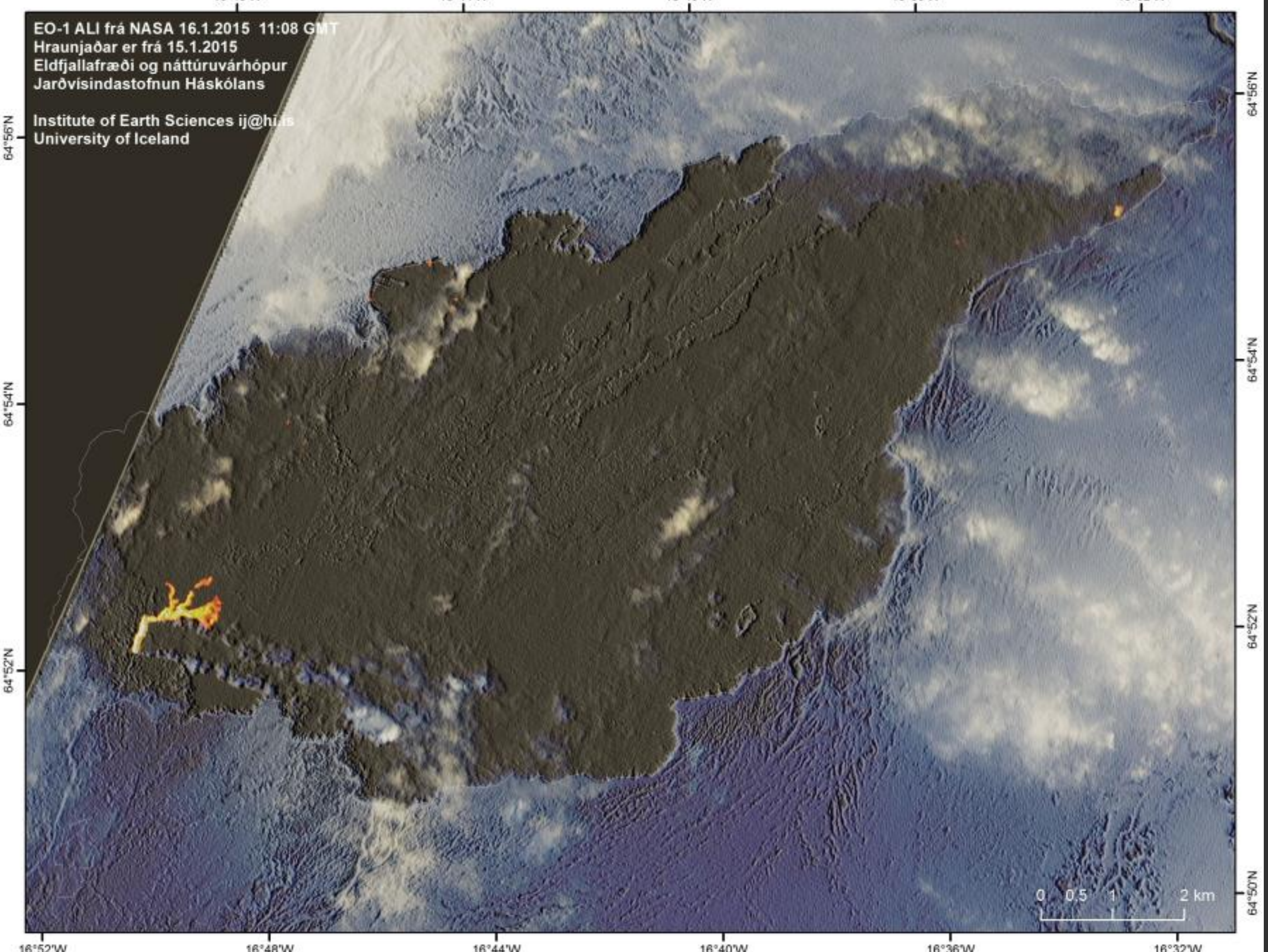
2014-2015 Holuhraun eruption (Iceland)



September 2014

Plume reached up to 6 km altitude

January 2015


EO-1 ALI frá NASA 16.1.2015 11:08 GMT
Hraunjaðar er frá 15.1.2015
Eldfjallafræði og náttúruvárhópur
Jarðvísindastofnun Háskólans
Institute of Earth Sciences ij@hi.is
University of Iceland
64°56'N
64°54'N
64°52'N
64°50'N
16°52'W
16°48'W
16°44'W
16°40'W
16°36'W
16°32'W
0
0.5
1
2 km

Largest eruption in Iceland in over 200 yrs

~1.5 km^3 of lava → covering Manhattan in 17 meters of lava!

Peak daily SO_2 emissions of 120 kt/d about 9x that from European industry (~13 kt/d).

Tropospheric plume detected by satellites and air quality monitoring sites

Why do we care?

Unique research opportunities!

- Focus has been on volcanic ash, Holuhraun provided excellent opportunity to study volcanic gas + aerosol impacts
- Case study for atmospheric models
  (transport, chemistry, deposition)
- Quantifying air quality impacts and health effects has implications for larger magnitude flood lava eruptions like 1783/84 Laki

Air quality impacts Sep’14

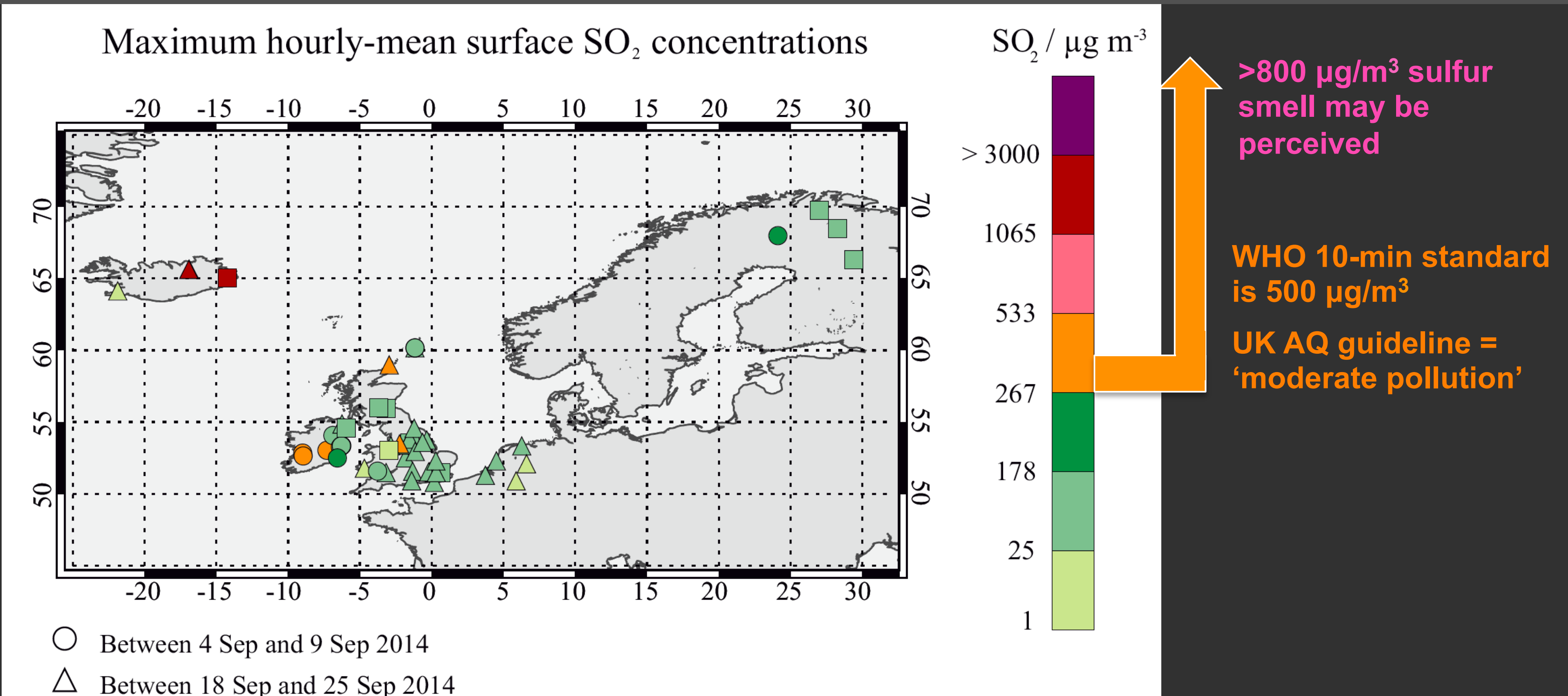
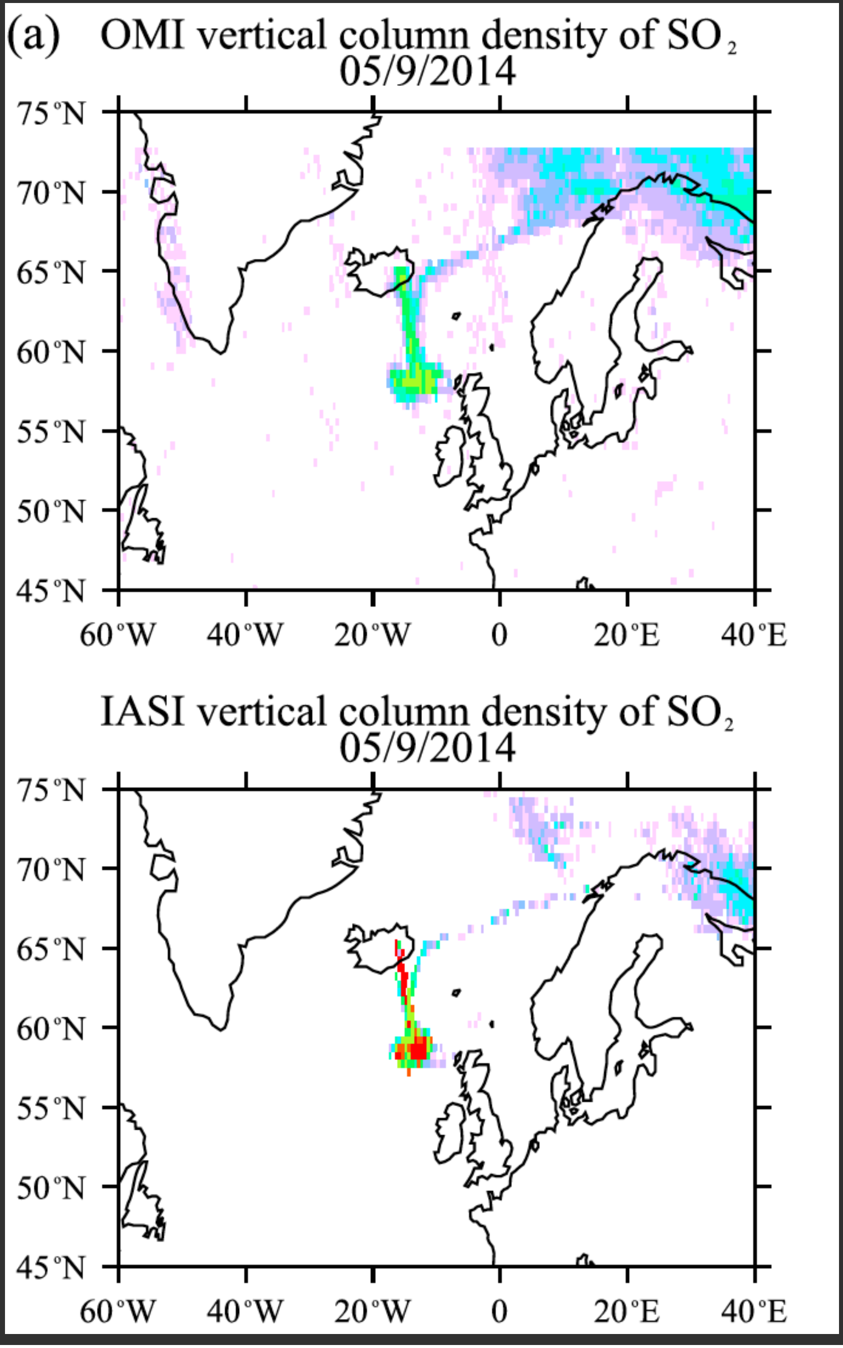


Figure: Schmidt et al., 2015, JGR

- Record high concentrations in Iceland
- Europe: highest measured SO_2 concentrations since 1980s
- SO_2 was transported over distances of >2700 km



OMI + IASI used to detect low-altitude plume throughout Sep/ Oct 2014

IASI also used to retrieve plume heights

→ Talk by Elisa Carboni

Combined observations with atmospheric modelling to derive fluxes independent of ground-based measurements

→ Schmidt et al., 2015, JGR

MODIS r_{eff} vs HadGEM3 r_{eff}

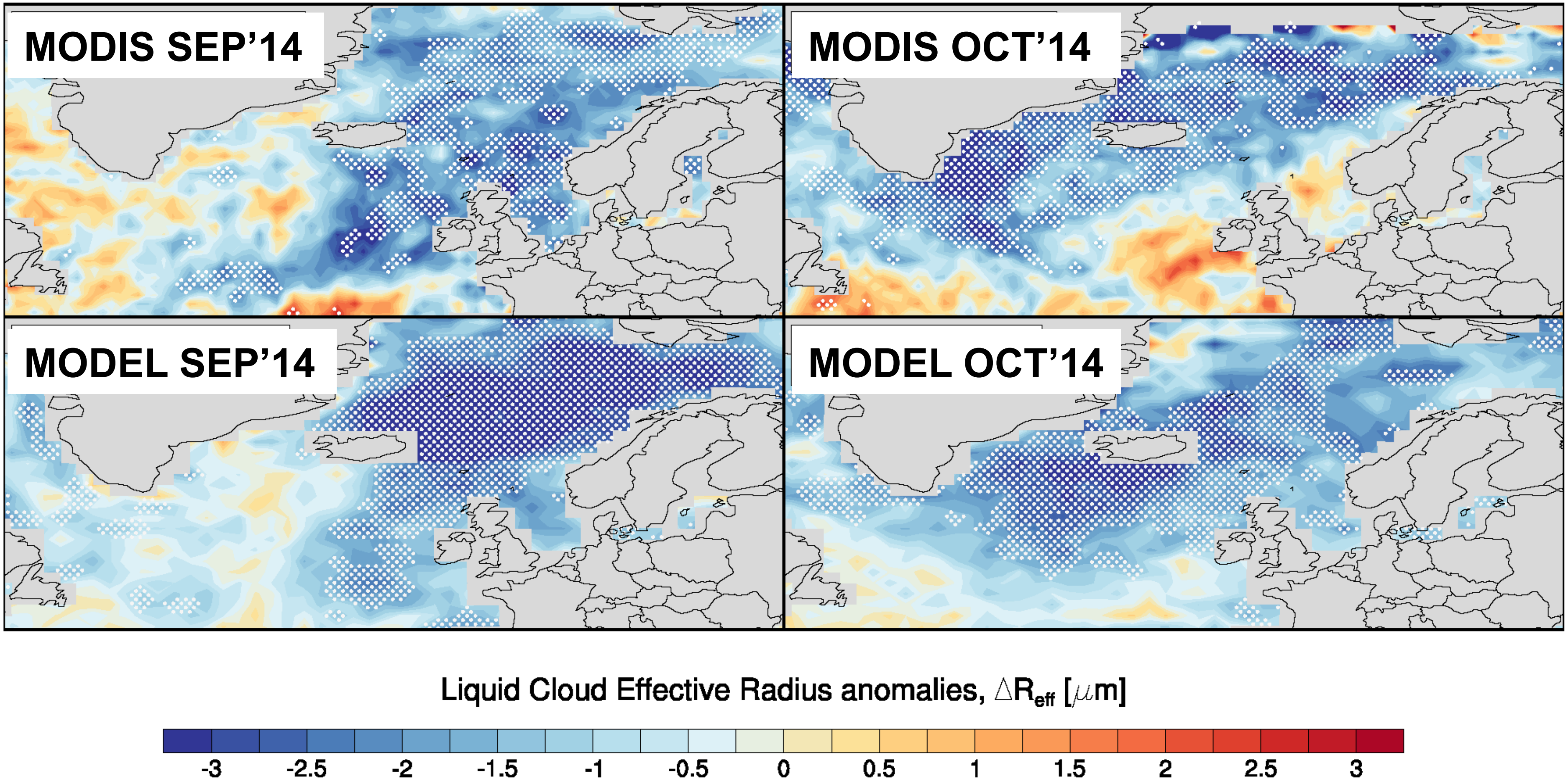
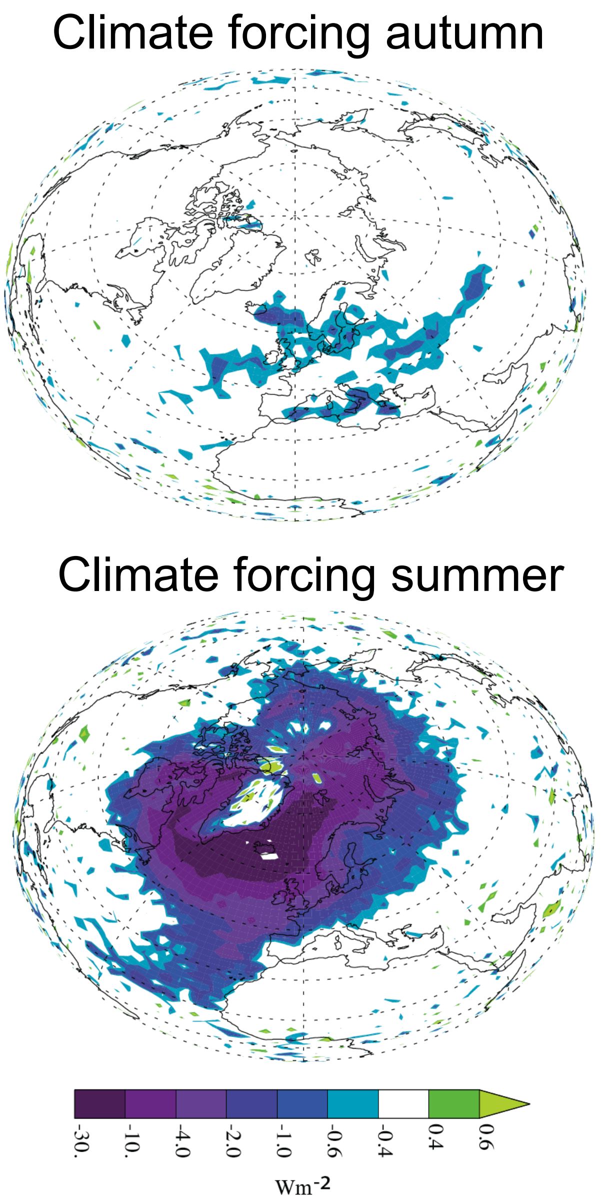


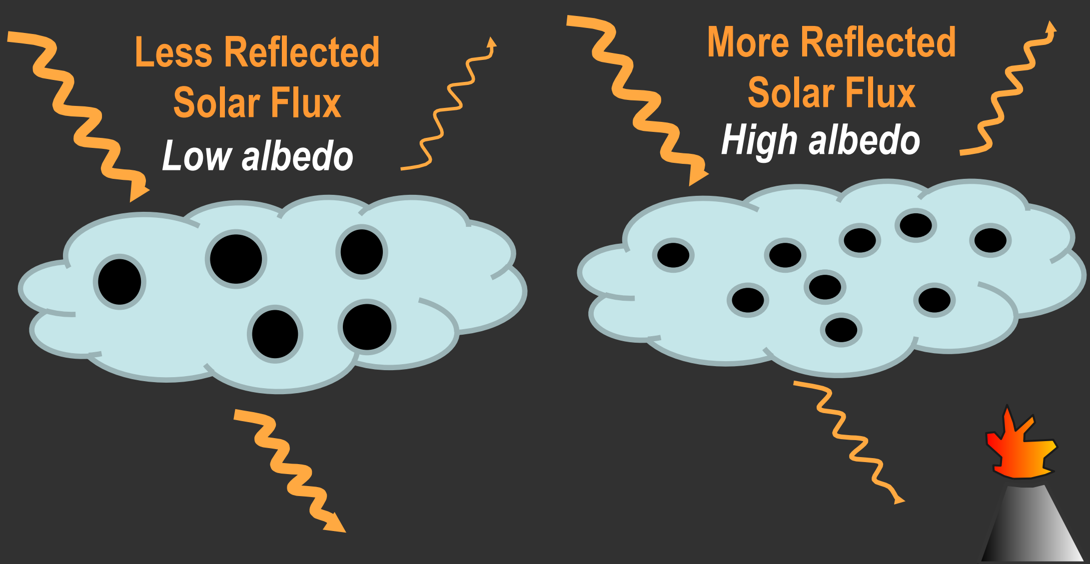
Figure: Haywood et al. (under review)

Supported by McCoy & Hartmann, 2015

CESM radiative forcing



- Emissions did not reach stratosphere, but affected brightness of low-level clouds ('aerosol indirect effect') [e.g., Schmidt et al., 2010, 2012]
- Climate forcing over N. Atlantic and W. Europe could have exceeded that from current anthropogenic emissions in same region
- Opportunity for in-situ observations, etc



Gettelman, Schmidt & Kristjansson, 2015, Nature Geoscience

1783-1784 CE Laki Eruption in Iceland

8 June 1783 – 7 February 1784

Lava = 14.7 km^3

Tephra = 0.4 km^3

SO_2 = 122 Tg

into 9-13 km altitude

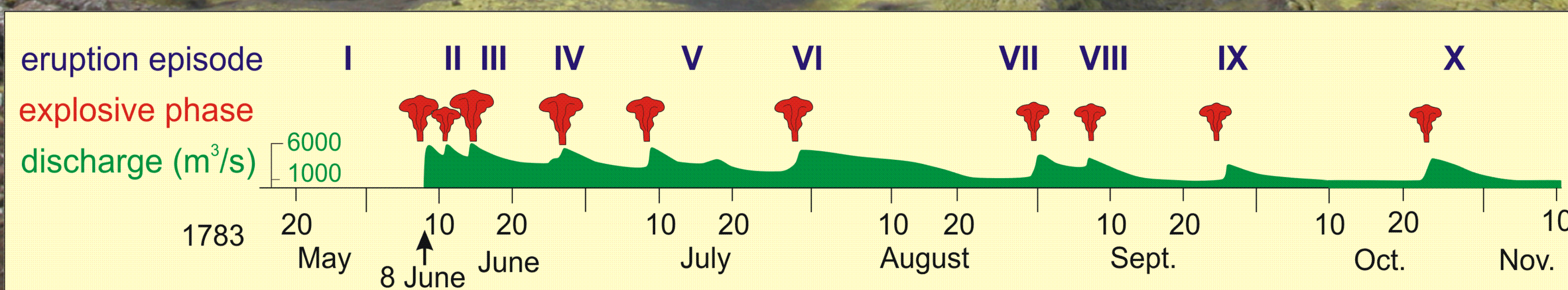


Photo courtesy of Alan Robock

Historical records of aftermath

Laki was the biggest atmospheric pollution event in historic times.

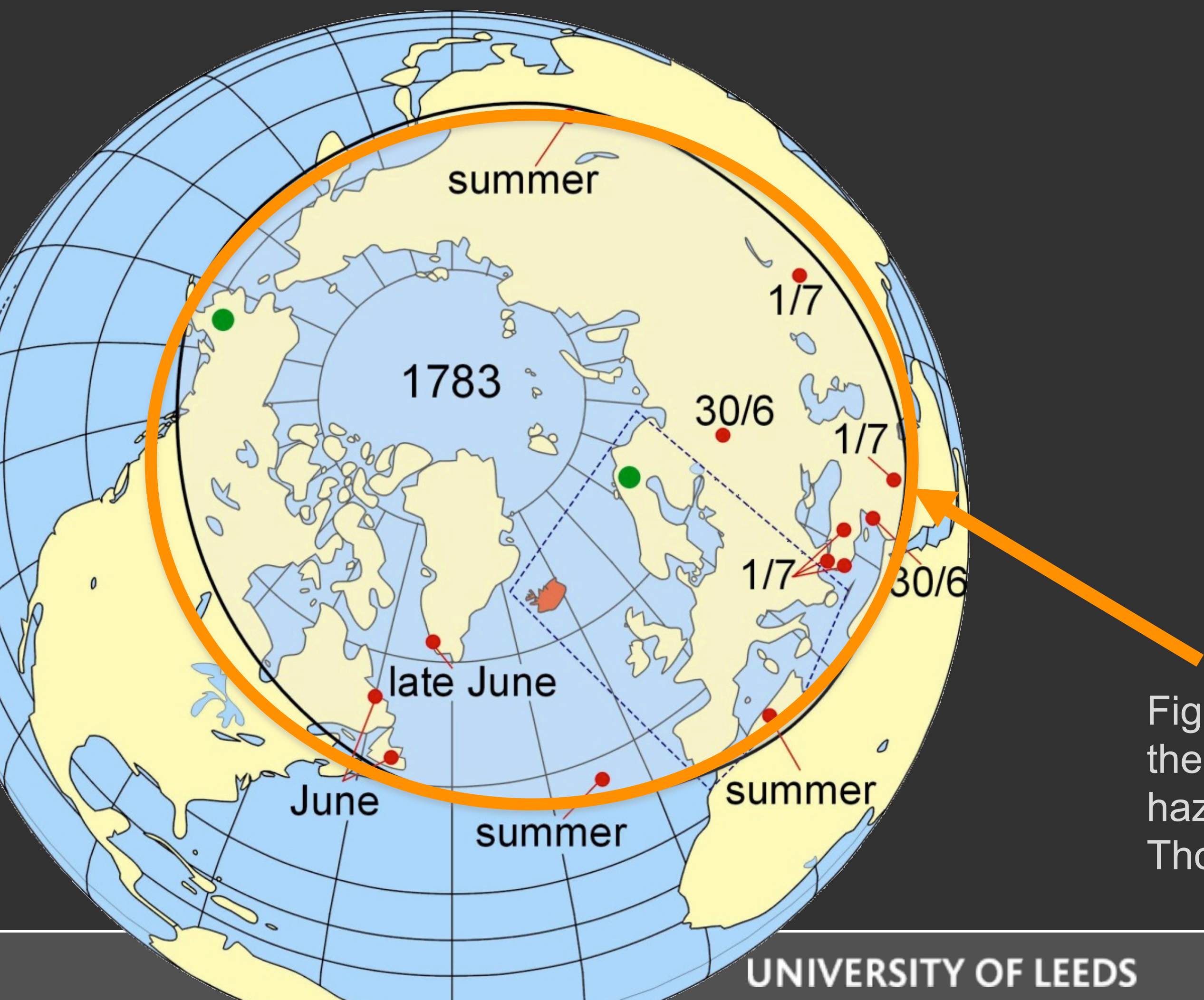
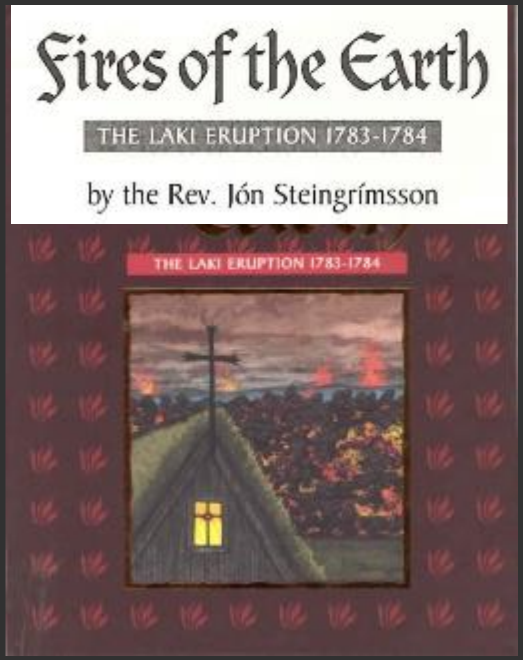
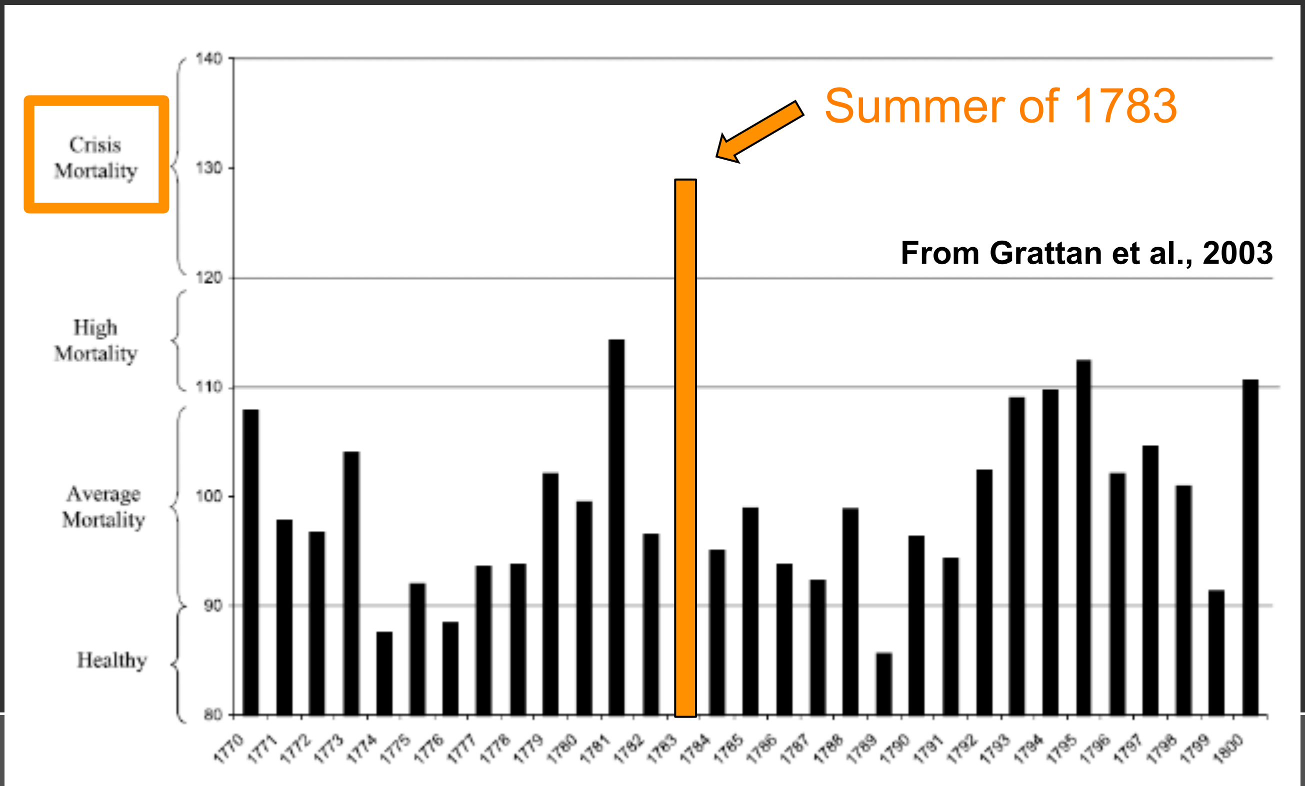


Figure showing extent and date of the first appearance of the Laki haze at the surface (from Thordarson & Self, 2003).

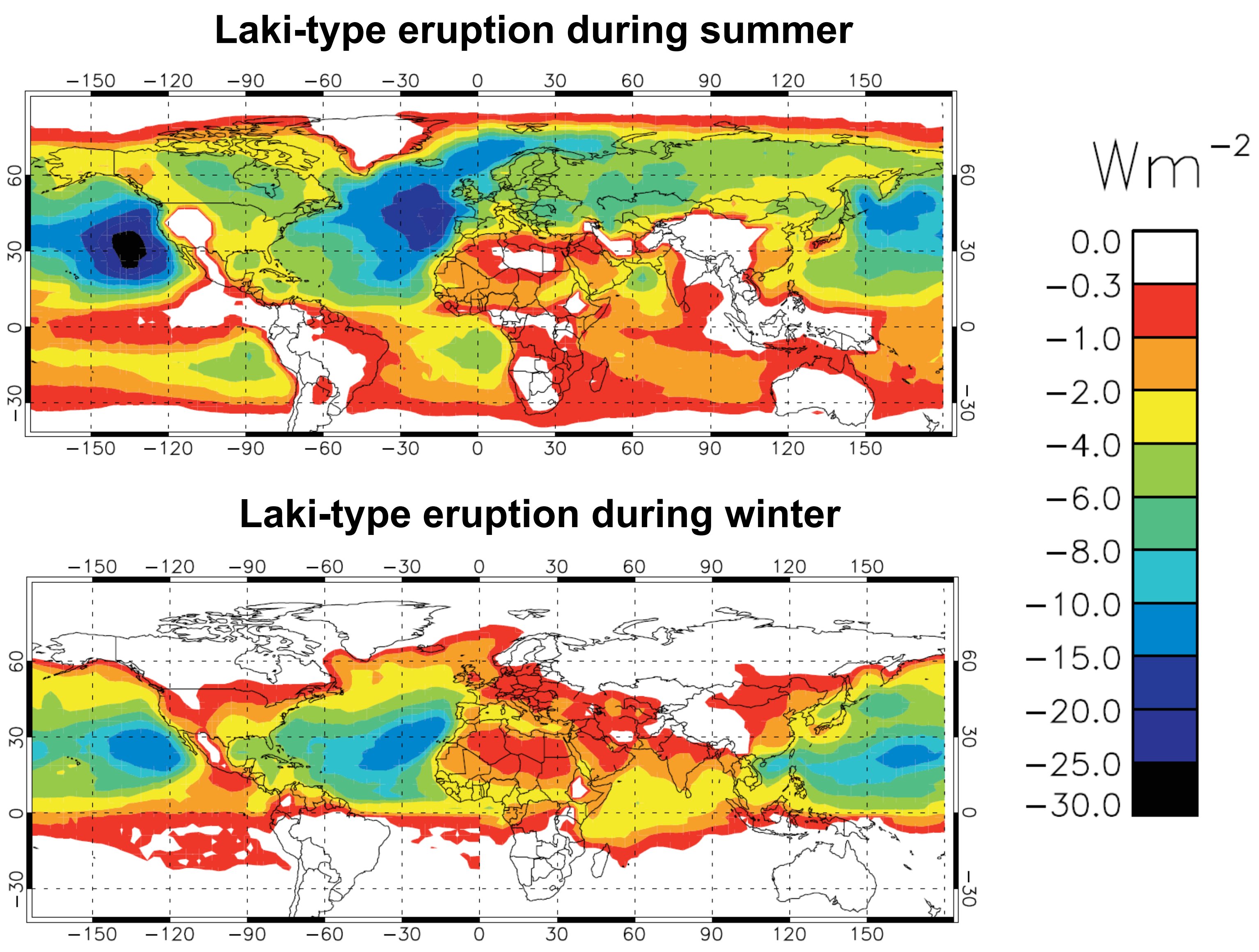
Historical records of aftermath

- **Iceland: ~21%** of the human population and **75%** of livestock perished
- Parish mortality records: **mortality in England in summer 1783 was 10-20%** above 51-year moving mean
- Several other accounts: in **France**, the **Netherlands**, **Italy** and **Sweden**





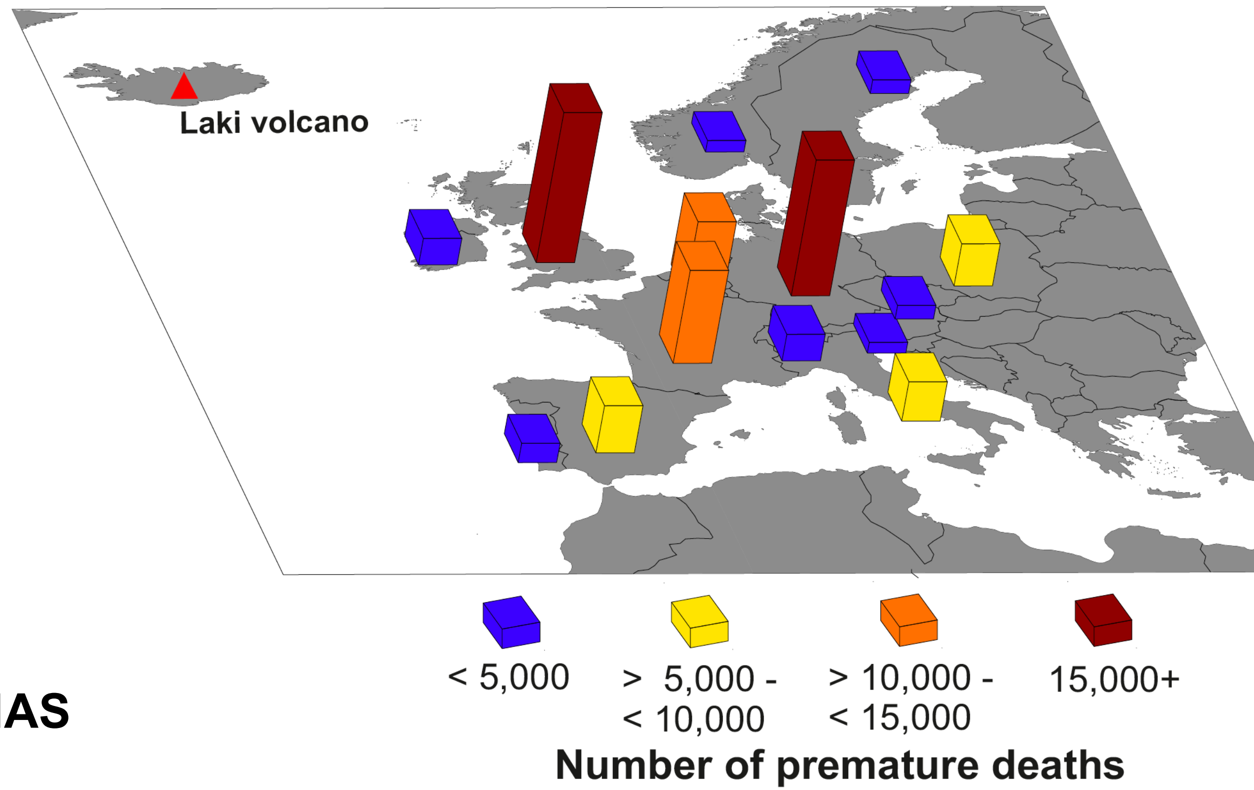
Cloud albedo forcing due to Laki



A future Laki-type eruption

Simulated impact on air quality
+
Population data
+
Baseline fatalities
+
Concentration-response functions

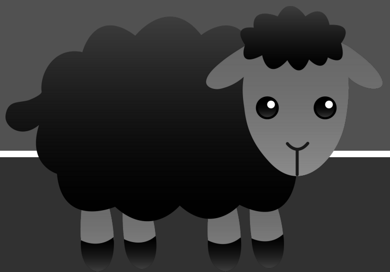
Cardiopulmonary deaths in year after onset of a Laki-type eruption



Schmidt et al, 2011, PNAS

- **>100,000 additional fatalities due to volcanic air pollution**
- Exceeds annual mortality rate due to seasonal influenza
- Context: Europe about 400,000 deaths caused by outdoor air pollution

Summary



- **Significant effects on air quality possible**
  - Holuhraun 2014-2015:
    - Air quality effects short-lived in far-field → no health effects there
    - Near-field air quality badly degraded → health effects are being investigated
  - A future Laki-type eruption:
    - Long-lasting degradation of air quality possible + health effects / increase in baseline mortality implied from modelling
- **Regional brightening of clouds possible**
  - Unprecedented opportunity to quantify/observe impacts on low-level clouds
- **2014/15 Holuhraun a missed opportunity in terms of in-situ measurements?**

Schmidt et al., 2010, 2011, 2012
Gettelman, Schmidt, and Kristjansson, 2015, Nature Geoscience
Schmidt et al., 2015, JGR

THANK YOU! @volcanofile

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NERC SCIENCE OF THE ENVIRONMENT
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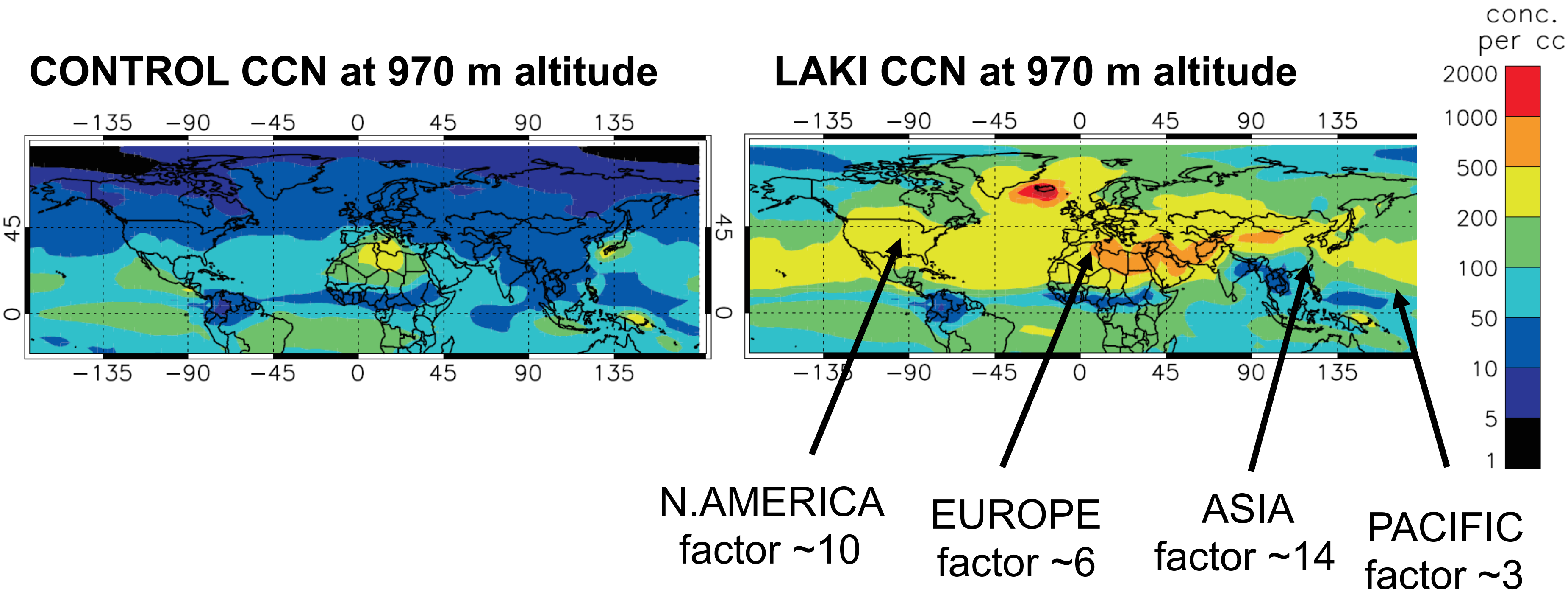
Additional slides

Widespread impact on CCN



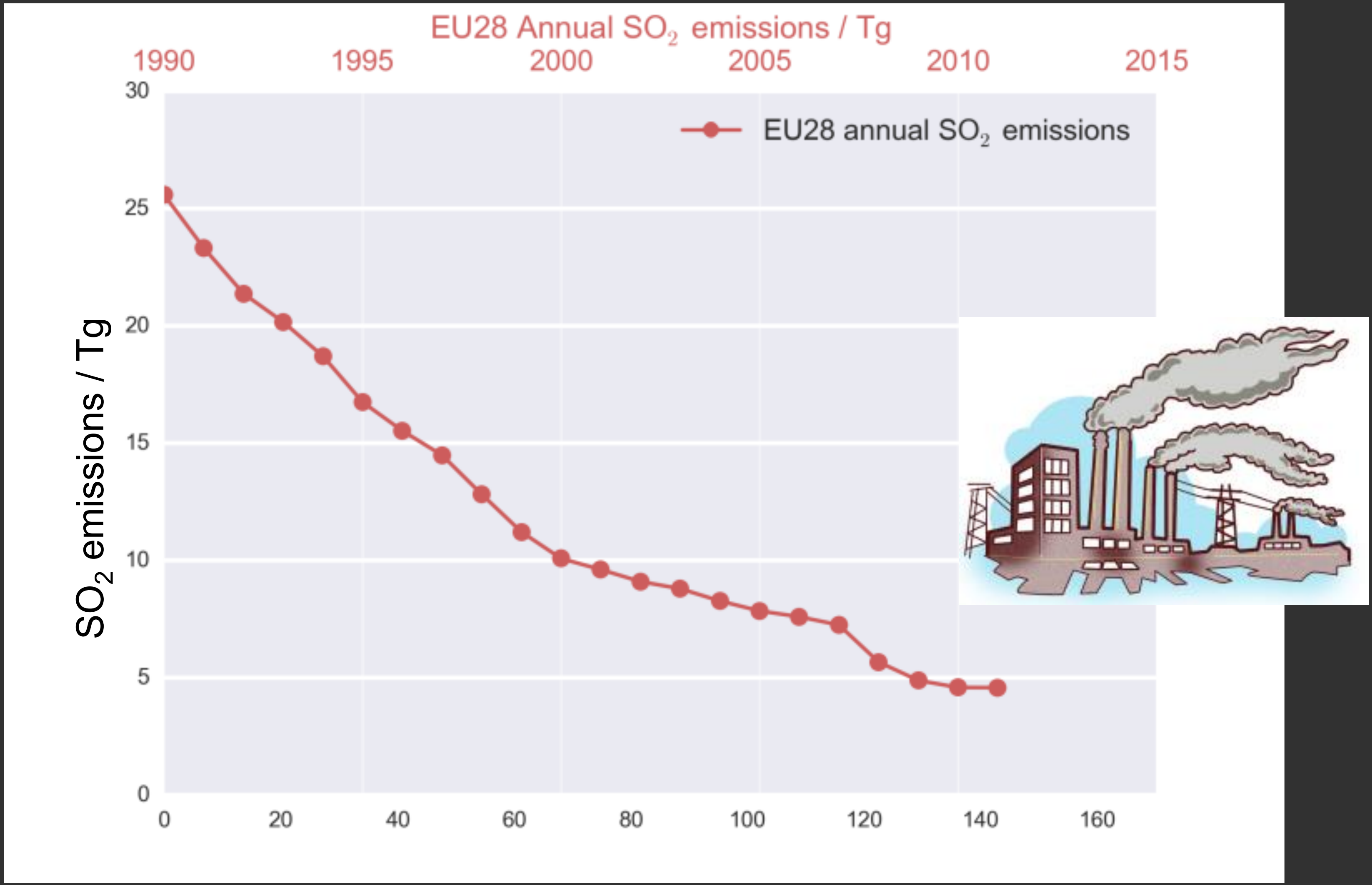
Schmidt et al. (2010), ACP

Satellite data & model set-up

- **OMI and IASI satellite data for Sep'14**
- **UK Met Office NAME** Lagrangian dispersion model [e.g., Jones et al., 2007]
- **Baseline simulation**
  - 31 Aug to 30 Sep 2014
  - 40 kt/d emitted uniformly into 1500 to 3000 m altitude
  - NWP meteorology for Sep 2014 (i.e. 'observed meteorology')
- **Sensitivity simulations**
  - Betw. 20 kt/d and 120 kt/d
  - Varied emission altitude ranges up to 4500 m a.g.l.
  - … many more …
- **Model evaluation**
  - Vertical column densities of SO_2 using OMI and IASI satellite retrievals
  - Surface SO_2 measurements across Europe for Sep 2014

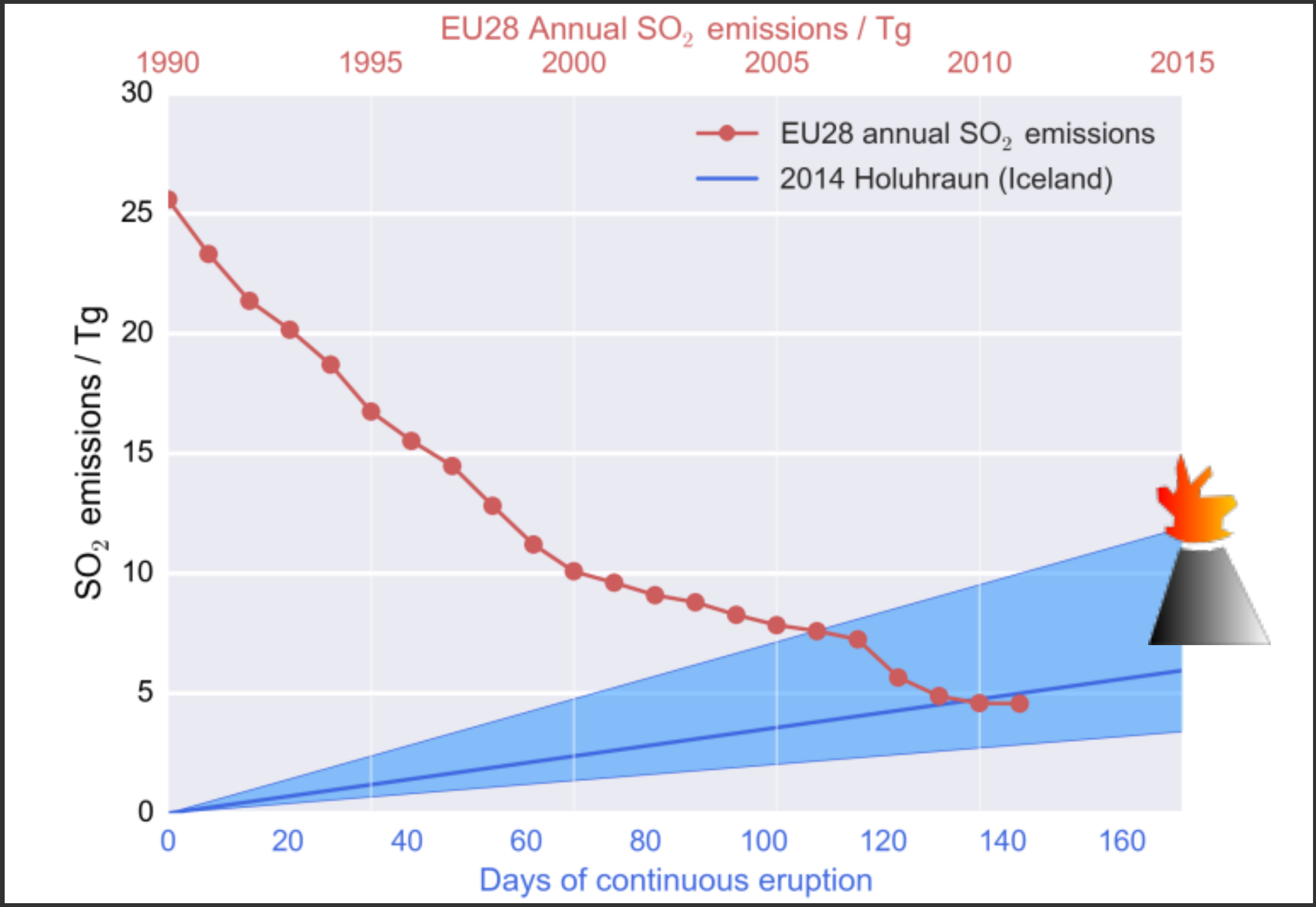
e.g., Schmidt et al., 2014; Webster et al., 2012; Devenish et al., 2012a,b; Witham et al., 2012; Jones et al., 2007

How much SO_2 was emitted?



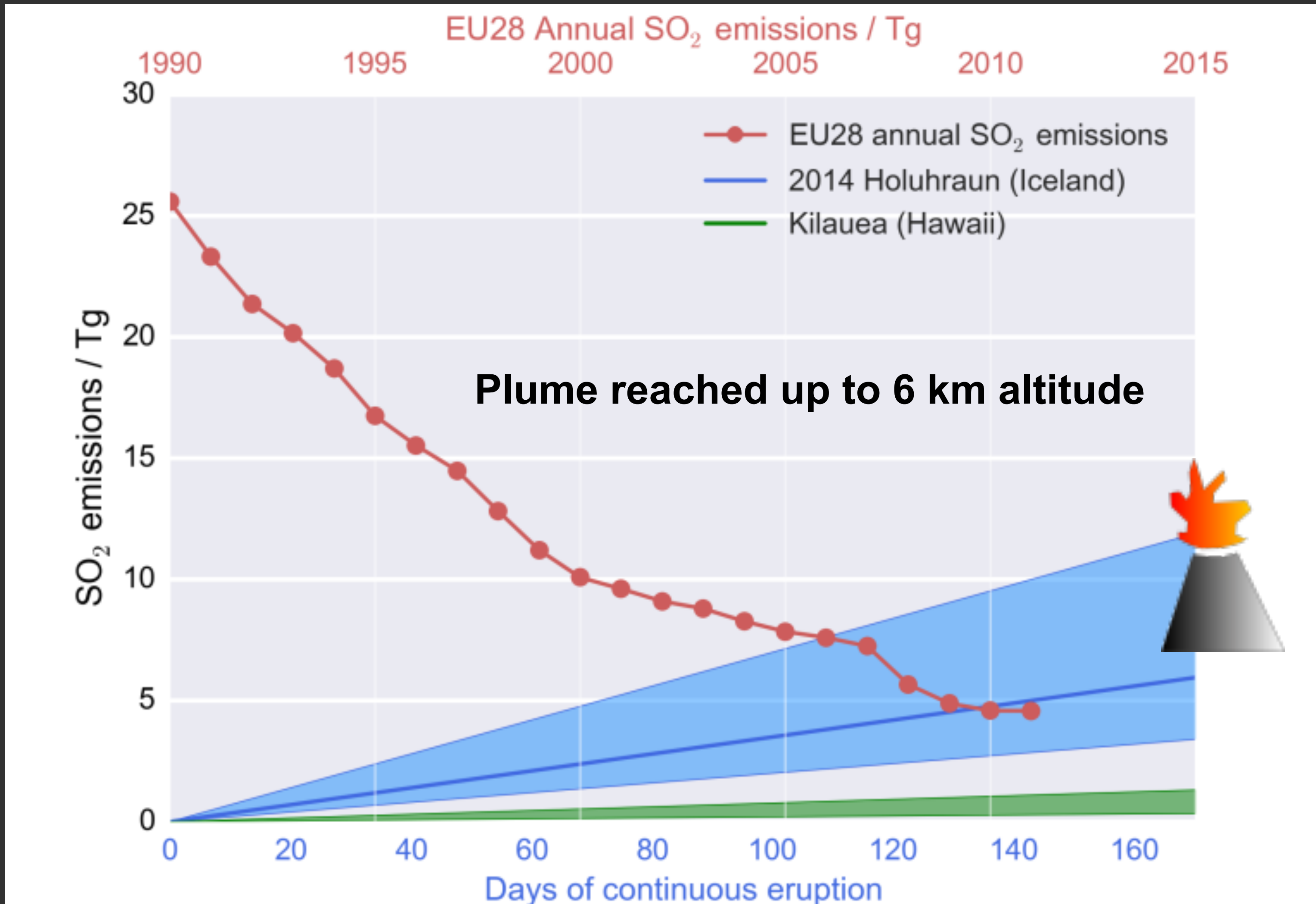
Data from: http://www.eea.europa.eu/data-and-maps/daviz/emission-trends-of-sulphur-oxides#tab-chart_2

How much SO_2 was emitted? A lot!

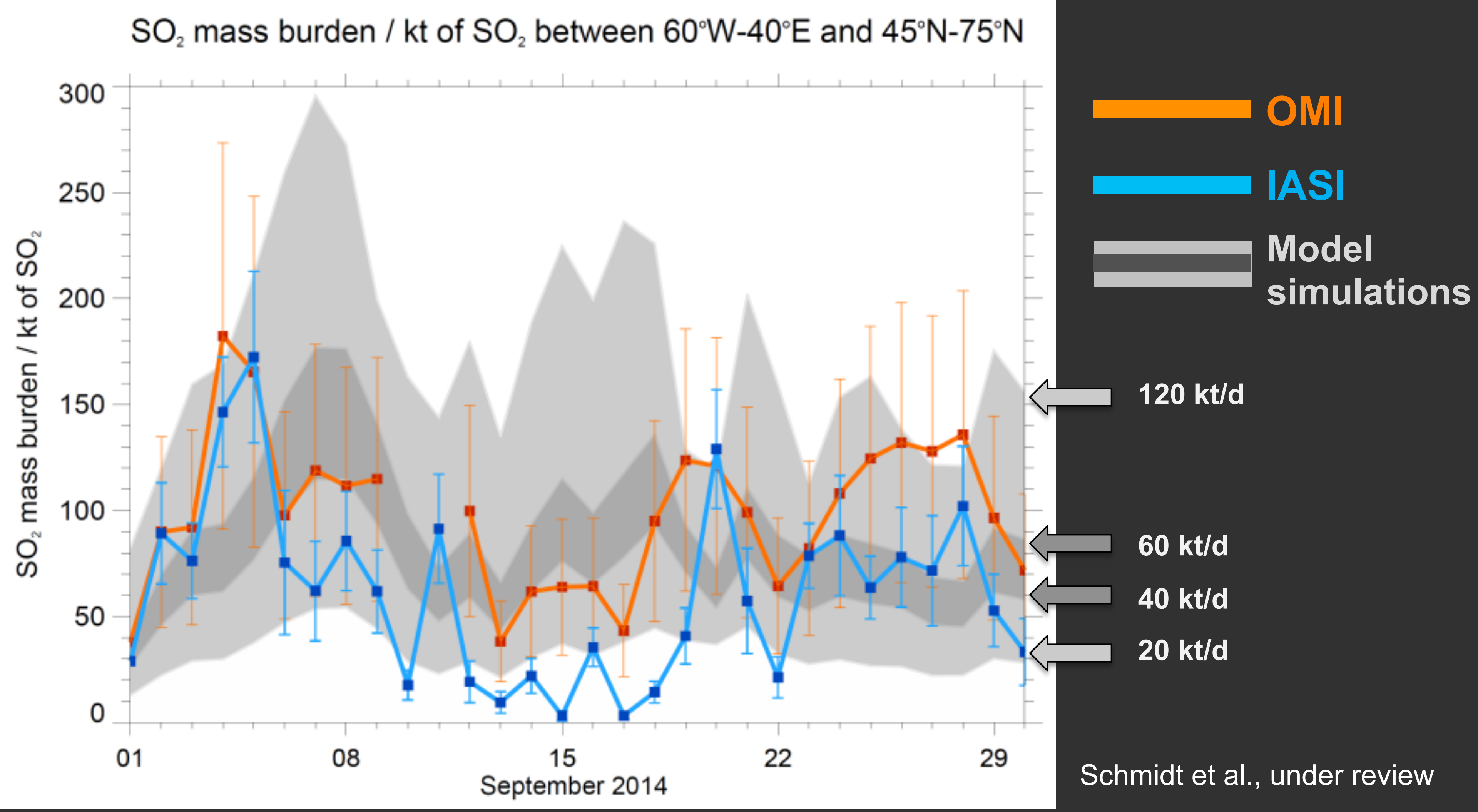


Based on Icelandic Met Office estimates of 35 kt/d of SO_2 on average (shading assumes 20 kt/d and 120 kt/d)

How much SO_2 was emitted? A lot!



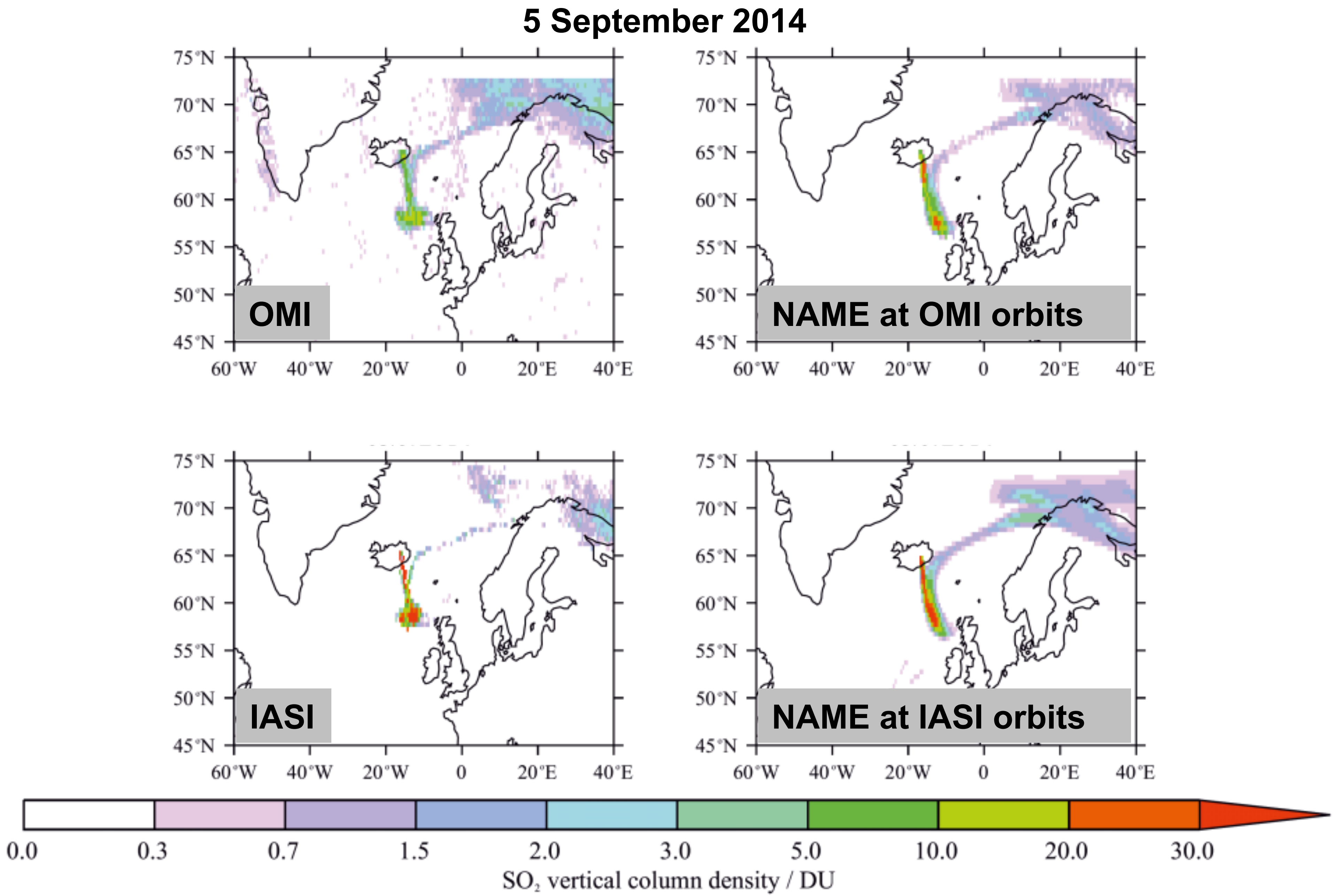
Based on Icelandic Met Office estimates of 35 kt/d of SO_2 on average (shading assumes 20 kt/d and 120 kt/d)



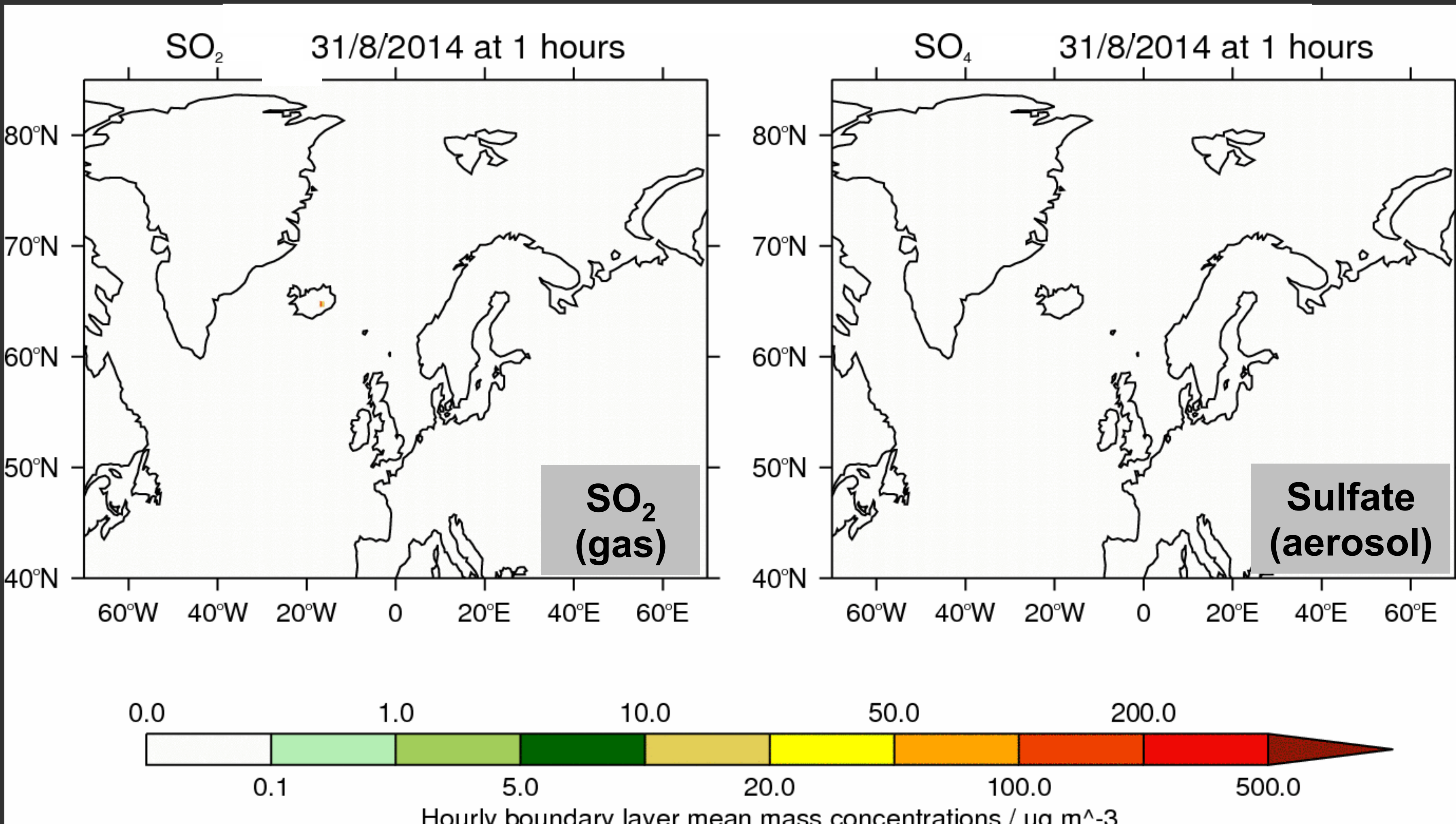
Schmidt et al., under review

- Average daily SO_2 mass burden Sep'14: 99±49 kt (OMI) & 61±18 kt (IASI)
- SO_2 emission rates to up to 120 kt/d during early Sep'14, followed by decrease to 20-60 kt/d between 6-18 Sep, followed by increase to 60-120 kt/d

OMI vs IASI vs NAME SO_2 VCDs



Dispersion of SO_2 & sulfate aerosol



CESM AOD & radiative effects

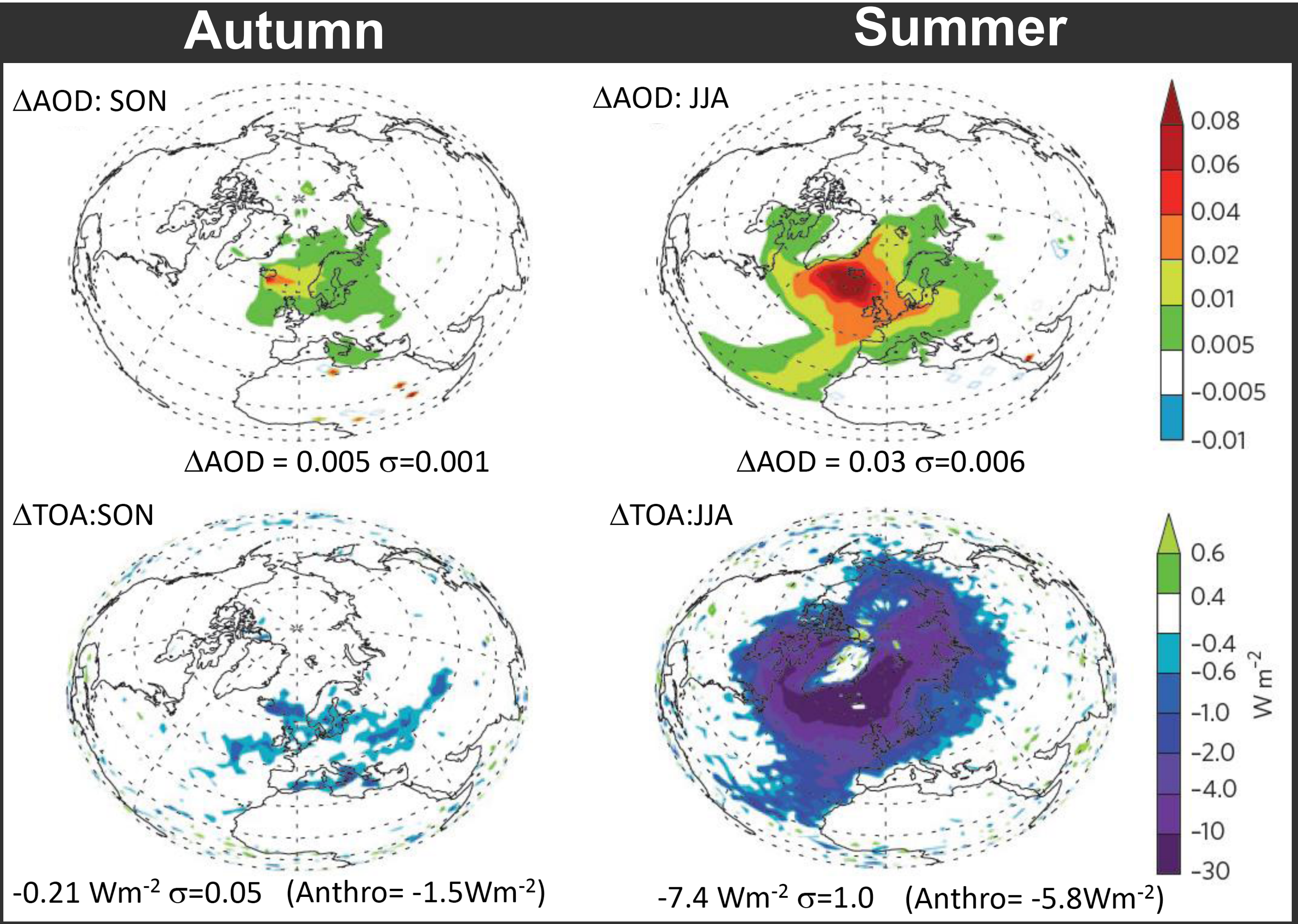


Figure: Gettelman et al., 2015, Nature Geoscience

Table 2. Maximum SO_2 Mass Concentrations ($\mu g/m^3$) Measured at Surface Air Quality Monitoring Stations During September 2014 (See Also Figure 2)[a]

Country	Air Quality Monitoring Station	Longitude	Latitude	Date	Distance From Eruption Source (km)	Maximum Hourly Mean SO_2 Concentration ($\mu g/m^3$)
Iceland	Reyðarfjörður Hjallaleyra	14.24°W	65.03°N	13 Sep 2014 02:00	123	1509.3
Iceland	Reykjahlíð Grunnskóli	16.89°W	65.64°N	24 Sep 2014 17:00	86	1450.6
Ireland	Ennis	8.98°W	52.84°N	6 Sep 2014 17:00	1409	524.2
Ireland	Portlaoise	7.29°W	53.03°N	6 Sep 2014 16:00	1422	310.7
Ireland	Askeaton	8.95°W	52.63°N	6 Sep 2014 18:00	1432	451.6
Finland	Sammaltunturi	24.12°E	67.98°N	7 Sep 2014 22:00	1818	186.5
Scotland	Kirkwall	2.96°W	58.98°N	21 Sep 2014 08:00	974	322.9
Netherlands	Philippine-Stelleweg	3.74°E	51.29°N	22 Sep 2014 14:00	1916	82.4
England	Harwell	1.32°W	51.57°N	22 Sep 2014 15:00	1725	96.6
England	Wicken Fen	0.29°E	52.29°N	22 Sep 2014 14:00	1703	96.1
Austria	Masenberg	15.89°E	47.35°N	22 Sep 2014 13:00	2755	247.0

Table: Schmidt et al., 2015, JGR

Research question

Can atmospheric models reproduce the AQ measurements?

- Model performance for volcanic eruptions mainly assessed in free troposphere and for volcanic ash [e.g., Webster et al., 2012; Witham et al., 2012]
- Few studies looked at simulating ash concentrations in the boundary layer [e.g., Devenish et al., 2012a,b]
- For other scenarios (e.g., nuclear accident) the pollutant is released in boundary layer instead of being released into the free troposphere

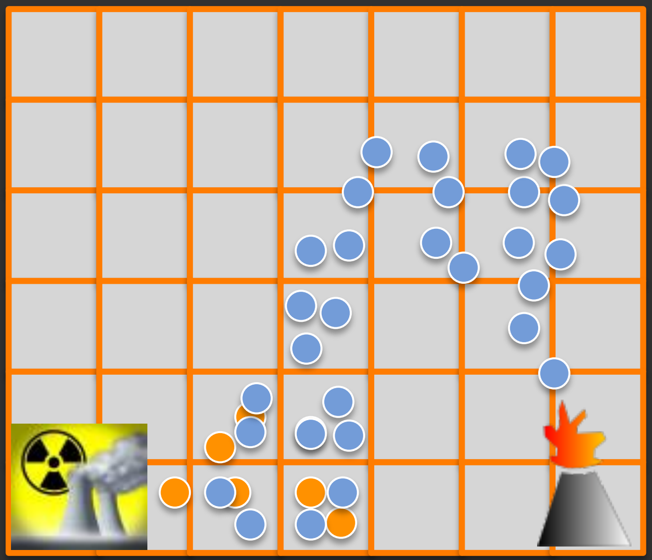
Great case study!

Boundary layer processes are generally difficult to get right in 'coarse resolution' atmospheric models.

Emissions into free troposphere. Interested in concentrations at flight level, i.e. the free troposphere

Emissions into free troposphere. Interested in concentrations at the surface

Emissions into boundary layer. Interested in concentrations in the boundary layer



GLOMAP – global aerosol model

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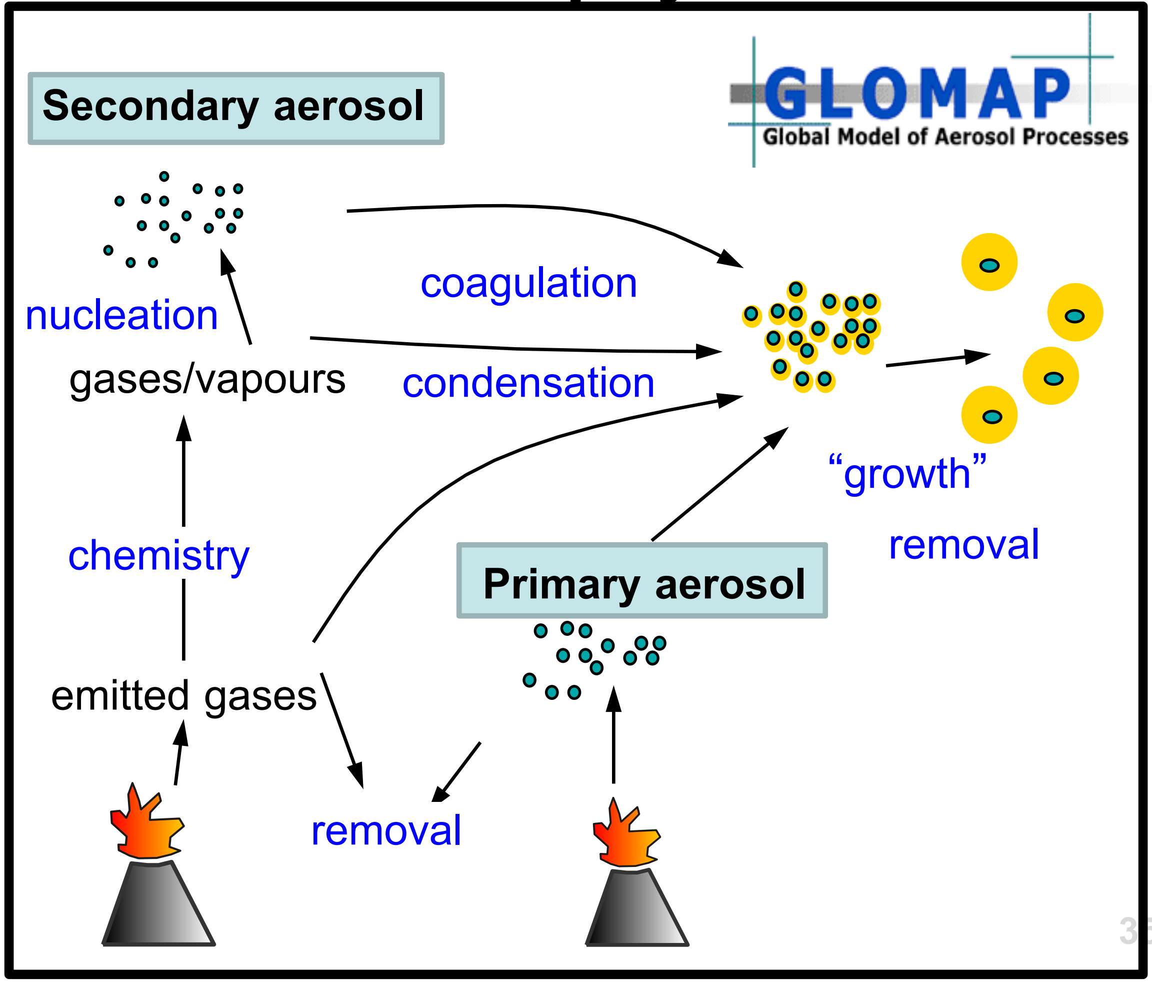
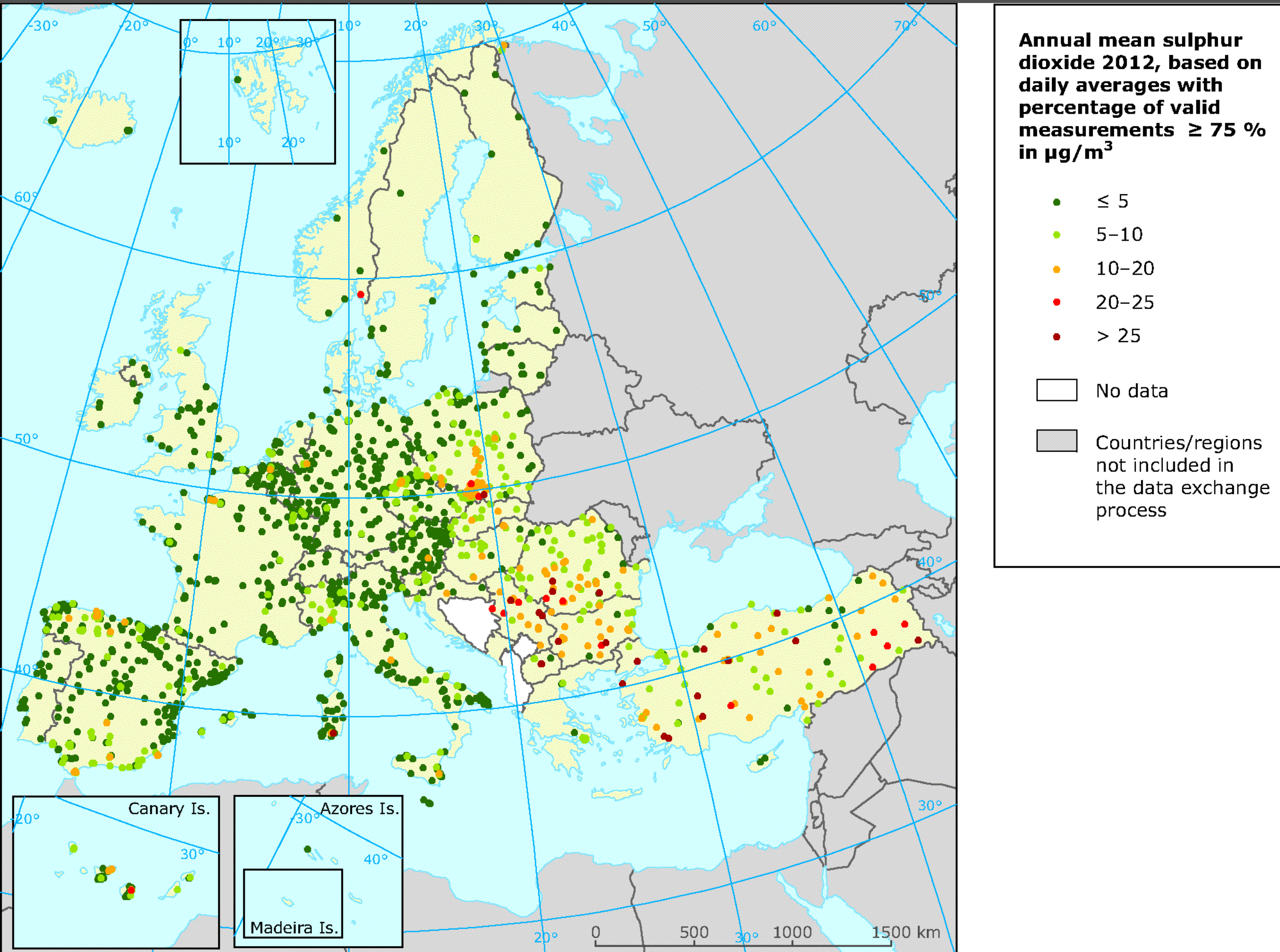
Aerosol microphysics model

Volcanological datasets →



Number + size of aerosol particles ←

Effects on chemistry, aerosol microphysics, climate, air quality, health, soils, ...


Annual mean sulphur dioxide 2012, based on daily averages with percentage of valid measurements ≥ 75 % in µg/m3
≤ 5
5–10
10–20
20–25
> 25
No data
Countries/regions not included in the data exchange process
Canary Is.
Azores Is.
Madeira Is.
0
500
1000
1500 km